Hydrologic Modeling of a Probable Maximum Precipitation Event Using HEC-HMS and GIS Models – A Case Study of Two Watersheds in Southern Virginia

William John Kingston III

Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Civil Engineering

Panayiotis Diplas (Chair)
Robert J. Bodnar
Glenn E. Moglen

June 11, 2012
Blacksburg, Virginia

Keywords: Probable Maximum Storm, HEC-GeoHMS,
PMP, PMF, Coles Hill

Hydrologic Modeling of a Probable Maximum Precipitation Event Using HEC-HMS and GIS Models – A Case Study of Two Watersheds in Southern Virginia

William John Kingston III

ABSTRACT

Presented in this thesis is a case study of two study watersheds located in south central Virginia. For each, a HEC-HMS event-based hydrologic model was constructed to simulate the rainfall-runoff response from the Probable Maximum Storm (PMS), the theoretical worst-case meteorological event that is capable of occurring over a particular region. The primary goal of these simulations was to obtain discharge hydrographs associated with the Probable Maximum Flood (PMF) at key locations in each of the watersheds. These hydrographs were subsequently used to develop flood inundation maps of the study areas and to characterize sediment transport phenomena in the study reaches under severe flooding conditions.

To build the hydrologic basin models, ArcHydro, HEC-GeoHMS and ArcGIS were employed to assimilate the substantial amount of input data and to extract the pertinent modeling parameters required for the selected simulation methods. In this, the SCS Loss and Transform Methods, along with the Muskingum Routing Method, were adopted for the HEC-HMS simulations.

Once completed, the basin models were calibrated through a comparison of simulated design storm flows to frequency discharge estimates obtained with regional regression techniques and a flood frequency analysis. The models were then used to simulate their respective PMS events, which were developed following recommendations from the Hydrometeorological Branch of the National Weather Service and the U.S. Army Corps of Engineers.

Descriptions of each of the study sites, explanations of the modeling theory and development methodologies, and discussions of the modeling results are all detailed within.

ACKNOWLEDGEMENTS

I would first like to express my sincere gratitude to my research advisor, Dr. Panos Diplas, and my research partners, Celso Castro-Bolinaga, Edgardo Zavaleta, and Lindsay Lally, for their support and encouragement throughout the course of this project. Their advice and insight proved invaluable in helping me understand and overcome the issues that arose in my research. I would also like to thank my committee members, Dr. Glenn Moglen and Dr. Robert Bodnar, for their time and assistance over the past couple years.

In addition, I would like to convey my genuine appreciation to the Virginia Tech Civil and Environmental Engineering Department for selecting me as a recipient of the prestigious Charles E. Via Master's Fellowship. I would like to acknowledge the assistance granted from this award, as well as the support that I have received from Virginia Uranium, Inc., both of which have enabled me to pursue and achieve my graduate education. I sincerely thank VUI, Walter Coles, Sr., Joseph Aylor, Alan Kuhn, and the rest of the members of the VT/VUI research group for their thoughtful discussions, guidance, and suggestions over the course of this project.

Finally, I would like to acknowledge my family and friends for their continuous love and encouragement. It is because of them that I have made it this far.

TABLE OF CONTENTS

Abstract ... ii

Acknowledgements ... iii

List of Figures ... vii

List of Tables ... xvii

Glossary/Abbreviation Key ... xxiv

1. Introduction ... 1

1.1 Overview ... 1

1.2 Motivation/Objectives of Overall Studies ... 2

1.2.1 Contribution of this Thesis to the Overall Work ... 3

1.3 Description of the Study Areas ... 4

1.3.1 General Site Description ... 4

1.3.2 Whitethorn Creek Study Watershed Analysis ... 6

1.3.3 Banister River Study Watershed Analysis ... 7

1.4 Key Engineering Questions ... 9

2. Background / Literature Review ... 10

2.1 Event Hydrologic Modeling ... 10

2.2 Probable Maximum Precipitation/Hydrometeorological Branch Studies ... 11

3. Hydrologic Modeling Theory and Methodology ... 15

3.1 Model Description ... 15

3.1.1 HEC-HMS ... 15

3.1.2 ArcHydro/HEC-GeoHMS ... 16

3.2 Overview of Model Development ... 17

3.2.1 HEC-HMS Basin Model Development ... 18

3.2.2 HEC-HMS Meteorological Model Development ... 29

3.3 Model Calibration/Comparison Techniques 35
3.3.1 USGS Regional Regression Equations for Estimating Peak Discharges 36
3.3.2 Bulletin 17B Flood Frequency Analysis 39
4. Case Study – Whitethorn Creek / Banister River Study Watersheds 41
4.1 Geospatial / Standard Regression / Field-collected Data Sources 41
4.2 GIS based Hydrologic Modeling – Basin Model Development 42
4.2.1 Watershed/Subbasin Delineation 42
4.2.2 Loss Method Parameter Determination... 45
4.2.3 Transform Method Parameter Determination 47
4.2.4 Hydrologic Routing Method Parameter Determination 54
4.2.5 Discussion on Canopy, Surface, and Baseflow Methods 56
4.3 Meteorological Model Development 56
4.3.1 Frequency Storm Meteorological Model Development 56
4.3.2 Probable Maximum Precipitation/Probable Maximum Storm 60
4.3.3 Specified Hyetograph Meteorological Model Development......................... 63
4.4 Control Specifications Model 65
4.5 Hydrologic Simulation of PMS 65
5. Results and Discussion...66
5.1 Frequency Storm Comparison Results – Whitethorn Creek Analysis 66
5.2 Frequency Storm Comparison Discussion – Whitethorn Creek Analysis 70
5.3 Frequency Storm Comparison Results – Banister River Analysis 71
5.4 Frequency Storm Comparison Discussion – Banister River Analysis........................ 82
5.5 PMP/PMS Simulation Results 85
6. Conclusion...88
6.1 Answers to Key Engineering Questions 88

6.2 Concluding Remarks 91

7. References 93

Appendix A: The Development of a Hydrologic Basin Model Using HEC-GeoHMS, ArcHydro, and ArcGIS…………………………………………………………………..…....99

Appendix B: NOAA Atlas 14 Precipitation Frequency Data……………………..………..….132

Appendix C: Development of the PMP/PMS for the Study Watershed Following the HMR Methodology……………………………………………….…………….……137

Appendix D: Background Data Used to Compute T_c the Banister River Analysis……………197

Appendix E: HEC-HMS Basin Model Input Parameter Tables.……………...……………..…204

Appendix F: HEC-HMS Outflow Hydrographs for Comparison Point Locations - Frequency Storms & PMS……………………………………………………………………215

LIST OF FIGURES

Figure 1: Location Map of Coles Hill in Relation to Downstream Waterways and Drinking Water Intakes (Baker, 2011) 5

Figure 2: Location Map of Study Watersheds within Pittsylvania and Halifax Counties, Virginia 6

Figure 3: Location Map of the “Whitethorn Creek Study Watershed” Showing Modeling Extents and Key Basin Features - Inset Map Showing Project Site Location in Virginia. 7

Figure 4: Location Map of the "Banister River Study Watershed” Showing Modeling Extents and Key Basin Features - Inset Map Showing Project Site Location in Virginia. 8

Figure 5: All-Season PMP Map (in.) for a 10 mi^2 Drainage Area for a 6hr. Storm Duration (Schreiner & Riedel, 1978) 12

Figure 6: Schematic of Basic Components of the Hydrologic Modeling Process 18

Figure 7: Steps Involved in the Thiessen Polygon Interpolation Scheme 32

Figure 8: Physiographic Peak-Discharge Regions of Virginia (Bisese, 1995) 36

Figure 9: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Whitethorn Creek Study Watershed 44

Figure 10: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Banister River Study Watershed........................ 44

Figure 11: Whitethorn Creek Study Watershed Basin Model Open in HEC-HMS 45

Figure 12: Banister River Study Watershed Basin Model Open in HEC-HMS 45

Figure 13: SCS CN Grids Corresponding to ARC II (left) ARC III (right) for the Banister River Study Watershed 47

Figure 14: SCS CN Grids Corresponding to ARC II (left) ARC III (right) for the Whitethorn Creek Study Watershed 47

Figure 15: NOAA Atlas 14 PFDS Gauging Stations with Thiessen Polygons in Relation to the Banister River Study Watershed 59

Figure 16: Selected PMS Isohyetal Distribution for the Whitethorn Creek Study Watershed..... 61

Figure 17: Selected PMS Isohyetal Distribution for the Banister River Study Watershed 62

Figure 18: Map Showing the Two Selected Bisese Comparison Points Used for the Whitethorn Creek Analysis 67

Figure 19: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 1 69

Figure 20: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 2 70

Figure 21: Map Showing the Three Selected Bisese Comparison Points Used for the Banister River Analysis 72

Figure 22: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 1 76

Figure 23: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 2 76

Figure 24: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 3 77

Figure 25: Graphical HEC-SSP Bulletin 17B FFA Results for the Banister River USGS Stream Flow Gauge at Halifax, VA (USGS 02077000) - 82-yr Period of Record (1929-2010) 79

Figure 26: HEC-HMS Simulated Discharges vs. HEC-SSP FFA Expected Probability Discharges - 2-yr to the 1000-yr 24-hr Frequency Storms –Banister River at the Bethel Rd. Bridge Crossing in Halifax, VA 81

Figure 27: PMF Outflow Hydrograph at the Outlet Point of the Whitethorn Creek Study Watershed Resulting from the 72-hr PMS – ARC III & NRCS Basin Lag Equation......... 86

Figure 28: PMF Outflow Hydrograph at the Outlet Point of the Banister River Study Watershed Resulting from the 72-hr PMS – ARC III & NRCS Basin Lag Equation.......... 87

Figure 29: ArcHydro Tools 9 – Terrain Preprocessing Menu 102

Figure 30: Digital Elevation Model for the Whitethorn Creek Study Watershed 103

Figure 31: Digital Elevation Model for the Banister River Study Watershed 103

Figure 32: Threshold Stream Definition Grid for the Whitethorn Creek Study Watershed – Based on a Threshold of 1 km2 105

Figure 33: Threshold Stream Definition Grid for the Banister River Study Watershed – Based on a Threshold of 6 km^2 106

Figure 34: Threshold Stream Segment Catchment Grid for the Whitethorn Creek Study Watershed 107

Figure 35: Threshold Stream Segment Catchment Grid for the Banister River Study Watershed 108

Figure 36: NLCD 2006 Land Cover for the Whitethorn Creek Study Watershed 111

Figure 37: NLCD 2006 Land Cover for the Banister River Study Watershed 111

Figure 38: SSURGO Soil Data by Hydrologic Soil Group for the Whitethorn Creek Study Watershed 113

Figure 39: SSURGO Soil Data by Hydrologic Soil Group for the Banister River Study Watershed 113

Figure 40: SCS/NRCS CN_{II} Grid for the Whitethorn Creek Study Watershed 117

Figure 41: SCS/NRCS CN_{II} Grid for the Banister River Study Watershed 117

Figure 42: SCS/NRCS CN_{III} Grid for the Whitethorn Creek Study Watershed 118

Figure 43: SCS/NRCS CN_{III} Grid for the Banister River Study Watershed 118

Figure 44: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Whitethorn Creek Study Watershed 121

Figure 45: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Banister River Study Watershed 122

Figure 46: Whitethorn Creek Study Watershed Basin Model Open in HEC-HMS 130

Figure 47: Banister River Study Watershed Basin Model Open in HEC-HMS 130

Figure 48: Depth-Area-Duration Curves for the Whitethorn Creek Study Watershed 142

Figure 49: Depth-Area-Duration Curves for the Banister River Study Watershed 142

Figure 50: Depth-Duration Curves for Selected Area Sizes for the Whitethorn Creek Study Watershed 144

Figure 51: Depth-Duration Curves for Selected Area Sizes for the Banister River Study Watershed 145

Figure 52: Smoothing Curve for First 6-Hour Incremental Values at Selected Area Sizes for the Whitethorn Creek Study Watershed 148

Figure 53: Smoothing Curves for Second and Third 6-Hour Incremental Values at Selected Area Sizes for the Whitethorn Creek Study Watershed 148

Figure 54: Smoothing Curve for First 6-Hour Incremental Values at Selected Area Sizes for the Banister River Study Watershed 149

Figure 55: Smoothing Curves for Second and Third 6-Hour Incremental Values at Selected Area Sizes for the Banister River Study Watershed 149

Figure 56: HMR52 Suggested Isohyetal PMP Storm Pattern 152

Figure 57: Selected Isohyetal Pattern and Storm Orientation for the Whitethorn Creek Study Watershed 153

Figure 58: Selected Isohyetal Pattern and Storm Orientation for the Banister River Study Watershed 154

Figure 59: HMR52 Suggested Orientations ± 40° 155

Figure 60: Model for Determining Isohyetal Pattern Reduction Factor Based on Deviation from HMR52 Suggested Orientations 157

Figure 61: HMR52 Example Computation Sheet Showing Typical Format 159

Figure 62: Area vs. Volume Curve for First Three 6-hr Increments for the Whitethorn Creek Study Watershed 167

Figure 63: Area vs. Volume Curve for First Three 6-hr Increments for the Banister River Study Watershed 167

Figure 64: Temporal and Spatial (Depth) Distribution of the PMS - 72 Hour Storm – Whitethorn Creek Analysis 194

Figure 65: Temporal and Spatial (Depth) Distribution of PMS – 72-hr Storm – Banister River Analysis 194

Figure 66: Subbasin Identification Map – Reference Table 72 for HEC-HMS Subbasin ID Numbers, Subbasin Names/Descriptions, and Subbasin Areas 198

Figure 67: 2-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 216

Figure 68: 5-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 216

Figure 69: 10-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 217

Figure 70: 25-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 217

Figure 71: 50-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 218

Figure 72: 100-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 218

Figure 73: 200-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 219

Figure 74: 500-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 219

Figure 75: PMF Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1 220

Figure 76: 2-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 220

Figure 77: 5-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 221

Figure 78: 10-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 221

Figure 79: 25-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 ... 222

Figure 80: 50-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 ... 222

Figure 81: 100-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 ... 223

Figure 82: 200-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 ... 223

Figure 83: 500-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 ... 224

Figure 84: PMF Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2 ... 224

Figure 85: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 ... 225

Figure 86: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 ... 225

Figure 87: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 ... 226

Figure 88: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 ... 226

Figure 89: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 ... 227

Figure 90: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 ... 227

Figure 91: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 228

Figure 92: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 228

Figure 93: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 229

Figure 94: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1 229

Figure 95: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 230

Figure 96: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 230

Figure 97: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 231

Figure 98: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 231

Figure 99: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 232

Figure 100: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 232

Figure 101: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 233

Figure 102: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 233

Figure 103: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 234

Figure 104: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2 234

Figure 105: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 235

Figure 106: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 235

Figure 107: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 236

Figure 108: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 236

Figure 109: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 237

Figure 110: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 237

Figure 111: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 238

Figure 112: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 238

Figure 113: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 239

Figure 114: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3 239

Figure 115: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 240

Figure 116: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 240

Figure 117: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 241

Figure 118: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 241

Figure 119: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 242

Figure 120: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 242

Figure 121: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 243

Figure 122: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 243

Figure 123: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 244

Figure 124: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000 244

LIST OF TABLES

Table 1: NEH Part 630, Ch. 10 CN Conversion Table (USDA NRCS, 2004) 24

Table 2: Statistical Summary of Basin Characteristics Tested in Regional Regressions (Bisese, 1995) and Single-Parameter Regional Regression Equations for the Southern Piedmont Physiographic Province (Bisese, 1995) 38

Table 3: Precipitation Frequency Data Used to Construct the Frequency Storm Meteorological Models for the Whitethorn Creek Analysis 58

Table 4: Precipitation Frequency Data Used to Construct the Frequency Storm Meteorological Models for the Banister River Analysis 59

Table 5: Isohyetal PMP Depths for Each 6-hr Period of the 72-hr PMS for the Whitethorn Creek Analysis 62

Table 6: Isohyetal PMP Depths for Each 6-hr Period of the 72-hr PMS for the Banister River Analysis 63

Table 7: Whitethorn Creek Study Watershed - PMS Specified Hyetograph Meteorological Model Input Data 64

Table 8: Banister River Study Watershed - PMS Specified Hyetograph Meteorological Model Input Data 64

Table 9: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Whitethorn Creek Analysis - Comparison Point 1 67

Table 10: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Whitethorn Creek Analysis – Comparison Point 2 67

Table 11: HEC-HMS Simulated Discharges for the Whitethorn Creek Study Watershed – Comparison Point 1 68

Table 12: HEC-HMS Simulated Discharges for the Whitethorn Creek Study Watershed – Comparison Point 2 68

Table 13: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Banister River Analysis – Comparison Point 1 73

Table 14: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Banister River Analysis – Comparison Point 2 73

Table 15: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Banister River Analysis – Comparison Point 3 73

Table 16: HEC-HMS Simulated Discharges for the Banister River Study Watershed – Comparison Point 1 74

Table 17: HEC-HMS Simulated Discharges for the Banister River Study Watershed - Comparison Point 2 74

Table 18: HEC-HMS Simulated Discharges for the Banister River Study Watershed - Comparison Point 3 74

Table 19: Annual Maximum Discharge Record for the USGS Stream Gauage on the Banister River in Halifax, VA (USGS 02077000) 78

Table 20: Tabulated HEC-SSP Bulletin 17B FFA Results for the Banister River USGS Stream Flow Gauge at Halifax, VA (USGS 02077000) - 82-yr Period of Record (1929-2010) 80

Table 21: HEC-HMS Simulated Discharges for the Banister River Study Watershed – Watershed Outlet Point at the USGS Stream Flow Gauge at Halifax, VA (USGS 02077000) 80

Table 22: Curve Number Look-up Table Considering Antecedent Runoff Condition II (Average Antecedent Conditions) 115

Table 23: Curve Number Look-up Table Considering Antecedent Runoff Condition III (Wet Antecedent Conditions) 116

Table 24: Precipitation Frequency Estimates for the Chatham, VA PFDS Rain Gauging Station 133

Table 25: Precipitation Frequency Estimates for the Danville, VA PFDS Rain Gauging Station 134

Table 26: Precipitation Frequency Estimates for the Halifax, VA PFDS Rain Gauging Station 134

Table 27: Precipitation Frequency Estimates for the Altavista, VA PFDS Rain Gauging Station 135

Table 28: Precipitation Frequency Estimates for the Brookneal, VA PFDS Rain Gauging Station 135

Table 29: Areally-Weighted Average PF Estimates of the Banister River Study Watershed – Obtained with Thiessen Polygon Interpolation Scheme 136

Table 30: D-A-D Data for Whitethorn Creek Study Watershed........ 141

Table 31: D-A-D Data for Banister River Study Watershed 141

Table 32: D-A-D Values for Standard Isohyets – Whitethorn Creek Analysis........ 143

Table 33: D-A-D Values for Standard Isohyets – Banister River Analysis 143

Table 34: 18-hr D-A-D Data for Standard Isohyets........ 145

Table 35: Incremental Differences between the First Three 6-hr Periods – Whitethorn Creek Analysis........ 146

Table 36: Incremental Differences between the First Three 6-hr Periods – Banister River Analysis........ 147

Table 37: User-Corrected Incremental Differences between the First Three 6-hr Periods – Whitethorn Creek Analysis........ 150

Table 38: User-Corrected Incremental Differences between the First Three 6-hr Periods – Banister River Analysis 151

Table 39: Reduction Factors Corresponding to a 29° Deviation from the HMR52 Recommended Orientation for Storm Isohyets Greater than 300 mi^2 156

Table 40: User Corrected Incremental Differences with Reduction Factors Applied – Banister River Analysis 157

Table 41: HMR52 Table 15a - 1st 6-hr Nomogram Values at Selected Area Sizes........ 161

Table 42: Cumulative Watershed Area Contained Within Each Isohyet for Each Analysis...... 164

Table 43: Sum of the Volumes of the First Three 6-hr Increments for Each Isohyet – Whitethorn Creek Analysis 166

Table 44: Sum of the Volumes of the First Three 6-hr Increments for Each Isohyet – Banister River Analysis 166

Table 45: Sum of the Volumes of the First Three 6-hr Increments for Both the Standard and Intermediate Isohyets – Whitethorn Creek Analysis........ 169

Table 46: Sum of the Volumes of the First Three 6-hr Increments for Both the Standard and Intermediate Isohyets – Banister River Analysis 170

Table 47: Completed Computation Sheet for the First 6-hr Increment for the Whitethorn Creek Study Watershed 171

Table 48: Completed Computation Sheet for the Second 6-hr Increment for the Whitethorn Creek Study Watershed........ 172

Table 49: Completed Computation Sheet for the Third 6-hr Increment for the Whitethorn Creek Study Watershed 173

Table 50: Completed Computation Sheet for the Intermediate Isohyets for the Whitethorn Creek Study Watershed 174

Table 51: Completed Computation Sheets for the First 6-hr Increment for the Banister River Study Watershed 175

Table 52: Completed Computation Sheets for the Second 6-hr Increment for the Banister River Study Watershed 177

Table 53: Completed Computation Sheets for the Third 6-hr Increment for the Banister River Study Watershed 179

Table 54: Cumulative Depth-Duration Values for the 50 mi2 Pattern of the Whitethorn Creek PMS 181

Table 55: Cumulative Depth-Duration Values for the 560 mi2 Pattern of the Banister River PMS 181

Table 56: Procedure Parameters Obtained for the 560 mi2 Area Size – Banister River Analysis 182

Table 57: Incremental Depth-Duration Values for the 50 mi^2 Pattern – Whitethorn Creek Analysis 182

Table 58: Incremental Depth-Duration Values for the 560 mi^2 Pattern – Banister River Analysis 182

Table 59: Smoothed Incremental Depth-Duration Values for the 50 mi2 Pattern – Whitethorn Creek Analysis 183

Table 60: Smoothed Incremental Depth-Duration Values for the 560 mi2 Pattern – Banister River Analysis 183

Table 61: Smoothed, Areally-Reduced Incremental Depth-Duration Values for the 560 mi2 Pattern – Banister River Analysis 183

Table 62: Incremental PMP Percentage Multipliers (Tables 15-18 from HMR52) Corresponding to a 50 mi^2 Area – Whitethorn Creek Analysis 184

Table 63: Incremental PMP Percentage Multipliers (Tables 15-18 from HMR52) Corresponding to a 560 mi^2 Area – Banister River Analysis 185

Table 64: Isohyetal PMP Depths for Each 6-hr Period in the 72-hr Storm – Whitethorn Creek Analysis 186

Table 65: Isohyetal PMP Depths for Each 6-hr Period in the 72-hr Storm – Banister River Analysis 186

Table 66: Basin-Averaged Incremental PMP Depths for the Whitethorn Creek Study Watershed 187

Table 67: Basin-Averaged Incremental PMP Depths for the Banister River Study Watershed. 187

Table 68: Computation Sheets for Determining the Incremental Basin-Averaged PMP Depths for the Whitethorn Creek Study Watershed 188

Table 69: Computation Sheets for Determining the Incremental Basin-Averaged PMP Depths for the Banister River Study Watershed 190

Table 70: Isohyetal PMP Depths for Whitethorn Creek Study Watershed 193

Table 71: Isohyetal PMP Depths for Banister River Study Watershed 193

Table 72: Selected Channel Roughness Coefficients (Manning's *n*) for Subbasins in the Banister River Study Watershed – Reference Figure 66 for Subbasin Map 199

Table 73: Sheet Flow Travel Time Computation Sheet Used to Find the NRCS Segmental Velocity T_c Lag Time for Each Subbasin in the Banister River Study Watershed 200

Table 74: Shallow Concentrated Flow Travel Time Computation Sheet Used to Find the NRCS Segmental Velocity Tc Lag Time for Each Subbasin in the Banister River Study Watershed 201

Table 75: Channel Flow Travel Time Computation Sheet Used to Find the NRCS Segmental Velocity T_c Lag Time for Each Subbasin in the Banister River Study Watershed 202

Table 76: Summary of T_c Segmental Travel Times and NRCS Segmental Velocity Tc Lag Times for Each Subbasin in the Banister River Study Watershed 203

Table 77: Whitethorn Creek Study Watershed Selected Basin Model Parameters – Basin Model #1 (ARC II & NRCS Watershed Lag Equation) 205

Table 78: Whitethorn Creek Study Watershed Selected Basin Model Parameters – Basin Model #3 (ARC III & NRCS Watershed Lag Equation) 206

Table 79: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #1 (ARC II & NRCS Watershed Lag Equation) 207

Table 80: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #2 (ARC II & NRCS Segmental Velocity Lag Equation (0.6 * Tc)) 209

Table 81: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #3 (ARC III & NRCS Watershed Lag Equation) 211

Table 82: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #4 (ARC III & NRCS Segmental Velocity Lag Equation (0.6 * Tc)) 213

GLOSSARY/ABBREVIATION KEY

CEE	Civil & Environmental Engineering
cfs	Cubic Feet Per Second
cms	Cubic Meters Per Second
CN	Curve Number
D-A-D	Depth-Area-Duration
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
FFA	Flood Frequency Analysis
ft	Feet
GIS	Geographic Information System
HDSC	Hydrometeorological Design Studies Center
HEC	Hydrologic Engineering Center
HEC-GeoHMS	Hydrologic Engineering Center – Geospatial Hydrologic Modeling Extension
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HMR51	Hydrometeorological Report Number 51
HMR52	Hydrometeorological Report Number 52
hr	Hour
in	Inch
km	Kilometer
LP3	Log Pearson Type III
m	Meter
mi	Mile
min	Minute
MLRC	Multi-Resolution Land Characteristics
NED	National Elevation Dataset
NEH	National Engineering Handbook
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration

NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PF	Precipitation-Frequency
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PMS	Probable Maximum Storm
SCS	Soil Conservation Service
SSURGO	Soil Survey Geographic Database
T_c	Time of Concentration
TIN	Triangulated Irregular Network
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USDoC	United States Department of Commerce
USGS	United States Geological Survey
VCTIR	Virginia Center for Transportation Innovation and Research
VDOT	Virginia Department of Transportation
VT	Virginia Tech (Virginia Polytechnic Institute and State University)
VTRC	Virginia Transportation Research Council
VUI	Virginia Uranium, Inc.
yr	Year

1. INTRODUCTION

1.1 Overview

In the United States and in many parts of the world, the concepts of Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) have become cornerstones in the design and assessment procedures of many of the high-risk structures and operations where failure and/or severe flooding cannot be tolerated. Whether designing a high-hazard dam, a nuclear power plant, or another large hydrologic or hydrologically-affected facility, the PMF is generally regarded as a baseline worst-case scenario flooding event against which the integrity of the structure must not be compromised. As defined by the U.S. Army Corps of Engineers (1979), the PMF is "the flood that may be expected from the most severe combination of meteorological and hydrologic conditions that are reasonably possible in the region." The PMF for a particular drainage area is dictated by a number of factors, among which are the antecedent conditions in a watershed, the rainfall amounts experienced, and runoff potential within the drainage at the time of the event. The PMF in any geographic location is generally considered to result from that region experiencing the Probable Maximum Storm (PMS), which is the spatially and temporally distributed storm that delivers the PMP.

The PMP is defined by the National Weather Service, the U.S. Army Corps of Engineers, and the Bureau of Reclamation as “the theoretically greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year” (Cudworth, 1989). In essence, the PMP represents the theoretical upper limit of precipitation that a watershed can experience based on what the local atmosphere is capable of producing. In addition, PMP values vary for different regions of the country and for different terrains, necessitating a site specific analysis for each project.

Through the use of hydrologic modeling software, the PMP/PMS for a study watershed can be simulated over the drainage to produce runoff hydrographs associated with the PMF. These discharge hydrographs can then be used directly or utilized in conjunction with a hydraulic model to determine flood inundation extents and the peak flow depths/water surface elevations that could be expected, or to characterize the sediment transport phenomena in a study reach under severe flooding conditions.

1.2 Motivation/Objectives of Overall Studies

Currently, the largest known undeveloped uranium ore deposit in North America, consisting of an estimated resource of 120 million pounds of uranium, is located at Coles Hill, near the town of Gretna, Virginia (Santoy Resources, 2009). This uranium resource is large enough to supply the fuel to all nuclear reactors currently in the United States for two years or the four reactors in Virginia for approximately forty years (U.S. Energy Information Administration, 2010). Because of this, there has been recent interest in trying to develop this resource, and a number of studies are being conducted to document current baseline conditions and to determine the potential implications of developing such a mining operation.

As part of these investigations, two PMP/PMF analyses have been conducted, each with a different overarching goal. The first of these studies involved generating a PMF inundation map for the area directly adjacent to the uranium deposit. The primary goal of this PMP/PMF analysis was to determine the spatial extent of flooding that would occur within a defined 22 km^2 (8.5 mi^2) study area (denoted as the "PMF Study Area" in Figure 3) as a result of the region experiencing the theoretical worst-case scenario precipitation event. This modeling was done primarily for site planning purposes to ensure that if the mining site were to be developed, that key structures and operations would not be impacted by flood waters during an extreme event. For naming purposes, this analysis will be referred to as the Whitethorn Creek study in the remainder of this document.

The second PMP/PMF investigation, referred to as the Banister River study henceforth, involved analyzing the impact of a tailings (mining by-products) containment cell failure during a catastrophic precipitation event. Tailings are what remain after uranium (approximately 0.05 to 0.3 percent of the parent material) has been extracted from the original ore rock (Baker Engineering, 2011). Therefore, over ninety-nine percent of the mined and milled ore, still containing approximately eighty-five percent of the original radioactivity, must be stored onsite in impoundment structures designed to last for over 1000 years without breaching and releasing their contents into the nearby environment (USNRC, 2002). Because the tailings could pose both an immediate threat to human health and a long-term threat of extensive environmental contamination, it is imperative to have an idea of what would happen to the tailings if a cell were to ever fail, however unlikely that may be (Dziuban, 2000). Results of this study may be used to assess the probability that tailings could be transported into a nearby waterway and into the rivers and reservoirs that serve as municipal drinking water supplies downstream of the site if one or more of the storage cells were to be breached during a PMP-type event. Primarily, this overall study focuses on modeling the sediment transport phenomena of the mine tailings downstream from the site during the high magnitude flows associated with the PMF.

1.2.1 Contribution of this Thesis to the Overall Work

Both PMP/PMF analyses discussed in the previous section utilized multiple models to attain their respective simulation goals. Among these, each analysis employed both a hydrologic model, to characterize the precipitation-runoff response of the study watershed to the PMS, and a hydraulic model, to simulate the river mechanics within the study reaches under PMF conditions. For each assessment, a meteorological model representing the 72-hr PMS was developed for the study watershed. These PMP storms were simulated in their respective event-based hydrologic models to obtain PMF response hydrographs at key locations in each of the basins. The PMF hydrographs were then routed through hydraulic models of the study sites to either characterize the flow dynamics and sediment transport phenomena within the study reaches or to determine the PMF flooding extent and the water surface elevations in the area.

The principal focus of this thesis and the work presented here involves the development and analysis of the hydrologic models that were generated for both study watersheds, as well as the determination of the PMP/PMS used to drive each model. Included is discourse on how the hydrologic modeling parameters were selected and how the functionality of each model was evaluated. Throughout the hydrologic modeling process, current and standard best engineering practices were employed to better ensure the accuracy and integrity of the simulation results. Further, the hydrologic analyses were conducted with a suite of industry-standard software applications developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE HEC), as well as with ArcGIS, a geographic information system software package from Environmental Systems Research Institute (ESRI).

As stated above, the output results from the hydrologic analyses were utilized in respective HEC-RAS hydraulic models to achieve the final study objectives (inundation mapping and characterization of sediment transport phenomena). However, the hydraulic modeling components of the two overall studies, and thus the overall results, are not presented or discussed here, but instead will be elaborated on in a subsequent thesis written by another member of the project team. As a result, this thesis primarily focuses on the generation of the required PMF flow inputs that were utilized in the second stages of these studies.

1.3 Description of the Study Areas

1.3.1 General Site Description

The Coles Hill uranium deposit consists of two individual ore bodies located in central Pittsylvania County near the town of Gretna, Virginia. The two main ore bodies on site are situated between two rural, unregulated streams: Whitethorn Creek to the north and one of its major tributaries, Mill Creek, to the south. After the confluence of these two waterways, flow travels approximately 5 km (3.1 mi) until it enters into the Banister River. Moving further downstream, the Banister River flows into the Dan River and then into the John H. Kerr Reservoir, the Roanoke River, and eventually into Lake Gaston, which passes from southern Virginia into North Carolina. Figure 1 depicts a map of the Coles Hill area and the downstream water bodies. From this figure, it can be noted that there are currently four municipal drinking water intakes that may be affected by mining activities at Coles Hill.

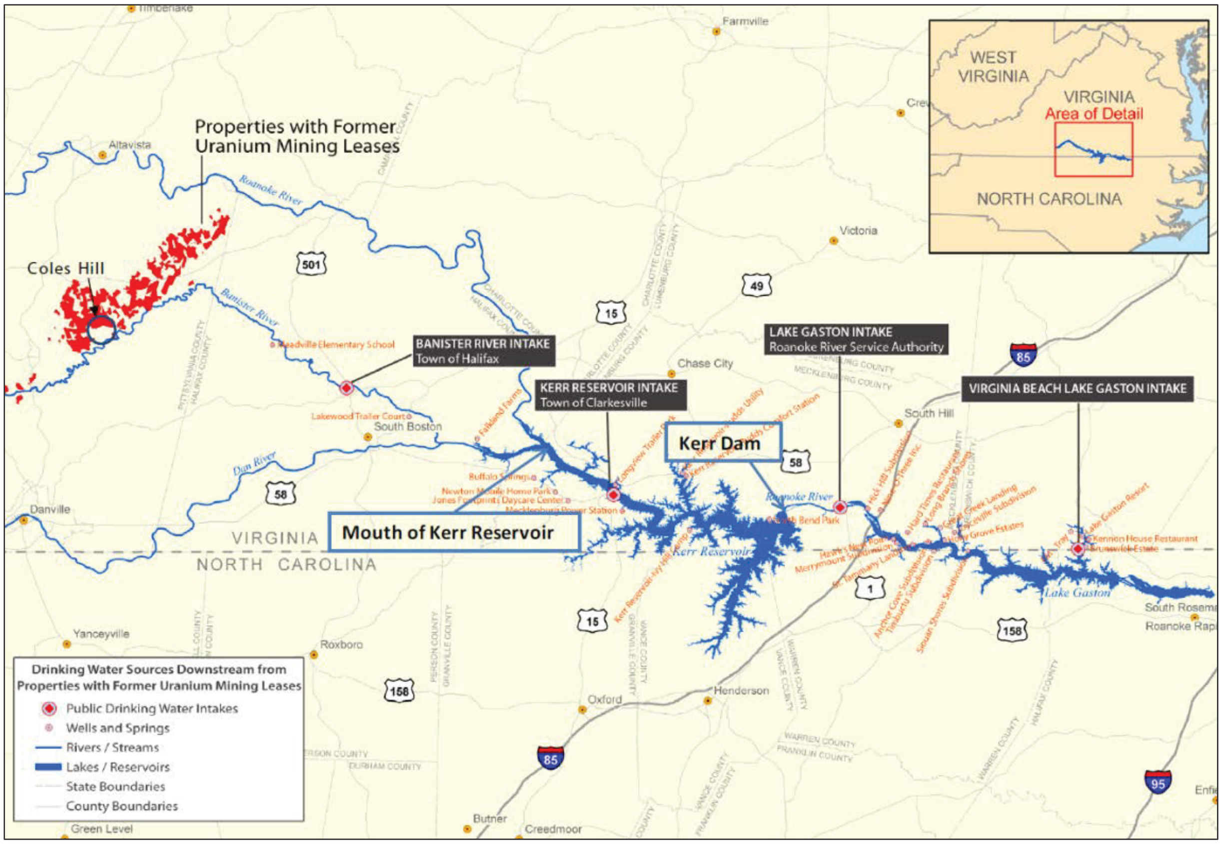

Figure 1: Location Map of Coles Hill in Relation to Downstream Waterways and Drinking Water Intakes (Baker, 2011)

As both of these studies directly relate to the ore deposits at Coles Hill, it should be noted that the areas and watersheds analyzed directly overlap one another, and that the Whitethorn Creek Study Watershed is included within the Banister River Study Watershed. To provide an idea of scale and exactly where these watersheds overlap, Figure 2 illustrates the locations of both the Whitethorn Creek and Banister River Study Watersheds as they relate to the ore deposits and to the counties in which they are located.

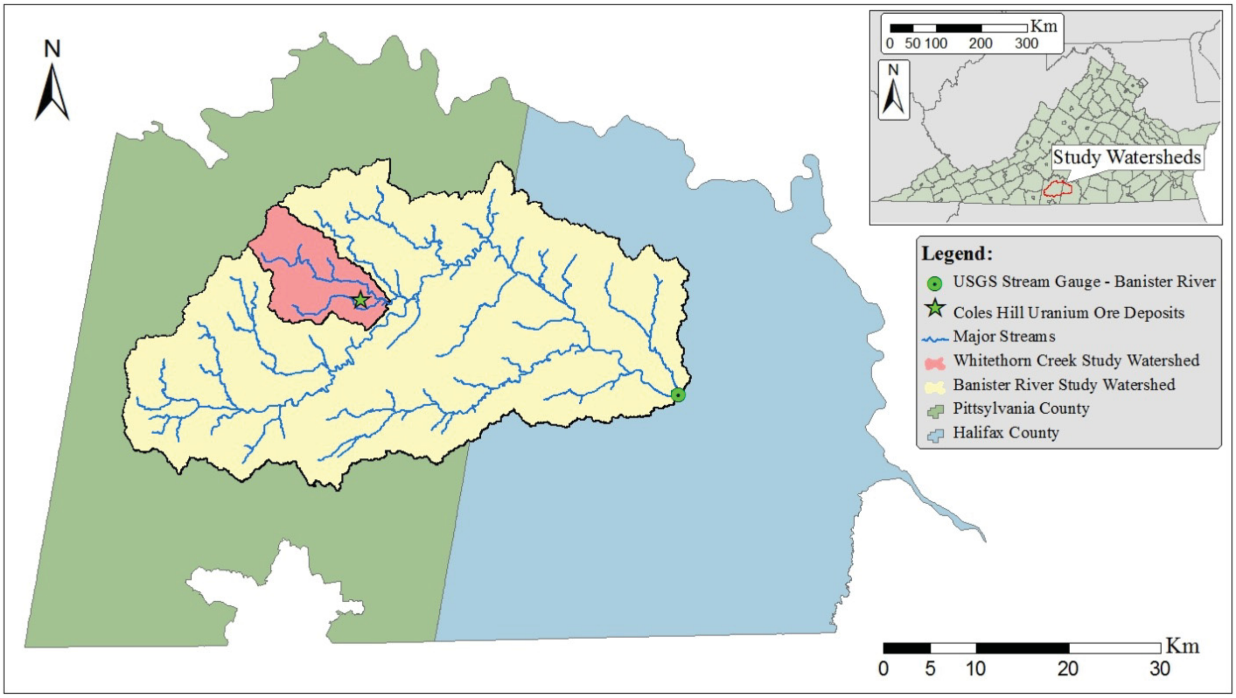

Figure 2: Location Map of Study Watersheds within Pittsylvania and Halifax Counties, Virginia

1.3.2 Whitethorn Creek Study Watershed Analysis

Because the ore deposits are located between Mill Creek and Whitethorn Creek, and because the future mining, milling, and storage facilities will likely be situated near the deposits, it was important to include both of these reaches in the PMF inundation analysis so that the influences of each are accounted for during an extreme flood. To fully capture the inundation effects from these two streams, as well as a third smaller stream (Dry Branch) that enters Whitethorn Creek just south of the Mill Creek confluence, the study watershed outlet point was selected as the confluence of Dry Branch and Whitethorn Creek. This point is approximately 4 km (2.5 mi) upstream of the mouth of Whitethorn Creek and corresponds to an area where the creek floodplains begin to become confined in a narrow valley. Figure 3 depicts the 107 km^2 (41.2 mi^2) Whitethorn Creek Study Watershed delineated upstream of the selected outlet point, as well as the 22 km^2 (8.5 mi^2) PMF study area in which the hydraulic modeling and inundation mapping took place (not detailed in this document). The figure also shows the ten subbasins that the watershed was divided into for hydrologic modeling purposes.

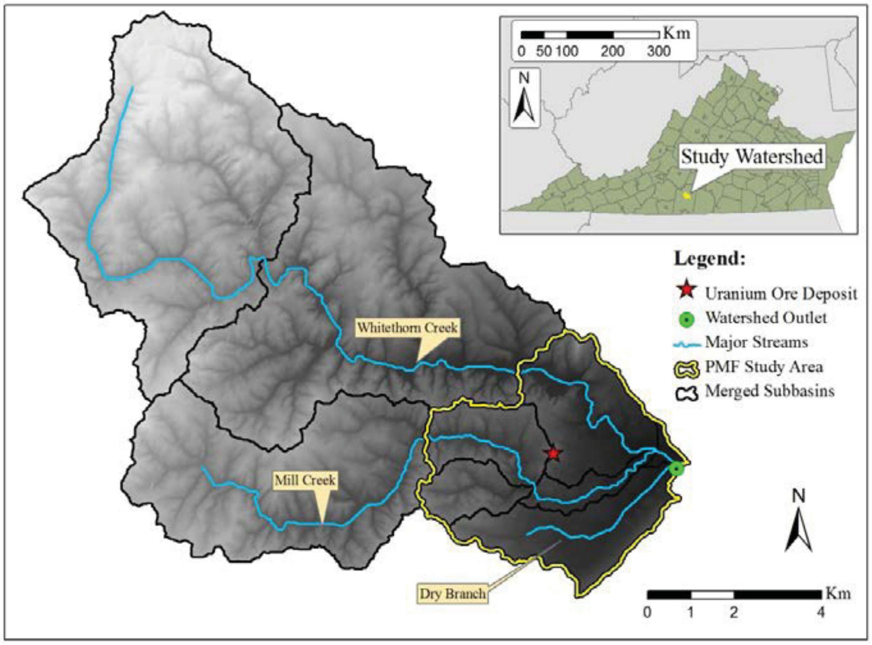

Figure 3: Location Map of the "Whitethorn Creek Study Watershed" Showing Modeling Extents and Key Basin Features - Inset Map Showing Project Site Location in Virginia.

The land cover of the watershed is characterized primarily as forested (46%) and agricultural land (hay/pasture – 37%) (Fry et al., 2011) and over 85% of the watershed is underlain with soil having a moderately low runoff potential (hydrologic soil group B) (USDA NRCS, 2009). Elevations within the study watershed range from 156 to 332 m above mean sea level and the average elevation and basin slope are approximately 223 m and 7.8%, respectively (Gesch, 2007; Gesch et al., 2002).

1.3.3 Banister River Study Watershed Analysis

The first public drinking water intake downstream of the Coles Hill site occurs in the town of Halifax, VA, near a hydroelectric dam across the Banister River. The Banister Lake Dam, constructed in 1921, provides the first major flow obstruction in this natural riverine system. As a result, a long (approximately 7.5 km (4.7 mi)), narrow reservoir, the Banister Lake, has formed upstream of the dam. This lake acts as a transition point in the system; as the river enters the lake, the flow velocity decreases, allowing sediments to settle out rather than continuing on downstream. For this reason, the primary objective of this component of the project involved characterizing the sediment transport from the project site near Coles Hill through the Banister Lake. For modeling purposes, however, the study watershed outlet point was not considered to be the dam, but instead was selected about 1 km (0.6 mi) downstream of the dam at a USGS stream flow gauging station (USGS 02077000). This allowed for the eighty-two year flow record to be used for the model calibration purposes, as it is the first gauge located downstream of the uranium deposit (USGS, 2011). Because of the run-of-the-river nature of the dam, and because the lake acts as a wide, deep section of river under severe flooding conditions, comparison flow rates for this study corresponding to the more extreme events were obtained using this flow record. For smaller events, however, for which the lake's attenuation capacity could significantly affect the gauge readings, regional regression techniques were employed to determine design discharges.

This study involved generating a hydrologic model of the 1415 km^2 (546.4 mi^2) watershed upstream of the USGS gauge, as well as creating a hydraulic model for a 5 km section of the Whitethorn Creek and a 54 km portion of the Banister River and Banister Lake (not detailed in this document). Figure 4 depicts the "Banister River Study Watershed" as it is delineated upstream of the USGS stream gauging station in Halifax, VA, as well as the hydraulic modeling extents and other key features within the watershed. The figure also shows the thirty-seven subbasins that the watershed was divided into for hydrologic modeling purposes.

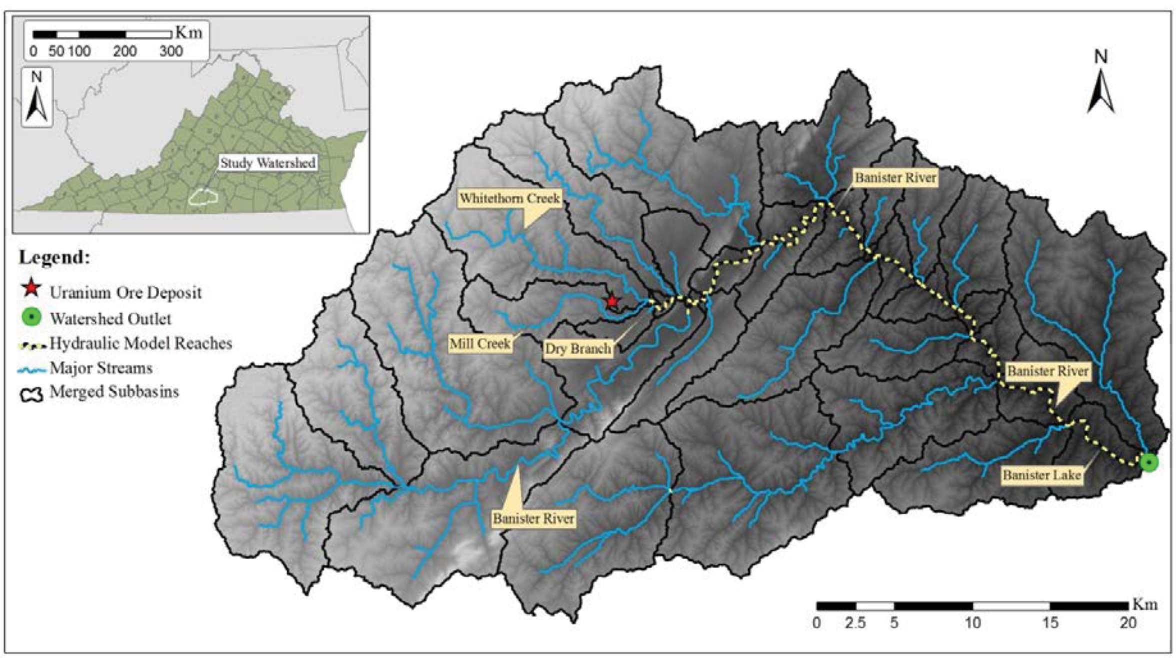

Figure 4: Location Map of the "Banister River Study Watershed" Showing Modeling Extents and Key Basin Features - Inset Map Showing Project Site Location in Virginia.

Similar to the Whitethorn Creek basin, the land cover of the Banister River Study Watershed is characterized primarily as forested (57%) and agricultural land (hay/pasture – 25%) (Fry et al., 2011) and over 84% of the watershed is underlain with soil having a moderately low runoff potential (hydrologic soil group B) (USDA NRCS, 2009). Elevations within the study watershed range from 100 to 362 m above mean sea level and the average elevation and land slope are approximately 192 m and 9.1%, respectively (Gesch, 2007; Gesch et al., 2002).

1.4 Key Engineering Questions

The primary questions addressed by this research are the following:

- How is an event-based HEC-HMS hydrologic model developed and how can it be used to simulate a PMP/PMS event?
- How are the theoretical PMP and PMS determined for a study watershed?
- How can a hydrologic model be calibrated/tested in the absence of observed rainfall or known stream discharges and what differences exist in the evaluation of a hydrologic model corresponding to an ungauged, unregulated watershed to that of a gauged, regulated watershed?
- Can a model developed following standard and best engineering practices accurately predict design discharges obtained through established statistical techniques?

This thesis and its associated appendices aim to address each of these questions in turn by discussing and explaining the theory and methodology behind each step of the modeling process. Information on how each model (basin, meteorological, control specifications) for each analysis was developed is presented to provide a deeper understanding of what is involved in this type of project, as well as to provide guidance on how to conduct similar future studies.

2. BACKGROUND / LITERATURE REVIEW

2.1 Event Hydrologic Modeling

When conducting a hydrologic analysis of a watershed, two approaches can be taken: event-based modeling or continuous modeling. The first approach aims to predict how a particular drainage basin will respond to an individual rainfall event, whereas the second approach aims to understand how a basin acts over a long period of time (months or even years). For continuous models, multiple storms are generally incorporated and the model attempts to predict how the basin will act during both dry and wet periods. Numerous parameters involved in the water cycle must be accounted for which tend to vary seasonally such as base flow and evapotranspiration rates (Chu & Steinman, 2009). For the analyses discussed in this thesis, however, an event-based approach has been adopted due to the need to determine how the study watersheds would react to a Probable Maximum Precipitation (PMP) event.

Event hydrologic modeling aims to accurately represent the precipitation-runoff processes of specific rainfall events. This necessitates the characterization of finer-scale hydrologic processes, generally requiring the overall basin to be broken up into much smaller, individual subbasins and stream reaches. In this way, the overall watershed response to extreme events is compartmentalized, allowing for separate analyses to be carried out at finer resolutions across the watershed. These individual subbasin responses can then be combined again at different points along the watershed flow network to obtain a large-scale response at key locations, such as at stream confluences or at the watershed outlet (Scharffenberg & Fleming, 2010).

Breaking up a watershed in this way enables the different parts of a basin to be analyzed with different parameters. This allows for a more accurate representation of the variable conditions and natural heterogeneities that exist within large watersheds. By modeling a larger drainage as a series of small, interconnected subbasins that are homogenous in and of themselves, the hydrologic processes that are being simulated for each can be tailored specifically to the region of the watershed that the subbasin represents. This is especially important when studying watersheds with varying characteristics, such as land cover, soil type, imperviousness, etc. If the basin was modeled as a single watershed, with only one set of parameters assigned to it, certain generalizations would be required, introducing error that could be minimized by selecting a finer resolution (Chu & Steinman, 2009; Chaubey et al., 1999).

2.2 Probable Maximum Precipitation/Hydrometeorological Branch Studies

One of the most common methodologies for determining the PMP/PMF utilizes a hydrometeorological approach of maximizing the combination of all of the appropriate physical parameters involved in flood development on a particular drainage area (Cudworth, 1989). This technique combines aspects of both surface hydrology and meteorology to develop a storm and runoff condition that would lead to the statistically most severe flood capable of impacting a specific location of interest. This approach is based on the meteorology of a number of historic severe storms that have occurred throughout the United States (Schreiner & Riedel, 1978).

Recognizing a need to estimate PMP values for various large scale projects, the U.S. Department of Commerce (USDoC), the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS), and the U.S. Department of the Army Corps of Engineers (USACE) began carrying out a number of studies in the mid-1960's and generating a number of reports and technical papers to address PMP issues. As part of this work, these agencies developed a series of Hydrometeorological Reports (HMR) to quantify the PMP depth-duration relationships for different parts of the United States. One of these reports, Hydrometeorological Report No. 51 (HMR51) (Schreiner & Riedel, 1978), provides PMP estimates for areas of the U.S. east of the 105th Meridian. HMR51 contains generalized PMP maps with estimated PMP depths for drainage areas of 10, 200, 1000, 5000, 10,000, and 20,000 square miles for storm durations of 6, 12, 24, 48, and 72 hours. The report also outlines procedures for interpolating between these areas and durations to allow for PMP depths to be obtained for conditions outside of what are provided. An example of one such HMR51 map is depicted in Figure 5.

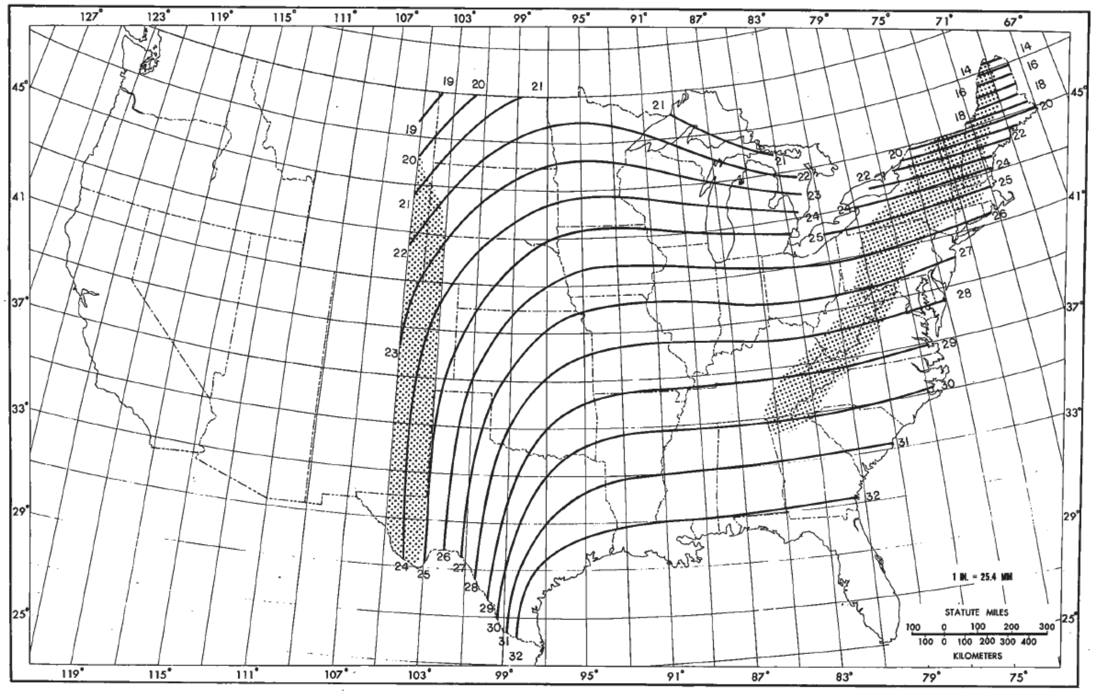

Figure 5: All-Season PMP Map (in.) for a 10 mi^2 Drainage Area for a 6hr. Storm Duration (Schreiner & Riedel, 1978)

The map in Figure 5, like all of the HMR51 maps, contains a number of isolines that each represent a common estimated PMP depth for the given drainage size and storm duration. Review of the isolines in Figure 5 shows the primary role of latitude in setting the PMP depths; in general, the more northerly the latitude, the less moisture the atmosphere is typically capable of holding (Harrison, 2003).

Also shown on all of the HMR51 maps are two "stippled regions": (a) the Appalachian/Blue Ridge Mountains extending from Georgia to Maine and (b) a strip between the 103rd and 105th meridians. These stippled regions indicate areas within which the generalized PMP estimates provided by the isolines might be deficient. The detailed orographic terrain effects of these areas were not evaluated and therefore HMR51 does not reflect the greater probability of higher rainfall in and along these mountain ranges and elsewhere in these regions (Schreiner & Riedel, 1978). The authors of HMR51 state that they expected future studies by the Hydrometeorological Branch to involve detailed generalized studies covering the stippled regions, however, no such studies have yet been carried out. Additionally, the authors suggest that until such studies are completed, the generalized PMP values should not be used for the stippled areas and projects in these regions should be evaluated on a case-by-case basis as separate PMP studies. The area examined in this study is outside of the stippled region and therefore the PMP isolines depicted in Figure 5 are applicable for the study area.

It is important to note that the values provided by HMR51 are intended as "point" depths to be applied at a single location (usually considered as the storm center), rather than as distributive depths over large spatial areas. Also, these generalized values are not exact depths and should not be considered as such, as there is no direct means of computing and evaluating the accuracy of the results (Cudworth, 1989; Schreiner & Riedel, 1978). The authors of HMR51 acknowledge that there is still a margin of error in these values and state that: "In consideration of our limited knowledge of the complicated processes and interrelationships in storms, PMP values are identified as estimates." Therefore, it is possible that a storm may produce slightly greater precipitation depths than those outlined in HMR51.

In addition to HMR51, Hydrometeorological Report No. 52 (HMR52) (Hansen et al., 1982) is also applicable for areas east of the 105^{th} Meridian. HMR52 acts as an application guide for taking the point PMP values from HMR51 and transforming them into an elliptical storm pattern with a specific orientation, size, and temporal distribution that will cause the Probable Maximum Flood (PMF) for a particular watershed. In this way, the PMP values are converted into a Probable Maximum Storm (PMS) that builds up and dissipates over time. This provides a great advantage over using the point values from HMR51 because it enables different areas of the drainage to be assigned different rainfall depths based on the proximity to the storm center. This in turn allows one to more realistically model the precipitation-runoff response within a watershed, and also to model how flows in a watershed change as the storm evolves over time. Analytically, this is accomplished by overlaying and critically centering the PMS storm pattern over the basin and by computing the average precipitation for each isohyet (precipitation contour) of the storm. This precipitation is then distributed over time in a series of six-hour periods (twelve for a seventy-hour storm), which results in incremental basin average precipitation values that are used to generate the PMF hydrographs (Cudworth, 1989).

To better understand the derivation and mechanics of the PMP, Cudworth (1989) presents descriptions/explanations of what are considered to be the four conditions required to develop a

PMP-type storm cell: abundant atmospheric moisture, a lifting mechanism, condensation, and water droplet-ice crystal growth. In addition, he thoroughly details the storm maximization approach adopted by the authors of HMR51 to develop the PMP estimates for the applicable areas. In this, he explains the available database used (largest known observed areal-duration precipitation amounts) and the three processes utilized to develop the PMP: moisture maximization, storm transposition, and envelopment.

3. HYDROLOGIC MODELING THEORY AND METHODOLOGY

3.1 Model Description

3.1.1 HEC-HMS

One of the most frequently utilized and most widely accepted programs for hydrologic modeling is HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) (Razi et al., 2010). This publically-available, one-dimensional hydrologic model supersedes the HEC-1 Flood Hydrograph Package and was developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE HEC). HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. These dendritic systems are one of the most common types of drainage systems found in nature and generally consist of a main stream or river channel that branches out into a number of smaller contributing tributaries. These systems arise from patterns in the terrain, with the flow networks usually forming in the valleys created by the landscape (Scharffenberg & Fleming, 2010; Garcia et al., 2008).

HEC-HMS, like other rainfall-runoff models, simulates the precipitation-runoff response of a watershed or network of subwatersheds to a given amount and distribution of precipitation over a defined period of time. The model converts precipitation excess to overland flow and channel runoff using user-defined loss, transform, and routing methods (Knebl et al., 2005).

HEC-HMS requires three basic input components to run a simulation: a basin model, a meteorological model, and a control specifications model. The basin model is composed of individual hydrologic elements (subbasins, reaches, junctions, reservoirs, etc.) as well as information about their connectivity and contains all of the physical characteristics of these features. The meteorological model contains the precipitation/storm information (with respect to both space and time) for the events that are to be modeled. The control specifications model contains the temporal information for the simulation run (modeling time-step, simulation start and end times, etc.) (Olivera, 2001).

Provided with a basin model, a meteorological model, and a control specifications model, HEC-HMS can create a simulation run and output time-dependent discharge hydrographs at various points in the system. Each of these hydrographs corresponds to either a subbasin outlet point, a hydrologic junction, or a reach or reservoir outlet and contains time-series information so that a user can track how a flood-wave propagates through a watershed during an extreme event (Knebl et al., 2005; Garcia et al., 2008). This information can be used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation (Scharffenberg & Fleming, 2010).

3.1.2 ArcHydro/HEC-GeoHMS

HEC-HMS utilizes a graphical user interface to build a basin model and to set up the precipitation models and control variables for each simulation (Anderson et al., 2002). Using this interface, a modeler can construct and piece together these models one element at a time, determining and assigning every parameter to each component manually. However, the process can be very repetitive and time-consuming, especially for large watersheds that could potentially consist of hundreds or even thousands of elements. In addition to this, an outside GIS-based mapping program is usually required to generate many of the parameter values needed for the basin and meteorological models.

In an effort to streamline the data assimilation and model input development process, HEC developed HEC-GeoHMS (Hydrologic Engineering Center's Geospatial Hydrologic Modeling Extension), which acts as an intermediary program between the GIS platform (ESRI's ArcGIS) and HEC-HMS. Like HEC-HMS, HEC-GeoHMS is a publically available software package that can be accessed from the USACE HEC website. This program is a geospatial hydrology toolkit that interfaces between the two source programs to make the data transition easier and more efficient. HEC-GeoHMS, acting as an extension in ArcGIS, enables a user to visualize the basin model's spatial information and automates many of the processes involved in parameter selection that would normally need to be calculated by hand. This toolkit allows a modeler to perform spatial analysis, delineate subbasins and stream networks, and construct and export most of the input data and files required for a HEC-HMS simulation (Chu & Steinman, 2009; Fleming & Doan, 2010).

HEC-GeoHMS utilizes the ArcHydro Tools 9 toolkit (included in the HEC-GeoHMS software package) and the Spatial Analyst extension for ArcGIS to generate a number of hydrologic modeling inputs that the program can then combine and convert to a single .hms file that can be read and tested in HEC-HMS. By analyzing digital terrain data, HEC-GeoHMS is capable of transforming the drainage paths and watershed boundaries from ArcMap (ArcGIS' mapping and analysis component) into a hydrologic data structure schematic that represents the drainage network in HEC-HMS (Fleming & Doan, 2010).

3.2 Overview of Model Development

In order to accurately replicate the precipitation-runoff response of a particular watershed, a hydrologic model must be developed to characterize and simulate real-world conditions, concerning both the landscape and expected meteorology. The model is essentially a simplified, conceptual representation of the actual hydrologic features and systems in a study area, and utilizes established techniques/mathematical analogues to imitate physical processes. Regarding the modeling of a PMS-type event, a procedure similar to that presented in the flow chart in Figure 6 can be followed to develop such an event-based hydrologic model. For this, precipitation intensities or depths from weather monitoring stations in and around the watershed can provide estimates of rainfall that can be used in conjunction with stream discharge data to calibrate the model. By calibrating the model against available data or probabilistic storm estimates, the model parameters can be tailored and adjusted so that the modeling output accurately replicates observed or expected conditions. In the absence of observed data, modeling parameters can be determined using best engineering judgment and the simulation results can be compared to flow estimates obtained through a regional regression analysis or by other statistical means. For both studies presented here, a number of precipitation frequency design storms were modeled (ranging from a 2-year to a 1000-year return period) and used to prepare the hydrologic models for the PMP/PMF simulation.

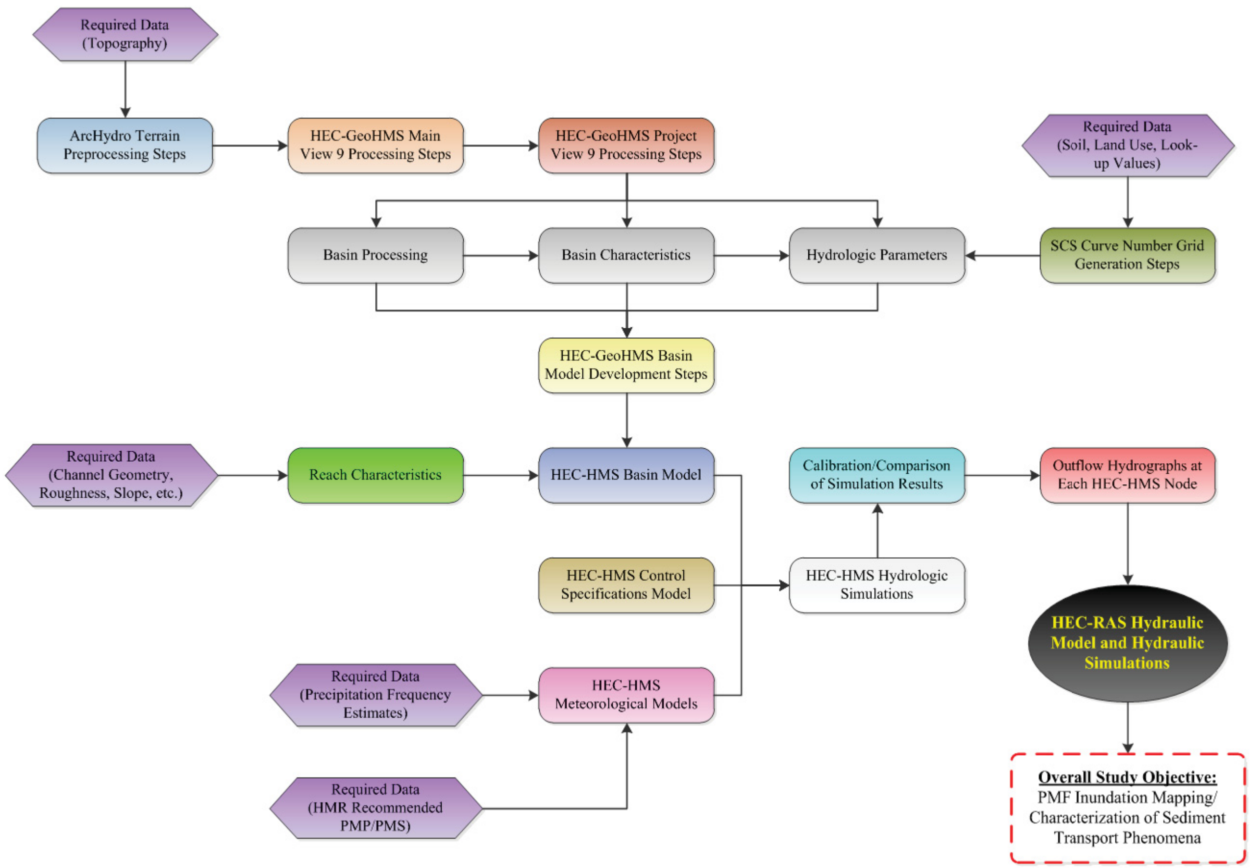

Figure 6: Schematic of Basic Components of the Hydrologic Modeling Process

3.2.1 HEC-HMS Basin Model Development

3.2.1.1 Watershed Delineation

The first step in any hydrologic analysis is to delineate the contributing watershed for the selected study reach or outlet point. This drainage basin consists of both the streams and rivers that convey water to the outlet point, as well as all of the land that drains to these reaches. In order to identify an outlet point's contributing area, the local terrain must be analyzed to determine the location of major surface-water drainage divides. These divides generally result from topographical peaks and ridges in the landscape and represent boundary lines separating areas that drain to different stream reaches.

The only input information required to delineate a catchment is a topographic dataset or elevation model of the study area and the location of the outlet point. Topography of the study areas was obtained in the form of Digital Elevation Models (DEMs) from the USGS National Elevation Dataset (NED). The NED is a seamless, continuously updated grid of elevation values across the U.S. that is publically available for download at varying spatial resolutions. This dataset is nationally available with at least a 1-arc-second (approximately 30 m by 30 m) grid cell size with certain regions of the country having higher resolution data (Gesch, 2007; Gesch et al., 2002). For much of south-central Virginia, a DEM having a spatial resolution of 1/3 arc-second (approximately 10 m by 10 m) is publically available.

Within a DEM, each cell is assigned a singular elevation value. When considered as a continuous grid, these discrete cell elevations combine to provide an indication of land slope and aspect, and act to represent realistic terrain conditions. Theoretically, finer resolution grids allow for a more accurate representation of the landscape. For example, nine discrete 10 m by 10 m cells will fit within the area of one 30 m by 30 m cell, allowing the 10 m grid to better characterize subtle changes in topography that would be overlooked at a coarser resolution. For this reason, it is desirable to use the most accurate DEM, with the highest resolution available, when developing any type of a hydrologic model. In this way, the simulated flow paths and watersheds delineated from the terrain model will better represent their actual counterparts, in both location and functionality (Knebl et al., 2005; Olivera, 2001).

Once a suitable DEM is obtained, the "terrain pre-processing" functions in ArcHydro (outlined and summarized in Appendix A) can be employed to delineate the overall watershed, the subbasins, and the stream network within the watershed. These functions utilize the raster-based (grid-based) algorithms developed by Jensen and Domingue (1988) to generate flow direction and flow accumulation grids of the study area, from which the basins and stream networks are determined. A flow direction grid looks at each cell and the eight cells surrounding it and determines which direction flow would travel leaving that cell. The program identifies the steepest decent from the study cell, or the surrounding cell with the lowest elevation compared to the study cell. In this way, a unique downstream path from each cell can be determined by connecting each cell to its downstream-draining cell. Sometimes, however, there are cells that have a lower elevation value than their neighboring eight cells which disrupts this process. These cells must be carefully analyzed to determine if they are a result of a natural depression or from some error in the DEM. Erroneous cells must go through a filling process so that flow can be routed across them. Natural depressions, however, (lakes, sinkholes, etc.) should be left alone, as they represent areas where ponding could occur, disrupting overland flow paths. The flow direction grid is used for determining how the flow will travel across the landscape and where stream networks will likely develop.

From the flow direction grid, a flow accumulation grid is created. In this grid, each cell is assigned a value indicating the accumulated number of cells upstream of it that eventually drain into it. This calculation is done for each cell in the input grid and can later be used to define stream networks and potential discharge points for various subbasins. With the flow accumulation grid and the specified watershed outlet point, the built-in watershed delineation functions in Spatial Analyst/ArcHydro can be used to determine all of the land area that drains to the specified outlet.

In addition to being used to delineate the overall watershed, the flow accumulation grid is also used to define the dendritic stream network in the watershed. Using an area-threshold method, a modeler selects a minimum area or cell number threshold that must be attained before the software will consider a stream to be initiated. In using the area approach, the program automatically calculates contributing area to each cell by multiplying the cell area (100 m^2 for a 10 m by 10 m grid) by the flow accumulation number assigned to that cell. Once the threshold has been specified, the program identifies all cells exceeding the selected value and assigns them to be part of the stream network. As a default, ArcHydro suggests the threshold to be one percent of the entire watershed area; however, a user may change this to any other desired threshold.

After the flow network is generated, the streams are segmented into individual stream links from which the subbasins are generated. Break points are added each time a tributary connects to another tributary or anywhere a fork in the stream network exists. Once the streams have been segmented, a “catchment grid delineation” can be conducted in ArcHydro to generate a number of smaller subbasins within the large overall watershed. To do this, the program identifies the contributing drainage area to each of the individual stream links. Adjacent subbasins can later be combined together to form larger subbasins, simplifying the overall hydrologic model. The subbasins and stream links generated in this way eventually become the basin nodes and stream reaches constituting the basic structure of the HEC-HMS basin model.

3.2.1.2 Loss Method – SCS Curve Number

Once the basic model structure has been established, characteristics for each of the subbasins must be defined. These parameters vary for different modeling methods and approaches used. One of the most important methods involved in hydrologic modeling is the loss method. The loss method aims to conceptually represent how infiltration, surface runoff, and subsurface processes interact in each subbasin element. A total of twelve different loss methods are available in HEC-HMS v3.5, some better geared towards event modeling, while others are more suited for continuous modeling (Scharffenberg & Fleming, 2010). Because the SCS Curve Number Loss Method was selected for this project, only its associated methodology is presented here.

The Soil Conservation Service (SCS) (now the Natural Resources Conservation Service (NRCS)) Curve Number Method is essentially an empirical, one-parameter event rainfall-runoff model. This technique is based on the assumption that precipitation mass is conserved. The sum of the infiltrated water and the precipitation that remains on the surface to become surface runoff is equal to the total incoming precipitation (Scharffenberg & Fleming, 2010). In the SCS Curve Number Loss Method, infiltration capacity is quantified through a parameter derived by the SCS called the Curve Number (CN). This CN provides an indication of storm runoff potential over an area based on that location's land use/cover, soil type, and its antecedent conditions (USDA NRCS, 1986).

To generate this CN grid, information regarding land cover and soil must be obtained for the study area. These land cover data are commonly obtained from the USGS seamless data server, as part of its National Land Cover Dataset 2006 (NLCD 2006). This dataset is publically available for download; however, the finest resolution available is only at a 1-arc-second cell size (approximately 30 m by 30 m). In this file, each cell is assigned to one of sixteen land cover classes based primarily on the unsupervised classification of LandSat Enhanced Thematic Mapper+ (ETM+) circa 2006 satellite data (Fry et al., 2011). The data were developed as a raster grid through remote sensing and automated classification so that each cell is assigned the NLCD land use code corresponding to the dominant land cover type within it (Kalyanapu et al., 2009).

With regard to soils data, the CN requires a soil map that is classified by hydrologic soil group (HSG). This dataset can be obtained from the Soil Survey Geographic (SSURGO) Database operated by the NRCS which is part of the United States Department of Agriculture (USDA) (USDA NRCS, 2009). The SSURGO file is made up of a mesh of polygons, each assigned to one of the four HSGs: A, B, C, and D. These classifications are based on characteristics such as the amount of intake and transmission of water under the conditions of maximum yearly wetness, whether the soils are subject to freezing or how much vegetated cover there is, and how much the expansive clays in the soil swell (USDA NRCS, 2007). An HSG A soil would have low surface runoff potential when thoroughly wet, where as an HSG D soil would display high surface runoff potential when thoroughly wet. HSG B and C soils are in between these, with B representing moderately low surface runoff potential and C indicating a moderately high surface runoff potential (USDA NRCS, 2007). There also exists what are called dual hydrologic soil groups (A/D, B/D, and C/D) that act as either A, B, or C soils under a drained condition and as a D soil for the undrained condition.

Once the land cover and soil datasets have been collected, HEC-GeoHMS can combine the two datasets with a tabular CN look-up table to obtain a useable parameter for predicting direct runoff or infiltration from rainfall excess. The look-up table values are selected from the Runoff Curve Number Tables generated by SCS/NRCS that can be found in the *USDA NRCS Technical Release 55, Urban Hydrology for Small Watersheds* (TR-55) document (1986). The CN values in this document were developed for "average" antecedent moisture conditions and range from 0 to 100, with the lower CNs representing low surface runoff potentials and the higher numbers representing high surface runoff potentials. For example, a pairing of a gravel roadway with underlying soil of HSG C would have a greater CN than a forested plot of land with the same underlying soil. It should be noted that the TR-55 cover types and land treatments do not exactly match up with the NLCD land cover types; the TR-55 values must be interpreted based on the modeler's sound engineering judgment.

The CN parameter is highly dependent on the antecedent moisture/runoff condition (AMC or ARC) that is considered. The ARC classification attempts to quantify the variability in a number of watershed characteristics, including rainfall intensity and duration, total runoff, soil moisture conditions, cover density, stage of growth, and temperature (USDA NRCS, 2004).

However, the ARC class is generally assigned based on the antecedent soil moisture, which is frequently correlated to the five-day antecedent precipitation experienced in the study watershed. The first ARC classification (ARC I) indicates dry antecedent conditions and is assigned if the sum of the total five-day antecedent rainfall is less than 1.25 cm (0.5 in) during the dormant season (November to May) or less than 3.5 cm (1.4 in) during the growing season (June to October). ARC II, for which the TR-55 CNs were developed, represents average antecedent conditions, and is chosen if the total five-day antecedent rainfall is between 1.25 cm (0.5 in) and 2.8 cm (1.1 in) during the dormant season or between 3.5 cm (1.4 in) and 5.3 cm (2.1 in) during the growing season. The third ARC class (ARC III) represents wet antecedent conditions and is used if heavy rainfall or light rainfall/low temperatures have occurred within the five days prior the hydrologic analysis. This classification is used when the soil is assumed to be saturated from a previous event and when the total five-day antecedent rainfall is greater than 2.8 cm (1.1 in) during the dormant season or greater than 5.3 cm (2.1 in) during the growing season (McCuen, 1998). For a worst-case scenario analysis, such as for a PMP event, the U.S. Army Corps of Engineers (1994) recommends selecting the antecedent conditions to be the most severe that can reasonably exist at the commencement of the storm. Because of this, the ARC III classification is commonly used for PMP-type events.

As previously mentioned, the CNs presented in the tables in TR-55 were developed for an assumed ARC II condition (average condition). To convert the CN_{II} values to either CN_{I} or CN_{III} values, a number of empirical relationships have been developed by different researchers. However, one method commonly used in practice is to reference the conversion chart in Table 10-1 of the *National Engineering Handbook, Part 630 Hydrology, Chapter 10: Estimation of Direct Runoff from Storm Rainfall* (USDA NRCS, 2004). This chart, presented in Table 1, provides a CN_{I} and CN_{III} value for each corresponding CN_{II} value.

When building the CN grid, HEC-GeoHMS overlays the land cover data and the HSG data and then cross-references the combined layer with the CN look-up table values to assign each cell of the map a CN. From this CN grid of the watershed, the program will average the CN values in each subbasin and assign an areally-weighted average CN to each (Merwade, 2010a). In this way, it assigns a single, lumped CN value to each individual subbasin which is representative of the average surface runoff potential for that area. The CN grid creation methodology is outlined in greater detail in Appendix A.

Table 1: NEH Part 630, Ch. 10 CN Conversion Table (USDA NRCS, 2004)

1	2	3	4	5	1	2	3	4	5
CN for ARC II	-- CN for ARC -- I	III	S values* (in)	Curve* starts where P = (in)	CN for ARC II	-- CN for ARC -- I	III	S values* (in)	Curve* starts where P = (in)
100	100	100	0	0	60	40	78	6.67	1.33
99	97	100	.101	.02	59	39	77	6.95	1.39
98	94	99	.204	.04	58	38	76	7.24	1.45
97	91	99	.309	.06	57	37	75	7.54	1.51
96	89	99	.417	.08	56	36	75	7.86	1.57
95	87	98	.526	.11	55	35	74	8.18	1.64
94	85	98	.638	.13	54	34	73	8.52	1.70
93	83	98	.753	.15	53	33	72	8.87	1.77
92	81	97	.870	.17	52	32	71	9.23	1.85
91	80	97	.989	.20	51	31	70	9.61	1.92
90	78	96	1.11	.22	50	31	70	10.0	2.00
89	76	96	1.24	.25	49	30	69	10.4	2.08
88	75	95	1.36	.27	48	29	68	10.8	2.16
87	73	95	1.49	.30	47	28	67	11.3	2.26
86	72	94	1.63	.33	46	27	66	11.7	2.34
85	70	94	1.76	.35	45	26	65	12.2	2.44
84	68	93	1.90	.38	44	25	64	12.7	2.54
83	67	93	2.05	.41	43	25	63	13.2	2.64
82	66	92	2.20	.44	42	24	62	13.8	2.76
81	64	92	2.34	.47	41	23	61	14.4	2.88
80	63	91	2.50	.50	40	22	60	15.0	3.00
79	62	91	2.66	.53	39	21	59	15.6	3.12
78	60	90	2.82	.56	38	21	58	16.3	3.26
77	59	89	2.99	.60	37	20	57	17.0	3.40
76	58	89	3.16	.63	36	19	56	17.8	3.56
75	57	88	3.33	.67	35	18	55	18.6	3.72
74	55	88	3.51	.70	34	18	54	19.4	3.88
73	54	87	3.70	.74	33	17	53	20.3	4.06
72	53	86	3.89	.78	32	16	52	21.2	4.24
71	52	86	4.08	.82	31	16	51	22.2	4.44
70	51	85	4.28	.86	30	15	50	23.3	4.66
69	50	84	4.49	.90	25	12	43	30.0	6.00
68	48	84	4.70	.94	20	9	37	40.0	8.00
67	47	83	4.92	.98	15	6	30	56.7	11.34
66	46	82	5.15	1.03	10	4	22	90.0	18.00
65	45	82	5.38	1.08	5	2	13	190.0	38.00
64	44	81	5.62	1.12	0	0	0	infinity	infinity
63	43	80	5.87	1.17					
62	42	79	6.13	1.23					
61	41	78	6.39	1.28					

* For CN in column 1.

With the subbasin averaged CNs, the potential retention, S, (infiltration storage capacity) for each subbasin is found using either Equation 1 or Equation 2, depending on the desired units:

$$S = \left(\frac{2540}{CN} - 25.4\right) \quad \text{for S in centimeters} \qquad (1)$$

$$S = \left(\frac{1000}{CN} - 10\right) \quad \text{for S in inches} \qquad (2)$$

Based on this storage value, an initial abstraction for each basin can be determined. This initial abstraction (I_a) is a measure of all of the precipitation losses (water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration) experienced before surface runoff begins. Through empirical observations made on a number of both small and large watersheds, it was determined that I_a can be approximated as 0.2 times the overall potential maximum retention (Equation 3 or 4) (USDA NRCS, 1986; Woodward et al., 2002). Further refinement of I_a is possible (with some studies suggesting I_a to be as low as 0.05 times the potential maximum retention (Hawkins et al., 2002)), but is usually not recommended because under typical field conditions, very little is known of the magnitudes of interception, infiltration and surface storage (Woodward et al., 2002).

$$I_a = 0.2 * S = 0.2 * \left(\frac{2540}{CN} - 25.4\right) \qquad \text{for } I_a \text{ in centimeters} \qquad (3)$$

$$I_a = 0.2 * S = 0.2 * \left(\frac{1000}{CN} - 10\right) \qquad \text{for } I_a \text{ in inches} \qquad (4)$$

HEC-HMS uses this initial abstraction value to directly determine how much of the precipitation is lost and how much is converted to surface runoff during a storm event.

3.2.1.3 Transform Method – SCS Unit Hydrograph

While the Loss Method conceptually represents the infiltration and initial precipitation loss that is experienced at the onset of a storm, the actual surface runoff calculations are performed by the Transform Method that is selected for each subbasin. A total of seven different Transform Methods are available within HEC-HMS, including a number of unit hydrograph methods, a kinematic wave technique, and a linear quasi-distributed procedure (Scharffenberg & Fleming, 2010). As only the SCS Unit Hydrograph Transform Method was used for this project, it is the only one of the transform methods that is described here.

The SCS Unit Hydrograph Transform Method, like the SCS Curve Number Loss Method, was developed from observed data collected in small to medium sized agricultural watersheds. To develop this method, a number of observed dimensionless hydrographs from various sites around the country were generalized and a "best-approximate" hydrograph was developed for universal application. This general SCS unit hydrograph has ordinates which are scaled by a basin lag time calculated for each subbasin. In general, the SCS unit hydrograph is designed so that 37.5% of the total runoff volume is encountered before the peak discharge is experienced and so that the total time base of the hydrograph is equal to five times the basin lag time for the subbasin (Scharffenberg & Fleming, 2010).

This method requires two inputs: a "graph type" and a basin lag time for each subbasin. The user must specify whether to use the "standard graph" or the "Delmarva graph". The Delmarva shape is recommended for basins located within the Atlantic coastal plain region of Delaware, Maryland, and Virginia. For regions of the U.S outside of the coastal plain, the standard graph is applied.

The second parameter, the basin lag time, is defined as the length of time between when the centroid of the precipitation mass occurs and when the peak flow of the resulting hydrograph happens (Scharffenberg & Fleming, 2010). Studies conducted by the SCS/NRCS concluded that this lag can be approximated as sixty percent of the time of concentration (T_c) or can be found with an empirically based formula derived from the Curve Number method (Fleming & Doan, 2010). The first approach uses the NRCS Segmental Velocity Method for estimating T_c, as outlined in TR-55 (USDA NRCS, 1986), whereas the second approach utilizes the NRCS Watershed Lag Equation Method (Mockus, 1961). Both of these methods are elaborated on in greater detail in Chapter 4. Once the basin lag time has been estimated for each subbasin and the graph type has been selected, the HEC-HMS model can transform excess precipitation into surface runoff that is then conveyed through the study reaches with a Routing Method.

3.2.1.4 Canopy, Surface, Baseflow Method

In addition to the Loss and Transform Methods, HEC-HMS has the capability to employ a Canopy Method, a Surface Method, and a Baseflow Method within each subbasin to better simulate real-world hydrologic conditions. The Canopy Method is used to represent the presence of plants in the landscape. This method is meant to provide a measure of interception, or how much precipitation is captured on leaves and plants that never makes it to the ground to become runoff. The Surface Method is used to represent the surface depression storage capacity within the watershed. Using this method, surface runoff would only initiate after the precipitation rate exceeded the infiltration rate and after the surface storage was filled (Scharffenberg & Fleming, 2010). The HEC-HMS v.3.5 User's Manual states that both the Canopy and Surface Methods are generally only used for continuous simulation applications, and are not commonly incorporated into event-based simulations. Because of this and the nature of this project, the Canopy and Surface Methods are not elaborated on in this document.

The Baseflow Method aims to represent the subsurface processes within the watershed such as the surface water-groundwater exchange. Within HEC-HMS, there are four available Baseflow Methods, some of which are designed primarily for simulating events while others are intended for continuous simulation. By not selecting a Baseflow Method, HEC-HMS only considers direct runoff from the transform method.

3.2.1.5 Hydrologic Routing Method - Muskingum

In order for the model to convey flow from one subbasin to another, and eventually down to the overall watershed outlet point, a flow routing method must be selected for each reach in the basin model. This allows the model to simulate how flow leaving an upstream subbasin travels through the stream channel in the adjacent downstream subbasin. Without a selected routing method, HEC-HMS would instantaneously send the outflow from one outlet point to the next without accounting for the travel time and flow attenuation that the upstream runoff volume would experience as it traveled across the landscape. Consequently, this would provide a grossly erroneous series of outflow hydrographs and a severely misrepresented flood wave through the watershed.

Before deciding on a routing method, the hydrologic routing study reaches must be identified. Despite the fact that there are theoretically just as many stream reaches in the model as there are subbasins, not all of the reaches are considered for routing purposes. Many of stream segments used to delineate the subbasins are considered to be "spurious reaches", or reaches that do not convey flow from an upstream element to a downstream element. This means that the headwater reaches in the most upstream subwatersheds are not incorporated into the routing component of the model. Only reaches that function to convey flow from the headwater outlets through downstream basins are included (Olivera, 2001). However, the effects of these spurious reaches are still accounted for in the unit hydrograph transform method.

HEC-HMS contains a total of six different hydrologic routing methods for simulating open-channel flows. As only the Muskingum Routing Method was used for this project, it is the only one of the six that is described in this section. The Muskingum model is a reach routing algorithm which accounts for both mass translation of flow and for peak flow attenuation when it is applied to an open-channel situation (Olivera, 2001). This method assumes that the water surface in a reach is linear, but non-level, and in doing so, makes it possible to represent increased storage capacity during the rising side of a flood wave and decreased storage capacity during the receding flood wave (Scharffenberg & Fleming, 2010).

To approximate peak flow attenuation, Muskingum incorporates an approximate reach travel time (Muskingum K) and a weighting factor (Muskingum X) representing the influence of inflow and outflow in the reach. The Muskingum K can be estimated for each reach with knowledge of the reach length and flow velocity, as length divided by velocity gives a travel time. It should be noted that the velocity here cannot be extracted from the spatial data and should be obtained through the use of Manning's Equation or another approximation approach and then manually entered into the HEC-HMS basin model. The Muskingum X ranges from 0.0 (maximum attenuation) to 0.5 (no attenuation). Experience has shown that for channels with mild slopes and flows that go out of bank, X will be closer to 0.0. For steeper streams, with well-defined channels that do not have flows going out of bank, X will be closer to 0.5 (USACE, 1994). A frequently used Muskingum X value for natural streams is 0.2 (Scharffenberg & Fleming, 2010; McCuen, 1998).

In addition to the K and X parameters, the number of subreaches that each reach is broken up into must be specified. This is done to maintain numerical stability during simulation. HEC suggests that this number should be approximately equivalent to the reach length divided by the product of the wave celerity and the simulation time step. With these three reach parameters, HEC-HMS can successfully apply the Muskingum method to the appropriate reaches to route flow through the system. A more detailed explanation of how these values can be estimated is presented in Chapter 4.

3.2.2 HEC-HMS Meteorological Model Development

When attempting to model how a watershed will respond to an extreme precipitation event, a modeler must develop both the basin model to simulate the real-world watershed conditions, as well as a meteorological model to serve as the rainfall input over the basin. For each meteorological model, three methods can be specified: a precipitation method, an evapotranspiration method, and a snowmelt method. Seven different precipitation methods are available to choose from in HEC-HMS, however only the Frequency Storm and Specified Hyetograph Methods are detailed in this document, as these are the methods that were used for this project. As evapotranspiration and snowmelt were not considered in either of the event-based PMP analyses for this project, these methods are not elaborated on here. More information on these methods, as well as on the precipitation methods not used for this project, is available in the HEC-HMS User's Manual (Scharffenberg & Fleming, 2010).

3.2.2.1 Frequency Storm Method - NOAA Atlas 14 Precipitation Frequency Estimates

The Frequency Storm Method in HEC-HMS involves developing a synthetic design storm from statistical precipitation data. For this data, one of the most common sources is the National Weather Service's (NWS) *NOAA Atlas 14: Precipitation-Frequency Atlas of the United States* (Scharffenberg & Fleming, 2010). NOAA Atlas 14 (Bonnin et al., 2006) contains precipitation frequency estimates with associated confidence limits for most of the U.S. based on precipitation data collected from a number of rain gauges around the country. These data are also accompanied by additional information such as temporal distributions for rainfall and information concerning seasonal and regional variability. According to the authors of the Atlas, it is intended as the official documentation of precipitation frequency estimates and associated information for the U.S. (Bonnin et al., 2006).

The Atlas is divided into volumes based on geographic sections of the country. Of concern for this project, NOAA Atlas 14 Volume 2 Version 3.0 is used to determine Precipitation-Frequency (PF) estimates for the following states: Delaware, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia, and the District of Columbia. In addition, NOAA's Hydrometeorological Design Studies Center (HDSC) operates the Precipitation Frequency Data

Server (PFDS) (found at http://dipper.nws.noaa.gov/hdsc/pfds/), which was developed and published in tandem with the Atlas. This PFDS is an online portal that allows a user to navigate to a specific location on a map, or to a particular rain gauge, and to pull off the PF estimates associated with it. This server provides the PF results in both tabular and graphical form, as well as in a GIS and cartographic map format (Bonnin et al., 2006). For a discussion of the Atlas 14 and PDFS development methodologies, refer to the document itself, as these are not elaborated on further in this thesis.

For the state of Virginia, the PDFS contains probabilistic data on both precipitation depths and precipitation intensities for either the partial duration or annual maximum time series. By interactively selecting a point on the map or selecting a specific station, a user can obtain point PF estimates, along with ninety percent confidence limits, for a number of duration and average recurrence interval/annual exceedance probability combinations. Available durations are: 5-min, 10-min, 15-min, 30-min, 60-min, 2-hr 3-hr, 6-hr, 12-hr, 24-hr, 2-day, 3-day, 4-day, 7-day, 10-day, 20-day, 30-day, 45-day, and 60-day. Available average recurrence intervals/annual exceedance probabilities are: 2-yr (1/2), 5-yr (1/5), 10-yr (1/10), 25-yr (1/25), 50-yr (1/50), 100-yr (1/100), 200-yr (1/200), 500-yr (1/500), and 1000-yr (1/1000).

When modeled in HEC-HMS, a frequency storm is assigned a single recurrence interval/exceedance probability ranging from 0.2 percent (500-yr) to 50 percent (2-yr). However, the return interval specified is not directly used in the program so HEC-HMS can still be used to simulate events outside of the available range options. In addition to the probability, the user must specify the input type (partial duration or annual duration), the output type (partial duration or annual duration), as well as the intensity duration (5-min, 15-min, 1-hr, 2-hr, 3-hr, or 6-hr) and storm duration (3-hr, 6-hr, 12-hr, 1-day, 2-day, 4-day, 7-day, or 10-day). The intensity duration refers to the shortest time period of the storm, usually set to a value close to the modeling time step and the storm duration is a measure of how long the total precipitation will last. Next, the user must select an intensity position (25 percent, 33 percent, 50 percent, 67 percent, or 75 percent), which denotes where in the storm the period of peak precipitation will occur. This selection does not change the total depth of the storm, but instead alters how the total depth is distributed over time during the storm. The user also has the option to assign a storm area to the frequency storm, which is used to determine a depth-area reduction factor to apply to the point

PF depths. If no area is specified, the program assigns a different hyetograph to each subbasin, computed using the subbasin area as the storm area (Scharffenberg & Fleming, 2010).

Finally, the modeler can enter the precipitation depths to be used in the storm. Each depth corresponds to a specific duration (5-min, 15-min, 1-hr, 2-hr 3-hr, 6-hr, 12-hr, 1-day, 2-day, 4-day, 7-day, and 10-day), the values of which are taken from NOAA Atlas 14 or the online PFDS. In this, rainfall depths are entered as a cumulative series (as presented by NOAA) and must be assigned for each duration from the specified intensity duration up to the storm duration. Following this procedure, a separate frequency storm can be generated for each return interval of interest.

3.2.2.2 Areal Distribution/Areal Reduction of Point Gauge Estimates

Often times a meteorological model is developed based on point estimates gathered from individual precipitation gauging stations. The PF estimates presented in the NOAA Atlas 14 document and from the PFDS function in this capacity, as the data from these sources correspond to only a single point on a map or to a single station. In order to more realistically utilize these data, the point estimates must be transformed into a spatially distributed storm using an interpolation scheme and by applying an areal-reduction factor to them.

One common interpolation scheme utilized for rainfall data is known as the Thiessen or Voronoi Polygon Method. This technique is one of the simplest interpolation routines, as it considers a two-dimensional surface with a series of points on it, dividing it up solely based on proximity to adjacent points (reference Figure 7). Starting with a series of randomly-spaced station points (1), a triangulated irregular network (TIN) is generated by connecting each of the points to the closest adjacent points with a series of lines (2). With the TIN, perpendicular bisectors are drawn for each triangle edge, truncating and forming vertices where the bisectors intersect one another (3). These perpendicular bisectors form the edges of the Thiessen polygons (4). In this way, any geographic point on the surface is assigned to the station point that it lies closest to (Chow et al., 1988).

With a rain gauge Thiessen polygon map overlain on top of the watershed, a single set of PF estimates for the basin can be obtained using areally-weighted approach. By clipping the polygon map to exist only within the bounds of a study watershed, and by determining the fraction of the total watershed that should be assigned to each station point, precipitation values can be obtained by summing up the products of each station depth and the fraction to which it is applied for each duration for each recurrence interval (McCuen, 1998).

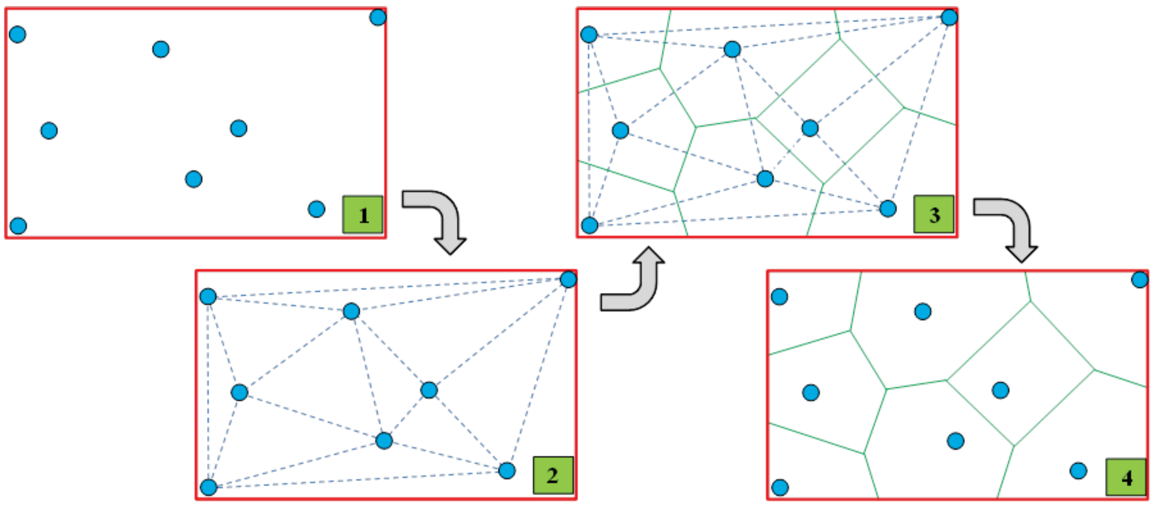

Figure 7: Steps Involved in the Thiessen Polygon Interpolation Scheme

Once the areally-weighted precipitation values have been found and a singular frequency series has been developed for a specific return period, an areal-reduction factor should be applied to the data. This factor is used to compensate for the use of point precipitation estimates in a spatially distributed storm. There are a number of different methodologies for determining these reduction factors; however, the one commonly cited method is that presented by Hershfield (1961) in *Technical Paper No. 40* from the U.S. Department of Commerce and the Weather Bureau (now the NWS). This reduction factor is a single value based on watershed area to which all the PF values in the frequency storm are multiplied by, producing a new areally-weighted, areally-reduced precipitation frequency storm.

3.2.2.3 Specified Hyetograph Method - Probable Maximum Precipitation/Probable Maximum Storm (PMP/PMS)

The Specified Hyetograph Method in HEC-HMS is one of the most versatile precipitation methods offered, as it allows the user to build a storm hyetograph as he/she sees fit. This method allows the user to specify the exact time-series to use for each hyetograph for each subbasin.

This technique is especially useful when precipitation data are processed externally from HEC-HMS and then imported later, as is the case with the externally generated PMP time series (Scharffenberg & Fleming, 2010). Because it allows for separate parameter data to be applied to each subbasin, this meteorological model can be set up in such a way that each subbasin is essentially assigned its own precipitation gauge. These gauges are developed using HEC-HMS's Time Series Data Manager. In this, the modeler can choose to input rainfall data as either incremental or cumulative depths and must also select a regular time interval for the hyetograph periods (ranging from 1-min periods up to periods of 1-day). With the time interval set, HEC-HMS provides a table in which the user can specify the depths to be modeled (Scharffenberg & Fleming, 2010).

With regard to the PMP, this technique can be utilized to develop an individual precipitation time series/precipitation gauge for each subbasin in a model. By definition, the PMS is the spatially and temporally distributed storm which delivers the PMP. As the PMS is applied over a study watershed, the Specified Hyetograph Method can be utilized to compartmentalize the storm and develop a separate precipitation time series for each subbasin in the model. This enables the simulation to compensate for diminishing nature of rainfall as it moves out spatially from the storm center and also allows different areas of the watershed to be modeled with different rainfall inputs. This would theoretically improve the quality of the modeling results, as it allows for a more precise hyetograph to be simulated over a smaller area, with unique estimates of the location's hydrologic conditions.

As the PMP/PMS theoretically represents the worst-case rainfall that could be expected to impact an area, it is generally regarded as the upper limit in extreme event modeling. Because the PMP represents this hypothetical maximum, there are no actual data to use to confirm or validate any definite values for the PMP. However, the Hydrometeorological Report methodology developed by the USDoC, the USACE, and NOAA's NWS has become the standard procedure for generating PMP/PMS estimates in the U.S. (Cudworth, 1989).

The theoretical PMP for any location in the USA east of the 103th Meridian (with the exception of areas within the Appalachian/Blue Ridge Mountains) can be determined by following the procedures outlined in Hydrometeorological Reports No. 51 and 52

(HMR51/HMR52) (Schreiner & Riedel 1978; Hansen et al. 1982). These reports provide guidance on how to determine the 72-hr All-Season PMP (the theoretically greatest amount of rainfall that can occur in a particular watershed over a 72-hr period) for a watershed and how to transform the PMP into an idealistic, elliptical storm pattern with a specific size, shape, orientation, and temporal distribution. These recommendations are based on observed characteristics from a number of historic extreme precipitation events, as evaluated by the authors.

The analysis procedure from these reports is based on a number of All-Season PMP maps that were developed for and published in HMR51. From one of these maps, an example of which can be seen in Figure 5, a modeler can obtain a single PMP point value corresponding to a specific storm/drainage area size and storm duration for any location in the eastern United States (with the exception of areas in the Appalachian Mountains). However, these maps were only created for a very specific set of sizes and durations, as stated previously. Because a study watershed rarely falls precisely on one of these area sizes, HMR51 and HMR52 provide instruction on how to take the Depth-Area-Duration (D-A-D) point values from the maps and interpolate and spatially distribute the data so that it is applicable to the actual study area.

To develop the PMS to deliver the PMP, HMR52 recommends that the storm pattern be modeled as an idealized series of concentric ellipses, termed isohyets, each with a major to minor axis shape ratio of 2.5 to 1. Further, HMR52 suggests standard area sizes for each isohyet, allowing for a pattern of up to nineteen isohyets, covering a storm area of up to 155,400 km^2 (60,000 mi^2). The center isohyet represents the most intense precipitation and the intensity scales down with each subsequent ellipse. The area contained within or between two adjacent isohyets represents a unique, constant rainfall depth at a particular point in time. However, the same area is assigned different depths at different times during the storm, as the intensity of the simulated rainfall changes over the course of the storm event. In addition, the storm is generally positioned and orientated to maximize the precipitation falling within the drainage. This is accomplished by placing the greatest number of whole isohyets completely within the watershed, since the isohyets that enclose smaller area sizes contain proportionately higher rainfall amounts.

HMR52 recognizes that in a realistic storm situation, very intense rainfall cannot be sustained for long periods of time. It recommends dividing the 72-hr PMP event into twelve 6-hr periods, each with a different degree of intensity. The report also suggests different temporal distributions for modeling the storm, as the most intense period is not likely to occur at the very beginning or very end of a storm. A more thorough explanation of the PMP/PMS development and application procedure can be found in Chapter 4 and in Appendix C.

3.3 Model Calibration/Comparison Techniques

Before a hydrologic basin model can be used to simulate a precipitation event such as the PMP/PMS, it must first be tested to ensure that it is functioning as anticipated. An accurate watershed model should be able to mimic the hydrologic response of a basin and be able reproduce observed runoff results given an observed precipitation event or series of events. Ideally, a watershed would have numerous rain gauging stations, as well as a number of flow monitoring stations dispersed throughout the basin. This, however, is rarely the case for most moderately-sized basins, which may have only a couple of gauging stations, if any at all. If a basin is well-gauged, observed rainfall data can be used to generate a realistic meteorological model of a specific event that can then be simulated over the hydrologic basin model. Outflow results from the model can be compared to observed stream discharges at corresponding locations and the model parameters can be adjusted until the simulated flows match the observed flows. If the data are available, this should be done for multiple storms so that the model can be calibrated and validated over a range of flow conditions, as a watershed may respond differently to different magnitude events.

For study watersheds with sparse gauging networks or for watersheds that are ungauged entirely, a statistical/probabilistic approach can be adopted to test the model. This method carries with it much greater uncertainty than a calibration with actual data, but it is often the only alternative to use. There are a number of different techniques that can be applied using statistically generated rainfall and discharge estimates, two of which are elaborated here:

3.3.1 USGS Regional Regression Equations for Estimating Peak Discharges

Recognizing the need to be able to estimate peak flow rates in unregulated streams, the USGS began carrying out studies and publishing reports to take data from gauged watersheds around the country and develop blanket regional regression equations for estimating peak discharges for a number of different return period events in nearby ungauged basins. One such report, *Methods for Estimating the Magnitude and Frequency of Peak Discharges of Rural, Unregulated Streams in Virginia* (Bisese, 1995), was developed for this purpose for the state of Virginia. This report, referred to as the Bisese report hereafter, divided the state of Virginia into eight physiographic regions. For each of these regions, depicted in Figure 8, Bisese has conducted a separate regional regression analysis using data from a number of stream gauges in each (ranging from seventeen sites for the Appalachian Plateau to sixty-seven sites in the Southern Piedmont, each with unique characteristics). These analyses were conducted by fitting a Pearson Type III distribution to the logarithms of the unregulated annual peak-discharge records from the stream-gauging sites in each region (Bisese, 1995). With these distributions, regional regression equations were developed to estimate the peak discharges corresponding to recurrence intervals ranging from a 2-yr to a 500-yr event.

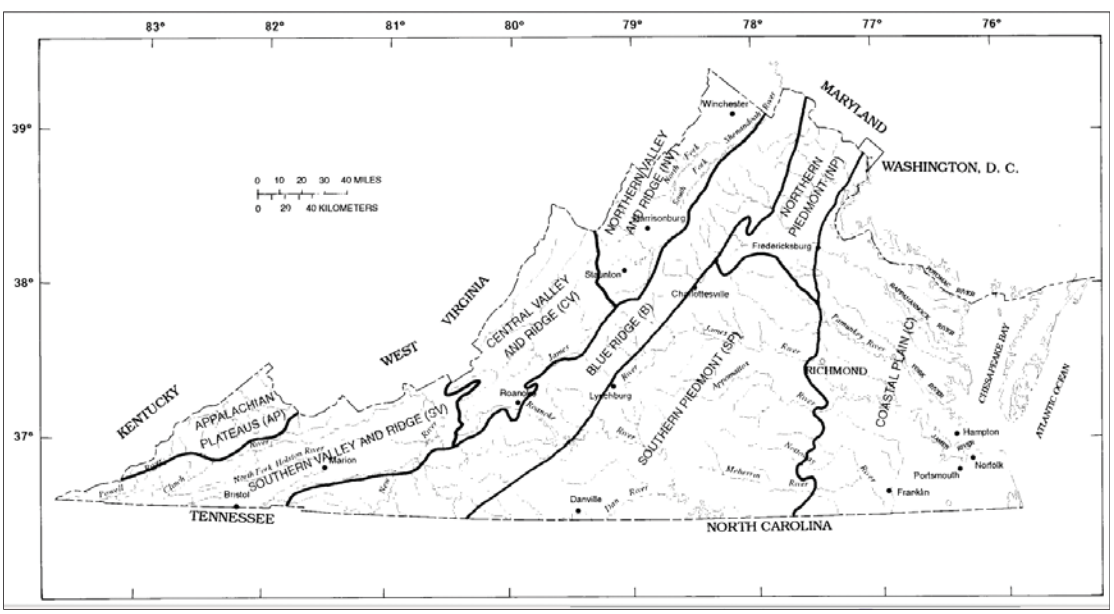

Figure 8: Physiographic Peak-Discharge Regions of Virginia (Bisese, 1995)

There are two types of regression equations presented in the Bisese report: single-parameter regional regression equations and multiple-parameter regional regression equations. The single-parameter equations are based solely on the ungauged basin's drainage area, while the multiple-parameter equations are based on one to three of the following watershed characteristics, depending on the region: drainage area, main channel length, main channel slope, mean basin elevation, percentage of forest cover, mean annual precipitation, and maximum rainfall intensity (Bisese, 1995).

As stated by Bisese, the regional regression equations presented in his report were computed following a generalized least-squares approach, accounting for spatial and temporal correlation between nearby gauging stations. This technique weights the significance of each station to the regional equation based on the length of records collected at each station, the correlation between annual peak discharges among the stations, and the standard deviation of the annual peak discharge for each station (Bisese, 1995). More information on the development methodology and the data used can be found in the Bisese report.

Of particular concern for this project, the Southern Piedmont single-parameter regional regression equations are presented along with their associated standard errors of prediction and equivalent years of record in Table 2. Also in this table is a statistical summary of the mean, median, minimum, and maximum values for each of the basin characteristics considered for the sixty-seven watersheds included in the Southern Piedmont analysis. In order for these regional regression equations to be applicable, the basin characteristics for a study watershed should fall within the range of the parameters analyzed (Bisese, 1995). This means that the single-parameter regional regression equations presented in the table are applicable for Southern Piedmont watersheds with drainage areas ranging from 0.8 km^2 to 7070 km^2 (0.3 mi^2 to 2730 mi^2).

Table 2: Statistical Summary of Basin Characteristics Tested in Regional Regressions (Bisese, 1995) and Single-Parameter Regional Regression Equations for the Southern Piedmont Physiographic Province (Bisese, 1995)

Basin characteristic	Mean	Median	Minimum	Maximum
Southern Piedmont (SP)—67 Sites				
Drainage area (mi^2)	279.5	46.0	0.3	2,730
Main channel slope (ft/mi)	35.6	17.4	2.6	173
Main channel length (mi)	30.3	10.3	0.7	184
Average basin elevation (ft)	522	485	80	1,100
Percent forest plus one (percent)	71	73	17	99
Average annual precipitation (in.)	43.3	43.0	39.5	48.3
Two year, 24-hour rainfall (in.)	3.4	3.4	3.0	4.0

Regression equation	Standard error of prediction (percent)	Equivalent years of record
Southern Piedmont (SP)—67 Sites		
$Q_{(2)} = 122\,(A)^{0.635}$	40.2	2.8
$Q_{(5)} = 233\,(A)^{0.610}$	38.7	5.4
$Q_{(10)} = 335\,(A)^{0.596}$	38.5	8.0
$Q_{(25)} = 504\,(A)^{0.581}$	40.8	10.9
$Q_{(50)} = 661\,(A)^{0.570}$	43.8	12.3
$Q_{(100)} = 849\,(A)^{0.559}$	47.7	13.2
$Q_{(200)} = 1{,}070\,(A)^{0.549}$	52.2	13.7
$Q_{(500)} = 1{,}418\,(A)^{0.538}$	59.0	13.9

It can be noted that the standard errors of prediction for these regression equations are relatively high, ranging from 38.5 percent to 59 percent for the Southern Piedmont region. These standard errors of prediction are estimates of how closely the regression equations can predict the peak discharges at ungauged sites based on the data analyzed. Further, the estimate of peak discharge computed at an ungauged site using the regression equations will be within one standard error of prediction about two-thirds of the time (Bisese, 1995).

For modeling purposes, a hydrologic model of a rural, unregulated, ungauged watershed can usually be considered calibrated if the simulated outflows from a specific set of frequency storms fall within the bounds of the regression equation estimates +/- one standard error of prediction at a corresponding geographic location. For example, if the regression equation peak discharge estimate for a 5-yr storm is 1000 cms and the standard error of prediction is 38.7 percent, a model simulating the 5-yr frequency storm would be considered calibrated for that magnitude event if the simulated outflow at the outlet point fell between 622 cms and 1387 cms.

3.3.2 Bulletin 17B Flood Frequency Analysis

If a study watershed contains one or more discharge gauging stations with sufficiently long periods of record, a Flood Frequency Analysis (FFA) can be conducted using the gauge records of one or more of the gauges. A FFA is performed to predict design flood discharges for different recurrence interval events and involves conducting a statistical analysis of observed annual peak flow data. The goal of a FFA is to develop frequency distributions in either a graphical or tabular format that present the likelihood of various discharges as a function of recurrence interval or exceedance probability.

In an attempt to promote a consistent approach to FFA determination, the U.S. Interagency Advisory Committee on Water Data (1982) developed a set of standard guidelines for determining flood flow frequency. These guidelines, known colloquially as Bulletin 17B, present a methodology for developing the flood frequency distribution for a gauged site using a Log-Pearson Type III (LP3) distribution. Concerning FFA, LP3 is a statistical technique for fitting frequency distribution data to predict design flood discharges at a specific site on a river. The LP3 distribution is a probability density function from which the probabilities of floods of various sizes can be extracted from the curve. The advantage of this particular technique is that extrapolation can be made of the values for events with return periods well beyond the observed flood events. Because of this, and because it usually provides a good fit to measured data, the LP3 technique is regarded as the standard technique used for flood frequency hydrology in the United States (McCuen, 1998). For a detailed description of the FFA LP3 methodology, refer to the Bulletin 17B document.

By considering the entire period of record for a gauge, the FFA assumes that the watershed has remained relatively stable and unchanged over the period of record. If this is not the case, such as with watersheds that have recently experienced a high degree of urbanization, using only a portion of the gauge record may be appropriate. This principle is also true for watersheds that have become regulated by a dam or other hydraulic structure at some point during the record. In this case, only data from after the regulation should be considered. Other key assumptions made during a FFA are that climatic trends and cycles remain relatively constant over a gauge record, that the annual peak events contained within the record are random and independent of one another, that the flow record contains minimal measurement error, and that all of the record events are of the same type (rainstorms, snowmelt, or a combination of the two) (U.S. Interagency Advisory Committee on Water Data, 1982).

With regard to model evaluation, the FFA provides a discharge-recurrence interval series against which modeled outflows from corresponding frequency storms can be compared. Because the FFA results are based on actual site-specific data, they should theoretically provide a better test/comparison series than that obtained through a blanket regional regression equation. However, this method is highly dependent on the length of available record, so it is not recommended for gauged sites with only a few years of usable records. Similar to the regional regression equations, the Bulletin 17B methodology produces a peak discharge estimate at each return interval, in addition to an upper and lower confidence limit discharge (0.05 and 0.95 confidence limits). A model can generally be considered calibrated if the simulated outflow at the gauge location falls between these confidence limit bounds for each corresponding return period.

4. CASE STUDY – WHITETHORN CREEK / BANISTER RIVER STUDY WATERSHEDS

4.1 Geospatial / Standard Regression / Field-collected Data Sources

The hydrologic modeling analyses performed for both the Whitethorn Creek and Banister River Study Watersheds involved a substantial assimilation of input data from a variety of publically available sources. These data include maps, imagery, topography, land cover characteristics, soil classifications, precipitation data, and historic flooding information, among other things. In addition, site-specific channel and reservoir bathymetry and stream sediment characteristics were collected through field reconnaissance and sampling campaigns to supplement and validate these data sources. Where these datasets proved to be insufficient for modeling needs, a number of standard USGS published methodologies were followed to estimate some of the required modeling parameters. Below is a list of select datasets used for the hydrologic model and the sources from which the data were obtained:

- *Watershed / Subbasin Characteristics:*
    - Topography in the form of a Digital Elevation Model (DEM) - National Elevation Dataset (NED) – 1/3 arc-second (approximately 10 m) resolution – U.S. Geological Survey (USGS)
    - Land Cover Data – National Land Cover Database 2006 (NLCD 2006) – 1 arc-second (approximately 30 m) resolution – Multi-Resolution Land Characteristics (MRLC) Consortium – U.S. Geological Survey (USGS)
    - Digital Soil Survey Data – U.S. Department of Agriculture, National Resources Conservation Service – Soil Survey Geographic Database (USDA NRCS SSURGO)
- *Reach Characteristics:*
    - Bankfull Depth, Width, and Cross-sectional Area Estimates – Report: "Regional Curves of Bankfull Channel Geometry for Non-Urban Streams in the Piedmont Physiographic Province, Virginia," - U.S. Geological Survey (USGS) and Virginia Transportation Research Council (VTRC) (currently the Virginia Center for Transportation Innovation and Research (VCTIR))

- Additional Channel Geometry/Bathymetry for Whitethorn Creek, Banister River, and Banister Lake – Field-collected data – VT CEE graduate students and the Virginia Department of Transportation (VDOT)
- Channel Roughness – Site reconnaissance/channel bed sampling campaigns along different points of Banister River, Whitethorn Creek, Mill Creek and Dry Branch, carried out by VT CEE graduate students, as well as from a review or relevant literature

➢ *Meteorological Data:*

- Point Precipitation Frequency Estimates for Chatham, VA, Halifax, VA, Danville, VA, Altavista, VA, Brookneal, VA Gauges - NOAA Atlas 14, Volume 2, Version 3 – National Oceanic and Atmospheric Administration (NOAA)
- Probable Maximum Precipitation Data – Hydrometeorological Reports No. 51 and 52 (HMR51 and HMR52) – U.S. Department of Commerce (USDOC), National Oceanic and Atmospheric Administration National Weather Service (NOAA NWS), and U.S. Army Corps of Engineers (USACE)

➢ *Peak Flow Rate Comparison Data:*

- Peak Discharge Estimates – Report: "Methods for Estimating the Magnitude and Frequency of Peak Discharges of Rural, Unregulated Streams in Virginia" - U.S. Geological Survey (USGS)
- Maximum Annual Peak Discharges for the Banister River (1929-2011) – USGS Surface-Water Annual Statistics for the Nation – USGS 02077000 Banister River at Halifax, VA

4.2 GIS based Hydrologic Modeling – Basin Model Development

4.2.1 Watershed/Subbasin Delineation

By definition, a watershed refers to an area or region that drains to a common outlet point. On this principle, a watershed serves as the fundamental hydrologic unit for almost all hydrologic analyses, as a modeler is usually interested in the response of a particular area to a driving hydrologic control upstream of the site. This is true for both the Whitethorn Creek and

Banister River watersheds, as the goal of these studies was to examine the effect of the PMP/PMS for each region.

Both analyses utilized the ArcHydro/HEC-GeoHMS tools to first identify an appropriate watershed outlet point and then to find the contributing area to that point. As stated previously, the outlet point for the Whitethorn Creek Study Watershed was chosen to be the confluence of Whitethorn Creek and Dry Branch, whereas the outlet point of the Banister River Study Watershed was selected to be the bridge crossing at Bethel Rd. in Halifax, VA at the USGS stream gauging site. With regard to topography, both study watersheds were located within one of the finer DEM resolution regions, and as a result, 1/3 arc-second (approximately 10 m by 10 m) DEMs were utilized for the terrain analyses. Based on these elevation models, the contributing areas for the Whitethorn Creek and Banister River outlet points were determined to be approximately 107 km^2 (41.2 mi^2) and 1415 km^2 (546.4 mi^2), respectively. These delineations were carried out following the general methodology outlined in Chapter 3 of this thesis. In addition, the step-by-step ArcHydro/HEC-GeoHMS procedures that were conducted for each are elaborated on in detail in Appendix A.

As part of these delineation procedures, each study watershed was broken down into a number of subbasins based on an arbitrarily assigned stream initiation threshold. For the Whitethorn Creek analysis, a stream threshold of 1 km^2 (0.4 mi^2) was selected, as this was approximately one percent of the entire watershed area (107 km^2 (41.2 mi^2)). This threshold roughly corresponds to the default one percent area threshold that ArcHydro/HEC-GeoHMS suggests for stream definition purposes (Fleming & Doan, 2010). This threshold produced forty-seven threshold subbasins that were then manually agglomerated into ten merged subbasins. These ten new subbasins had an average watershed area of 4.1 mi^2 and formed the basic structure of the hydrologic basin model. Figure 9 depicts the threshold basins for the Whitethorn Creek Study Watershed, as well as the ten final subbasins used in the hydrologic model.

For the Banister River analysis, a 6 km^2 (2.3 mi^2) stream threshold was adopted, constituting approximately 0.4 percent of the total watershed area (1415 km^2 (546.4 mi^2)). Using this threshold, some of the smaller streams near the Coles Hill site, such as Dry Branch, were defined, which would have been overlooked if the one percent recommended threshold had been chosen. The selected threshold resulted in 133 threshold subbasins within the Banister River Study Watershed. Similar to the Whitethorn Creek analysis, these 133 threshold subbasins were merged together into a total of thirty-seven agglomerated basins with an average area of 14.8 mi^2, as shown in Figure 10. In this, the threshold subbasins were combined so that each of the flow inputs into the Banister River resulted from an agglomerated subbasin rather than a series of smaller subbasins.

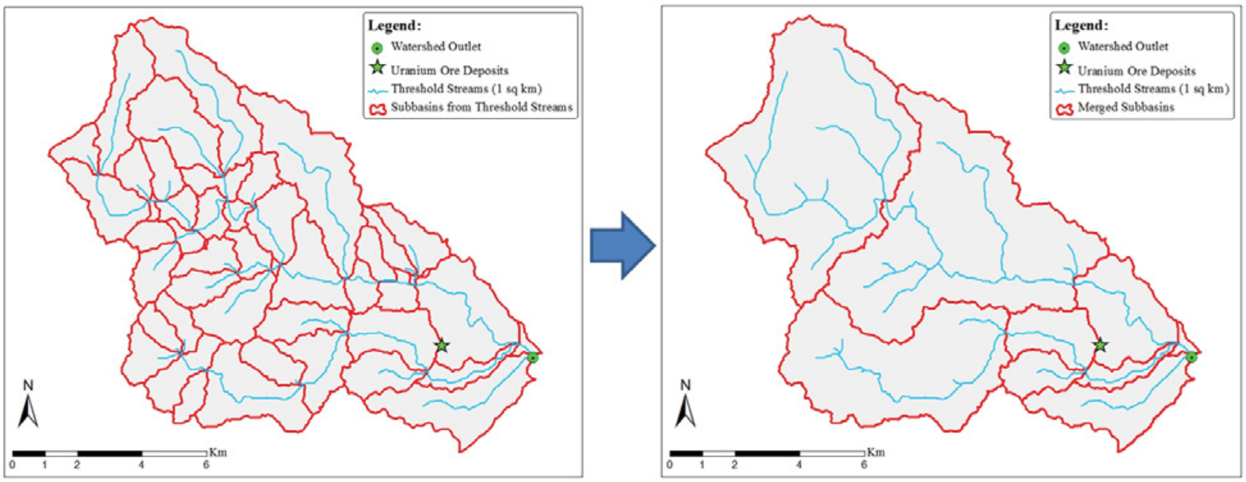

Figure 9: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Whitethorn Creek Study Watershed

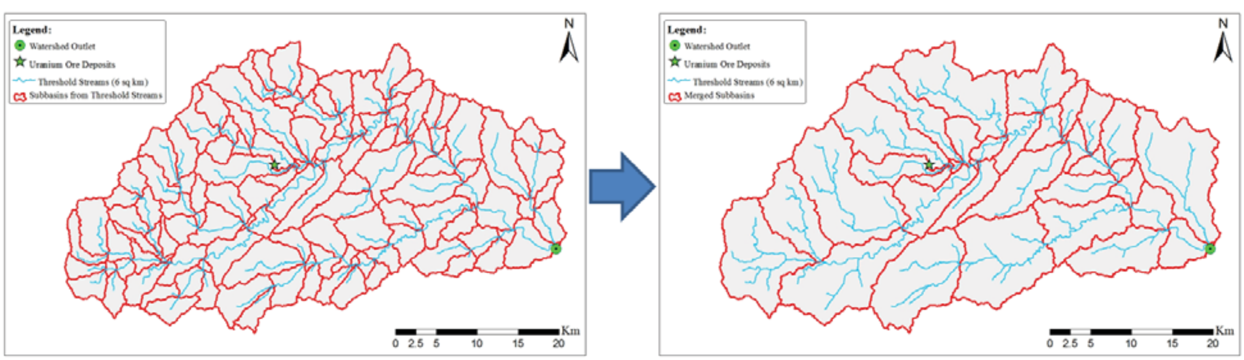

Figure 10: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Banister River Study Watershed

With the final subbasin configurations selected, the remaining basin model development steps were carried out for each watershed. These procedures are detailed in Appendix A. Figure 11 and Figure 12 illustrate the final HEC-HMS basin schematics that were used for the hydrologic simulations. Appendix E also contains a number of tables showing the final parameters that were selected for each basin model.

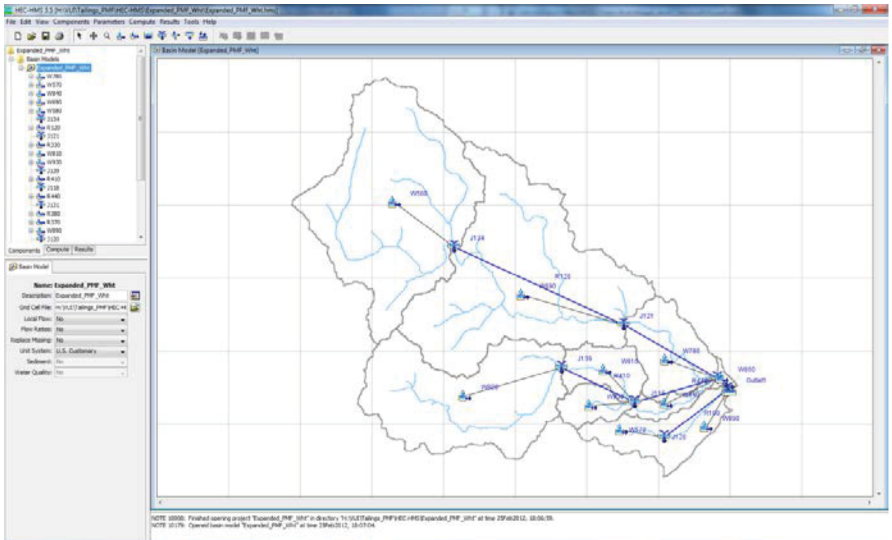

Figure 11: Whitethorn Creek Study Watershed Basin Model Open in HEC-HMS

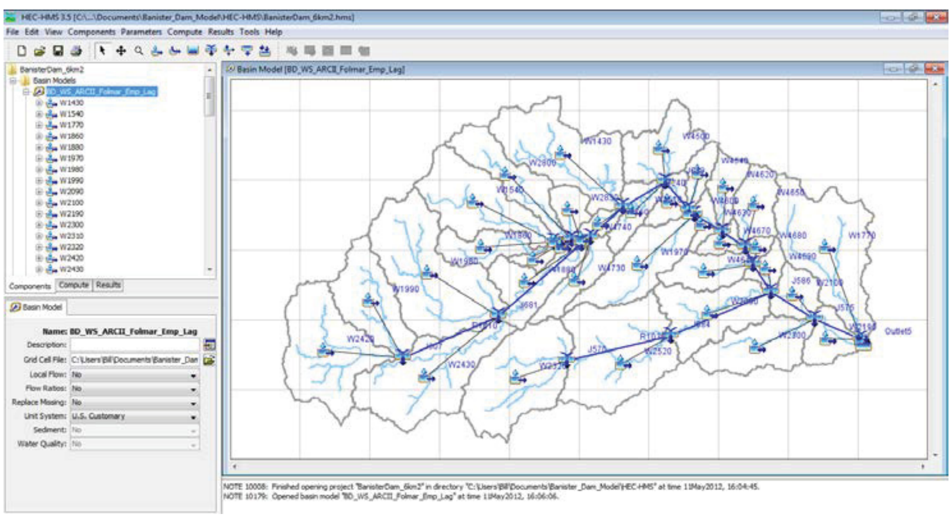

Figure 12: Banister River Study Watershed Basin Model Open in HEC-HMS

4.2.2 Loss Method Parameter Determination

Once the basic basin structure for each model was established, the required modeling parameters for the subwatersheds were defined. For each subbasin in each analysis, the HEC-HMS Loss Method was designated as the SCS Curve Number Loss Method. This method has been widely used for estimating rainfall-generated surface runoff in event-based hydrologic modeling on small agricultural watersheds (Chu & Steinman, 2009). For the SCS Loss Method, three parameters must be specified: the weighted CN, the initial abstraction, and the percent of impervious area.

This first parameter, the weighted CN, is an empirical parameter that provides an indication of storm runoff potential over an area, based on land use, soil type, and hydrologic condition (Knebl et al., 2005; Chaubey et al., 1999). Following the methodology outlined in Chapter 3 of this document, soil and land use data were combined and analyzed with a recommended CN look-up table to develop CN grids for the study watersheds. Two individual CN grids were generated for each analysis, the first corresponding to ARC II (average conditions) and the second to ARC III (wet conditions). From these grids, pictured in Figure 13 and Figure 14, weighted CN values were computed for each subbasin. It should be noted that the CN_{II} values were utilized in the model calibration procedure for the simulation of the frequency storms, whereas the CN_{III} values were used in the simulation of the PMP event, as recommended by the U.S. Army Corps of Engineers (1994). A detailed account of exactly how each CN grid was created for the two analyses is presented in Appendix A.

From the weighted CN values, a value for initial abstraction (I_a) was determined for each subbasin. This parameter represents the total rainfall lost before runoff initiates, including losses from interception, initial infiltration, surface depression storage, and evapotranspiration (USDA NRCS, 1986). The I_a for each subbasin was estimated following the SCS methodology using Equation 4 from Chapter 3. For the third required parameter, the percent of impervious area in each subbasin, a common value of zero percent was adopted for each subbasin. This was done at the recommendation of the HEC-HMS User's Manual so as to not double count the impervious area, as it was previously accounted for in the CN computation.

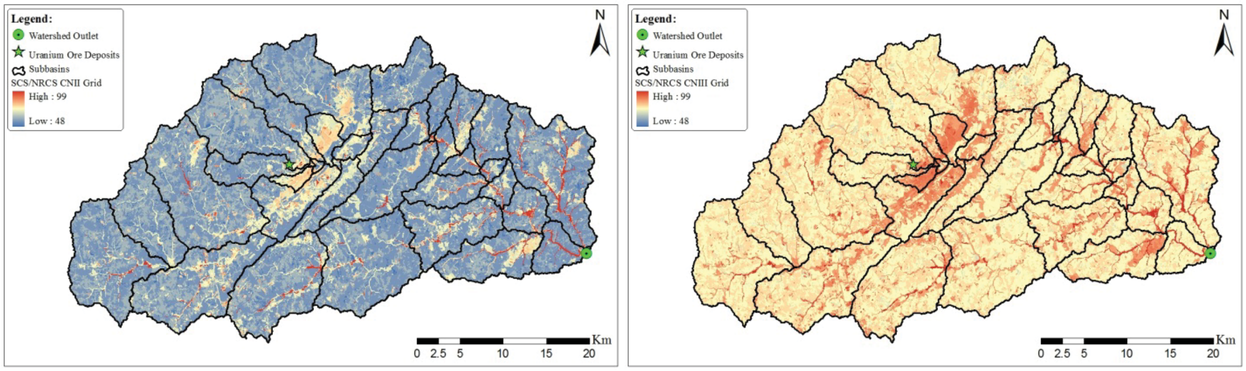

Figure 13: SCS CN Grids Corresponding to ARC II (left) ARC III (right) for the Banister River Study Watershed

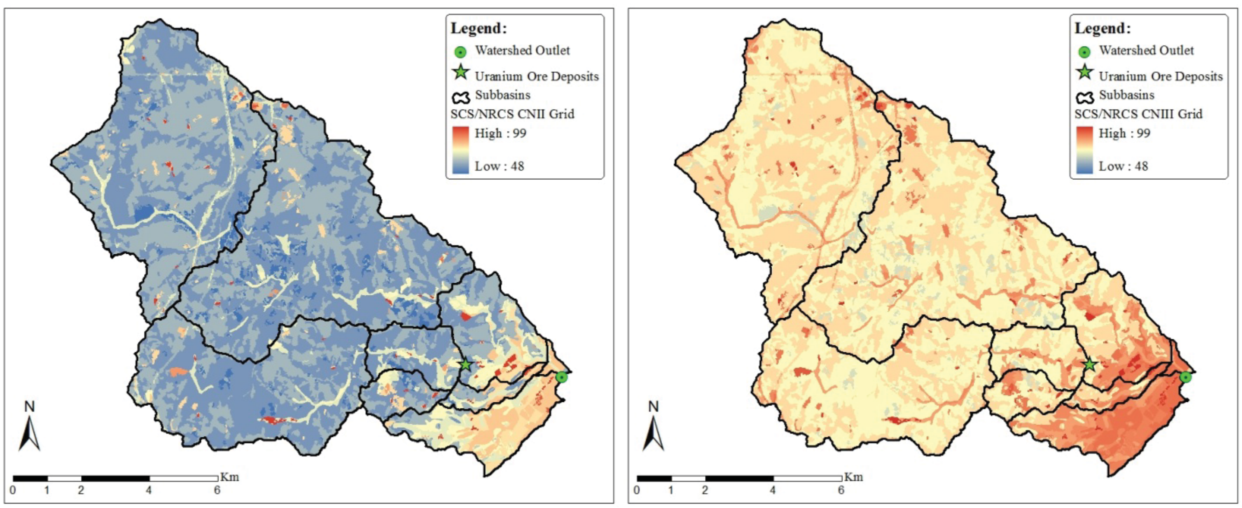

Figure 14: SCS CN Grids Corresponding to ARC II (left) ARC III (right) for the Whitethorn Creek Study Watershed

4.2.3 Transform Method Parameter Determination

After the appropriate Loss Method parameters were determined, the HEC-HMS Transform Method parameters were computed. For both the Whitethorn Creek and the Banister River studies, the SCS Unit Hydrograph Transform Method was chosen to carry out the actual surface runoff calculations. Like the SCS Curve Number Loss Method, this transform method was developed from observed data collected in agricultural watersheds and is commonly used for event-based modeling. As stated previously, this method requires two inputs: a graph type and a basin lag time for each subbasin. For the graph type, two options are available: the Delmarva graph (recommended for basins located within the Atlantic coastal plain region of Delaware, Maryland, and Virginia) and the standard graph (recommended for basins in the U.S. located outside of this Atlantic coastal plain region) (Scharffenberg & Fleming, 2010). Because both study watersheds are located in the Piedmont physiographic province outside of the Atlantic coastal plain, the standard graph was selected for each subbasin for modeling purposes.

After the graph type was selected, the basin lag time for each subbasin was estimated. For both analyses, this parameter was estimated using an empirically-based technique recommended by the NRCS commonly referred to as the NRCS Basin (or Watershed) Lag Equation Method. The method employs a formula empirically derived by Mockus (1961) based on a regression analysis he performed on 24 watersheds ranging in size from 0.0044 mi^2 to 21.3 mi^2 (Folmar et al., 2007). It should be noted that eleven of the thirty-seven subbasins used in the Banister River analysis have drainage areas that are greater than the maximum area size used by Mockus in his regression analysis (the largest with an area of 45.5 mi^2). However, because this method has been applied to larger watersheds in similar analyses presented in the literature (Kafle et al., 2007; Yawson et al., 2005), it was deemed acceptable to use for the study watershed.

The NRCS Basin Lag Equation is applicable for a broad set of conditions ranging from heavily forested watersheds with steep channels and a high percent of runoff resulting from subsurface flow, to meadows providing a high resistance to surface runoff, to smooth land surfaces and large paved areas (USDA NRCS, 2010). The NRCS Basin Lag Equation contains three key variables: the hydraulic length of the watershed (length of the longest flow path), the average subbasin land slope, and the maximum potential retention or storage, which is a factor of the weighted CN. All of these variables can be obtained fairly readily with the watershed GIS. For the study watersheds, these variables were obtained for each subbasin and the basin lag time was calculated using Equation 5:

$$Basin\ Lag\ Time\ (hrs) = \frac{(L^{0.8} * (S+1)^{0.7})}{(1900 * Y^{0.5})} \qquad (5)$$

Where:

- L = hydraulic length of the watershed (ft) – length of the longest flow path
- S = maximum potential retention or storage (in) = (1000/CN) – 10
- Y = average basin land slope (%)

In addition to the NRCS Basin Lag Time Equation, a second approach was employed to estimate the lag time for the Banister River analysis. This was done to compare the effects of how different basin lag determination methodologies affect the modeling results, keeping all other parameters the same. This second method approximates the basin lag time as sixty percent of the time of concentration (T_c), as calculated with the "Velocity Method for Estimating Time of Concentration" technique presented in Chapter 15 of the *NRCS National Engineering Handbook* (NEH) (USDA NRCS, 2010). This method involves first determining the hydrologically longest flow path in a subbasin, then dividing it into segments of sheet flow, shallow concentrated flow, and channel flow, and finally calculating the travel time for each of the three segments and summing them together. ArcHydro and HEC-GeoHMS were utilized to delineate these longest flow paths and to divide them into their respective segments. However, the travel times could not be calculated from geospatial data alone, requiring additional field collected data or data estimated using USGS published regression equations. For a comprehensive list of the data used for the calculation of T_c for the Banister River Study Watershed, reference the tables and figure presented in Appendix D. Due to the lack of in situ observations or field collected data for Whitethorn Creek Study Watershed, this second approach was not applied in the first study.

The first step in the T_c calculation procedure, determining sheet flow travel time, requires information regarding flow length, Manning's roughness coefficient, the 2-yr 24-hr precipitation frequency rainfall depth, and the land slope over which the sheet flow occurs. At the recommendation of the NRCS, the flow length for each subbasin was taken to be 30.5 m (100 ft). The Manning's roughness coefficient assigned for the sheet flow length was determined following the methodology outlined by Kalyanapu et al. (2009), deriving the roughness value from the NLCD 2006 land cover data for the sheet flow region. The 2-yr 24-hr rainfall data was obtained from NOAA's Atlas 14 PF Server (PFDS) and the land slope from each basin was extracted using a slope grid derived from the DEM with the spatial analyst extension in ArcMap. With these data defined for each subbasin, Equation 6 was used to calculate sheet flow travel time for each subbasin:

$$T_{t,sheet} = \frac{0.007(n*L)^{0.8}}{(P_2)^{0.5}*S^{0.4}} \tag{6}$$

Where:

- $T_{t,\ sheet}$ = sheet flow travel time (hrs)
- n = Manning's roughness coefficient
- L = sheet flow length, (ft)
- P_2 = 2-yr 24-hr rainfall (in)
- S = slope of land surface (ft/ft)

Once the sheet flow travel time was determined, the shallow concentrated flow travel time was found for each subbasin based on a surface description, a flow length, a watercourse slope, and a computed average velocity. For both analyses, the surface description for all subbasins was considered to be unpaved (grassed waterways) due to the rural nature of both study watersheds. Even though another surface description (forest with heavy ground litter and hay meadows, cultivated straight row crops, short grass pasture, or minimum tillage cultivation, contour or strip-cropped, and woodlands) may seem more appropriate to use to describe the actual land cover in some of the subbasins, a conservative approach was taken by considering the grassed waterways description. With this, the computed velocities are higher than with the other unpaved descriptions, forcing the lag time to be shorter and the floods to peak more sharply and quickly. The flow lengths and watercourse slopes were extracted from the GIS using ArcHydro/HEC-GeoHMS. For the flow lengths, the shallow concentrated segment was considered to initiate after the end of the 30.5 m (100 ft) of sheet flow and terminated when the longest flow path reached one of the channels delineated in the DEM derived flow network. An empirical formula presented in NEH Chapter 15 (Equation 7 below) was used to find the computed average velocity for the selected surface description (grassed waterway). With the average velocity and flow length, the shallow concentrated flow travel time was computed for each subbasin with Equation 8:

$$V = 16.135(S)^{0.5} \tag{7}$$

Where:

- V = computed average velocity for grassed waterways (ft/s)
- S = watercourse slope (ft/ft)

$$T_{t,shallow} = \frac{L}{3600*V} \quad (8)$$

Where:

- $T_{t,\,shallow}$ = shallow concentrated flow travel time (hrs)
- L = shallow concentrated flow length (ft)
- V = computed average velocity for grassed waterways (ft/s)

Finally, the channel flow travel time was calculated for each subbasin in each model. This was carried out through the use of Manning's equation for determining depth-average channel velocity and with knowledge of the channel flow length. Channel flow travel time is based on the same principle as the shallow concentrated flow travel time: travel time can be found by dividing the flow length by the average flow velocity. To find this velocity, Manning's equation requires a number of inputs, some of which can be gathered from a geospatial analysis, while others cannot. From the GIS, channel flow length was computed from the termination point of the shallow concentrated flow down the longest flow path length to the subbasin outlet point. With this, the channel slope was approximated from the DEMs by dividing the elevation difference over the channel flow length by the length itself.

Additional required inputs included the channel roughness coefficients (Manning's n values) for each subbasin channel, the average cross-sectional flow area in each channel, and the average wetted perimeter for each channel. For the roughness coefficients, values were chosen based on a combination of field observations from in situ reconnaissance campaigns and values cited in the literature for streams seeming to have similar characteristics to the study reaches (Barnes, 1967; Chow, 1959; Lotspeich, 2009). The selected coefficients ranged from 0.025 to 0.045 for the various subbasin reaches and were chosen with best engineering judgment on a subbasin by subbasin basis.

For the cross-sectional flow areas and wetted perimeters for each channel, the assumption that the channel flow in each reach was at a bankfull condition was made. This assumption was made as a conservative approach as the flow velocity would be greatest at or just below bankfull conditions, before the flow experiences the added roughness of the floodplains as it moves out of its banks. This greater velocity would lead to a shorter travel time, and thus to a more peaked hydrograph. The bankfull geometries were gathered from three separate sources, utilizing both field-collected observations and statistical approximations. At or near bridge crossings, bankfull dimensions were taken from Virginia Department of Transportation (VDOT) provided bridge surveys. For portions of the Banister River upstream on the Banister Lake, bankfull estimates were made based on observations made during field campaigns taken by the Virginia Tech Civil and Environmental Engineering (VT CEE) research team working on this project. For this, a canoe was taken from the Riceville Rd. (Co. Rd. 640) bridge crossing in Halifax County, VA downstream on the Banister River through the Banister Lake, totaling 42.5 km^2 (26.4 mi^2) of traversed river length. From the canoe, thalweg depth, channel width, and bank heights were measured at forty-five designated cross-sections with a Philadelphia rod and an Impulse 200 laser rangefinder, manufactured by Laser Technology, Inc. In addition, twenty cross-sections were measured in the Banister Lake using the rangefinder, an Acoustic Doppler Current Profiler (ADCP), and an echo-sounder.

For many of the subbasins, however, in situ observations were not available so bankfull estimates were obtained using regional regression curves for estimating bankfull conditions within the Piedmont region of Virginia (Lotspeich, 2009). These equations, developed by the USGS, were created to help estimate bankfull parameters such as bankfull discharge, bankfull cross-sectional area, bankfull mean channel depth, and bankfull channel width for non-urban streams. They were developed to approximate geometries and channel characteristics for streams based on commonalities observed from other streams in the same geographic region. These regression relationships are solely dependent on the drainage area upstream of the reach outlet point and are meant to be used only when there is a lack of field observed channel characteristics. The regression equations developed for the Piedmont for bankfull cross-sectional area, bankfull mean channel depth, and bankfull channel width are presented as Equations 9, 10, and 11, respectively:

$$CSA = 11.636 * (DA)^{0.7981} \quad (9)$$

$$W = 12.964 * (DA)^{0.4294} \quad (10)$$

$$D = 0.891 * (DA)^{0.3721} \quad (11)$$

Where:

- CSA = bankfull cross-sectional area (ft^2)
- W = bankfull channel width (ft)
- D = bankfull mean channel depth (ft)
- DA = drainage area (mi^2)

Once the bankfull widths and depths were found for each channel in each of the subbasins, the bankfull wetted perimeter for each channel was determined. For this, a rectangular cross-sectional shape was assumed. This means that the wetted perimeter (P_w) was found by adding the estimated bankfull channel width to two times the estimated bankfull mean channel depth (P_w=W+2D). This assumption was made based on a number of observed cross-sections in the Banister River that seemed to exhibit fairly rectangular cross-sections. Once all of the parameters required for Manning's Equation were determined, the channel flow travel time in each subbasin was estimated using Equation 12:

$$T_{t,channel} = \frac{L}{3600*V} = \frac{L}{3600*\left(\frac{1.486}{n}R_h^{2/3}S^{1/2}\right)} = \frac{L}{3600*\left(\frac{1.486}{n}\left(\frac{A}{P_W}\right)^{2/3}S^{1/2}\right)} \quad (12)$$

Where:

- $T_{t,\ channel}$ = channel flow travel time (hrs)
- L = channel flow length (ft)
- V = average flow velocity (ft/s) – from Manning's Equation
- *n* = Manning's roughness coefficient
- R_h = hydraulic radius (ft)
- S = average channel slope (ft/ft)
- A = averaged bankfull cross-sectional area of flow (ft^2)
- P_w = averaged bankfull cross-sectional wetted perimeter (ft)

After all three segmental travel times were estimated, the T_c for each subbasin was calculated by summing up the travel times of each of the three segments. Finally, basin lag time was found by taking the T_c and multiplying it by 0.6, as shown in Equation 13:

$$Basin\ Lag\ Time = 0.6*\left(T_{t,sheet} + T_{t,shallow} + T_{t,channel}\right) \quad (13)$$

Because two separate lag times were estimated for each subbasin in the Banister River model, two separate basin models were developed for each ARC (described in Section 4.2.2). These basin models are henceforth referred to as: ARCII NRCS Lag Eq., ARCII Segmental

Velocity T_c Lag Eq., ARCIII NRCS Lag Eq., and ARCIII Segmental Velocity T_c Lag Eq. The first two of these were used to evaluate the frequency storms and to calibrate the model and the second two of these were used to simulate the PMP for the Banister River analysis.

4.2.4 Hydrologic Routing Method Parameter Determination

After all of the required parameters for the selected Loss and Transform Methods were estimated, the Hydrologic Routing Method parameters were determined. As stated previously the Routing Method simulates how the flow hydrographs from the upland portion of the model are transposed down to the lower parts of the model, and eventually down to the overall watershed outlet point. It dictates how flow leaving an upstream subbasin is conveyed into and through the next downstream subbasin, paying heed to travel time and flood flow attenuation capacity. For both the Banister River and the Whitethorn Creek analyses, the Muskingum Routing Method was selected due to its widespread use for decades for this type of event-based reach modeling (McCuen, 1998).

Before estimating any of the reach routing parameters, the study watersheds were examined to determine which reaches would serve as modeled reaches within the basin model and which would be neglected as "spurious reaches". As only the reaches that act to convey flow from an upstream element to a downstream element are necessary, the reaches in the headwater subbasins are not included in the basin models. In this way, six of the original ten stream links in the Whitethorn Creek Study Watershed and nineteen of the original thirty stream links for the Banister River Study Watershed were chosen to be represented in the hydrologic models. For each of these modeled reaches, three routing parameters are required by HEC-HMS for the Muskingum Method: the Muskingum K, the Muskingum X, and the number of subreaches required to divide each reach into to maintain numerical stability.

The Muskingum K essentially represents the travel time in the reach from when a plug of water enters the reach until it exits the reach. For both studies, the reach travel times were approximated using a very similar approach to that presented for calculating channel flow travel time in the previous section. Manning's equation was utilized to calculate an average velocity for each reach and then travel time was determined by dividing the overall reach length by the flow velocity. Bankfull conditions were again assumed for this procedure, and the required Manning's equation variables were found in the same manner as that described earlier.

After the travel time was determined for each reach, the Muskingum X parameter was selected. This parameter is a weighting factor used to represent the amount of flow attenuation that occurs in each reach. Attenuation refers to the reduction in the peak of a hydrograph as it moves downstream. Ranging from 0.0 (maximum attenuation) to 0.5 (no attenuation), the Muskingum X provides an indication of how each reach functions and how it dissipates peak flows over the course of its length. As the Muskingum X is fairly difficult to estimate for natural streams, it is often considered a calibration parameter. For the Whitethorn Creek and Banister River analyses, different values for X were evaluated, but did not seem to have a significant impact on the magnitude of the PMF results. Therefore, the value of 0.2, commonly used for natural streams, was used in the final models (Scharffenberg & Fleming, 2010; McCuen, 1998).

In addition to the K and X parameters, the number of subreaches that each reach should be divided up into must be specified. This is done to maintain numerical stability during the hydrologic simulation. Following the recommendations of Scharffenberg and Fleming (2010) and Olivera and Maidment (2000), each reach was divided in such a way that the flow travel time in each subreach (k) satisfied the condition $2Xk < \Delta t < k$, where Δt is the simulation time step (5 min for both studies). From this relationship, the following relationship was defined: $\left(\frac{2X}{\Delta t} * \frac{L}{3600*V}\right) < N < \left(\frac{1}{\Delta t} * \frac{L}{3600*V}\right)$ and Equation 14 was applied to find the number of subreaches (N) for each reach:

$$N = int\left[\frac{Travel\ time\ (hrs)}{Modeling\ time\ step\ (hrs)} * (2 * X)\right] + 1 = int\left(\frac{2X}{\Delta t} * \frac{L}{3600 * V}\right) + 1 \qquad (14)$$

Where:

- N = number of subreaches
- X = Muskingum X
- L = total reach length (ft)
- V = average flow velocity (ft/s) – from Manning's Equation
- Δt = simulation time step (hrs)
- int[ ] takes the integer part of the argument (does not round the number)

4.2.5 Discussion on Canopy, Surface, and Baseflow Methods

The HEC-HMS v.3.5 User's Manual states that both the Canopy and Surface Methods are generally only used for continuous simulation applications, and therefore were not used for the event-based Whitethorn Creek and Banister River simulations. Similarly, the Baseflow Method was not specified for either analysis, as short-term baseflow was not considered for the PMP hydrologic simulation. However, a bankfull baseflow condition was considered as an initial flow condition in the hydraulic models of the study areas (not elaborated on in this document). In this way, baseflow is not entirely neglected from the PMF inundation analysis and the hydrologic model produces strictly a runoff response to the PMP without having to account for antecedent flow conditions.

4.3 Meteorological Model Development

A number of meteorological models were generated for this project. These served as precipitation inputs for both model calibration/comparison, as well as for the simulation of the PMS itself. To calibrate the model, nine 24-hr frequency storm models were developed for each of the hydrologic models, corresponding to the following recurrence intervals: 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr, and 1000-yr. To simulate the 72-hr PMS, a specified hyetograph meteorological model was created for each of the study watersheds. In this, the spatially and temporally distributed PMS was compartmentalized on a subbasin basis and separate hyetographs were assigned to each subbasin based on their proximity to the storm center. For all of the meteorological models used in these analyses, the effects of evapotranspiration and snowmelt were not considered.

4.3.1 Frequency Storm Meteorological Model Development

As discussed in Chapter 3, the Frequency Storm Method in HEC-HMS involves the creation of a theoretical design storm for a specified duration based on precipitation frequency estimates gathered for a particular location. For smaller watersheds, information from one rain gauging station may be sufficient to build a storm from; however for larger watersheds, data from multiple gauges are commonly used, adopting an interpolation scheme to find averaged values for the area. In both cases, an areal-reduction factor is employed to account for the use of point estimates on a spatially distributed area.

With regard to the Whitethorn Creek analysis, the precipitation frequency values were obtained from the NOAA Atlas 14 Precipitation Frequency Data Server (PFDS) for a point corresponding to the rain gauging station currently in operation in Chatham, VA. This station is approximately 4.3 km (2.7 mi) outside of the study watershed (see Figure 15) and is the closest PFDS station to it. Data (presented as Table 24 in Appendix B) were obtained as a partial duration precipitation depth series. The partial duration series was selected over the annual maximum series because the corresponding rainfall depths were higher for each return period and duration. However, both time series types produced very similar depths, with the largest deviations occurring in the 2-yr return interval. In addition, the greatest differences were observed for the 24-hr duration (longest duration considered) for each of the return periods. For reference, the greatest difference between the two series was 0.27 in. for the 2-yr 24-hr depth, with a difference of only 0.06 in. for the 1000-yr 24-hr depth (Bonnin et al., 2006). Following recommendations from Hershfield (1961) and using Equation 15 (Maryland Hydrology Panel, 2010), a reduction factor of 0.954 was obtained for the Whitethorn Creek Study Watershed and applied to the point PF estimates for Chatham. These areally-reduced PF estimates (Table 3) served as the frequency storm input data for the Whitethorn Creek hydrologic model.

$$RF_{24-hr} = 1 - 0.01044(A)^{0.4} \qquad (15)$$

Where:

- $RF_{24\text{-}hr}$ = areal reduction factor for 24-hr PF estimates
- A = drainage area (mi^2)

Table 3: Precipitation Frequency Data Used to Construct the Frequency Storm Meteorological Models for the Whitethorn Creek Analysis

Areally-Reduced PFDS Precipitation Frequency Estimates (in.) - Whitethorn Creek Analysis										
by duration for ARI:	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	500-yr	1000-yr
5-min:	0.34	0.41	0.49	0.53	0.60	0.65	0.69	0.73	0.77	0.80
10-min:	0.54	0.65	0.77	0.86	0.96	1.03	1.10	1.15	1.22	1.27
15-min:	0.68	0.82	0.98	1.09	1.22	1.30	1.38	1.45	1.54	1.59
30-min:	0.93	1.14	1.39	1.57	1.80	1.97	2.12	2.26	2.44	2.58
60-min:	1.16	1.42	1.78	2.05	2.40	2.66	2.92	3.18	3.50	3.76
2-hr:	1.38	1.69	2.14	2.48	2.94	3.30	3.68	4.05	4.57	4.97
3-hr:	1.49	1.82	2.30	2.66	3.17	3.55	3.96	4.36	4.90	5.33
6-hr:	1.84	2.23	2.81	3.28	3.94	4.47	5.04	5.63	6.47	7.14
12-hr:	2.22	2.70	3.42	4.04	4.90	5.63	6.42	7.27	8.53	9.57
24-hr:	2.67	3.24	4.13	4.89	6.01	6.95	7.99	9.15	10.85	12.29

Adopting a similar, yet more complex, approach for the Banister River Study Watershed, a number of frequency storms were generated using PFDS data from five individual rain gauging stations. These stations were located in Chatham, VA, Danville, VA, Halifax, VA, Altavista, VA, and Brookneal, VA (locations shown in Figure 15). The partial duration precipitation depth series data for all five of these stations are presented in Appendix B as Table 24, Table 25, Table 26, Table 27, and Table 28, respectively. Again, the partial duration series was selected because it contained greater PF depths than the annual maximum series. From these five sets of PF data, a single, areally-averaged set (Table 29 in Appendix B) was developed using the Thiessen Polygon interpolation scheme as detailed in Chapter 3 (polygons shown in Figure 15). Using the same areal reduction methodology as outlined above, an areal-reduction factor of 0.87 was obtained for the study watershed. Applying this factor to the areally-weighted PF values, a new, areally-weighted, areally-reduced PF series was obtained. This series, presented in Table 4, constituted the input information for the Banister River frequency storms.

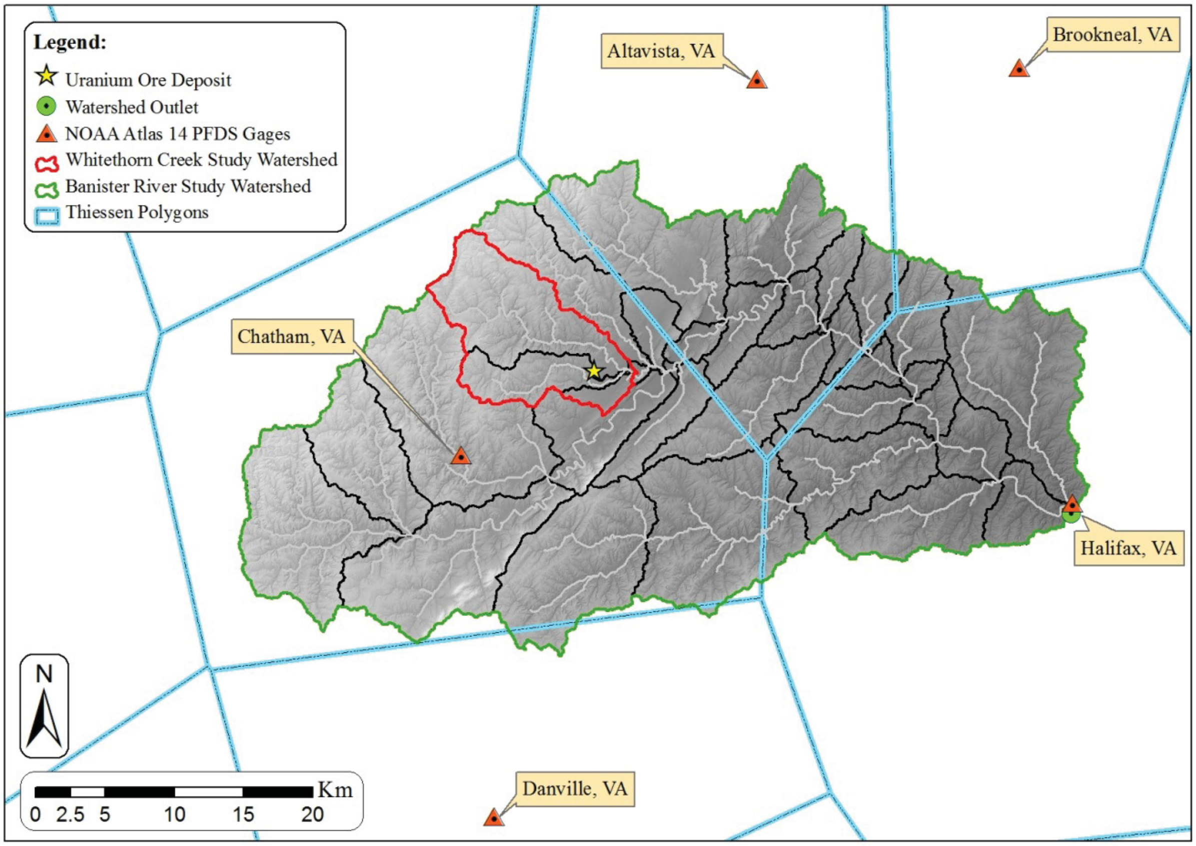

Figure 15: NOAA Atlas 14 PFDS Gauging Stations with Thiessen Polygons in Relation to the Banister River Study Watershed

Table 4: Precipitation Frequency Data Used to Construct the Frequency Storm Meteorological Models for the Banister River Analysis

Areally-Averaged, Areally-Reduced PFDS Precipitation Frequency Estimates (in.) - Banister River Analysis										
by duration for ARI:	1	2	5	10	25	50	100	200	500	1000 years
5-min:	0.31	0.37	0.44	0.49	0.55	0.59	0.63	0.66	0.70	0.73
10-min:	0.50	0.59	0.70	0.78	0.88	0.94	1.00	1.05	1.11	1.15
15-min:	0.62	0.75	0.89	0.99	1.11	1.18	1.26	1.32	1.40	1.45
30-min:	0.85	1.03	1.27	1.43	1.64	1.79	1.93	2.06	2.22	2.35
60-min:	1.06	1.30	1.62	1.87	2.19	2.42	2.66	2.89	3.19	3.42
2-hr:	1.26	1.53	1.94	2.25	2.67	3.00	3.34	3.68	4.15	4.51
3-hr:	1.35	1.65	2.08	2.41	2.87	3.22	3.59	3.95	4.45	4.83
6-hr:	1.67	2.02	2.54	2.97	3.56	4.04	4.56	5.09	5.85	6.45
12-hr:	2.01	2.44	3.09	3.64	4.42	5.08	5.79	6.56	7.69	8.62
24-hr:	2.40	2.91	3.70	4.39	5.38	6.23	7.16	8.19	9.71	10.99

For all frequency storms developed for this project, both the input and output type in the metrological models were selected as Partial Duration with an intensity duration and storm duration of five minutes and one day, respectively. In addition, all storms were assigned an intensity position of fifty percent, such that the most intense precipitation period was modeled as occurring halfway through the one day storm. This intensity position is the default option for frequency storms in HEC-HMS and was the only position evaluated in these studies. Storm area was not specified, and as a result, HEC-HMS computed a different hyetograph for each subbasin using the subbasin area as the storm area (Scharffenberg & Fleming, 2010).

4.3.2 Probable Maximum Precipitation/Probable Maximum Storm

As the goal of both the Banister River and Whitethorn Creek analyses involved determining the implications of a PMP/PMS event, the determination of the actual PMP/PMS was paramount. For each study, the 72-hr PMP/PMS was developed and evaluated using the methodologies outlined in HMR51 (Schreiner & Riedel, 1978) and HMR52 (Hansen et al., 1982), both published by the USDoC, the USACE, and NOAA's NWS. These reports detail how to determine the 72-hr All-Season PMP (the theoretically greatest amount of rainfall that can occur in a particular watershed over a 72-hr period) and how to spatially and temporally distribute the PMP into a PMS that can then be simulated over a study watershed.

Consistent with the recommendations made in HMR52, Figure 16 and Figure 17 depict the PMS spatial distribution and storm orientation that were selected for each study watershed. These storm patterns were modeled as idealized series of concentric ellipses, termed isohyets, each with a major to minor axis shape ratio of 2.5 to 1. HMR52 suggests standard area sizes for these isohyets, the first five and ten of which are denoted in the figures (Isohyets A-E and Isohyets A-J). Figure 17 also contains an additional intermediate isohyet (1450 km^2 (560 mi^2)) that was included because the maximum volume of precipitation was found to result from an area size between two of the standard isohyets. For both analyses, the number of isohyets used was dictated by the minimum number required to encompass the entire watershed area.

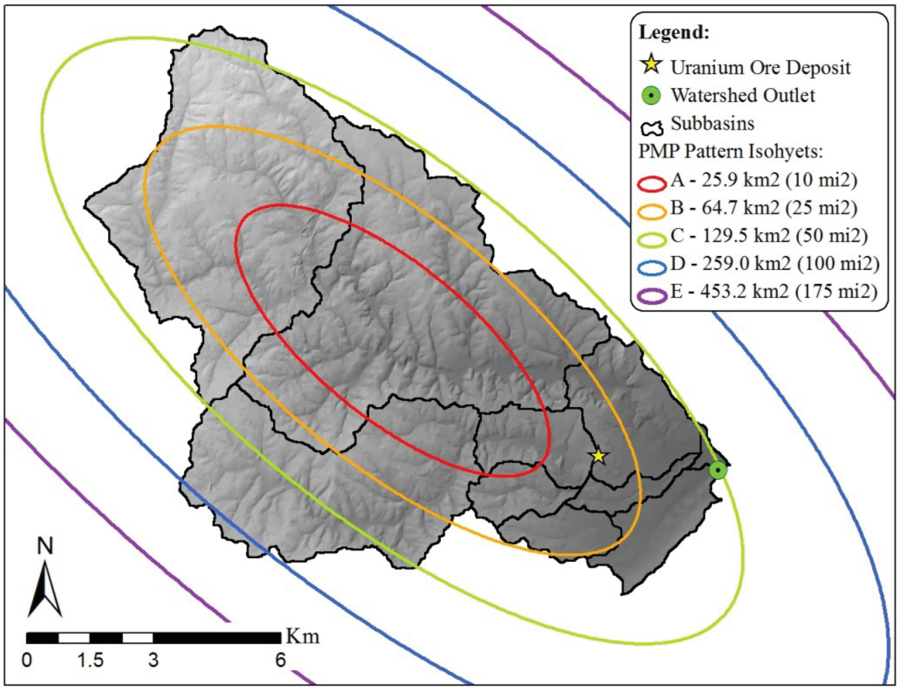

Figure 16: Selected PMS Isohyetal Distribution for the Whitethorn Creek Study Watershed

To maximize the precipitation falling within the drainage, the storms were positioned and orientated in such a way as to place the greatest number of whole isohyets completely within the watersheds. For the Whitethorn Creek analysis, an orientation of 310° from north was selected to best cover the drainage (Figure 16). In this way, the major axis of the storm pattern roughly corresponded to the apparent axial orientation of the watershed. For the Banister River analysis, however, four different orientations were evaluated. This was done due to the ambiguity associated with the axial orientation of the basin. After carrying out the PMP development procedure for each of the four orientations, a final orientation of 274° from north was selected as it proved to be the orientation that produced the greatest 72-hr precipitation depth (Figure 17). This orientation is consistent with that of one of the historic near-PMP events that have occurred in Virginia. That storm, experienced in August of 1969, had a reported storm orientation of 270° from north and was centered over the unincorporated community of Tyro in Nelson County, VA (approximately 130 km (80 mi) from the Coles Hill site) (Schreiner & Riedel, 1978; Hansen et al., 1982).

.

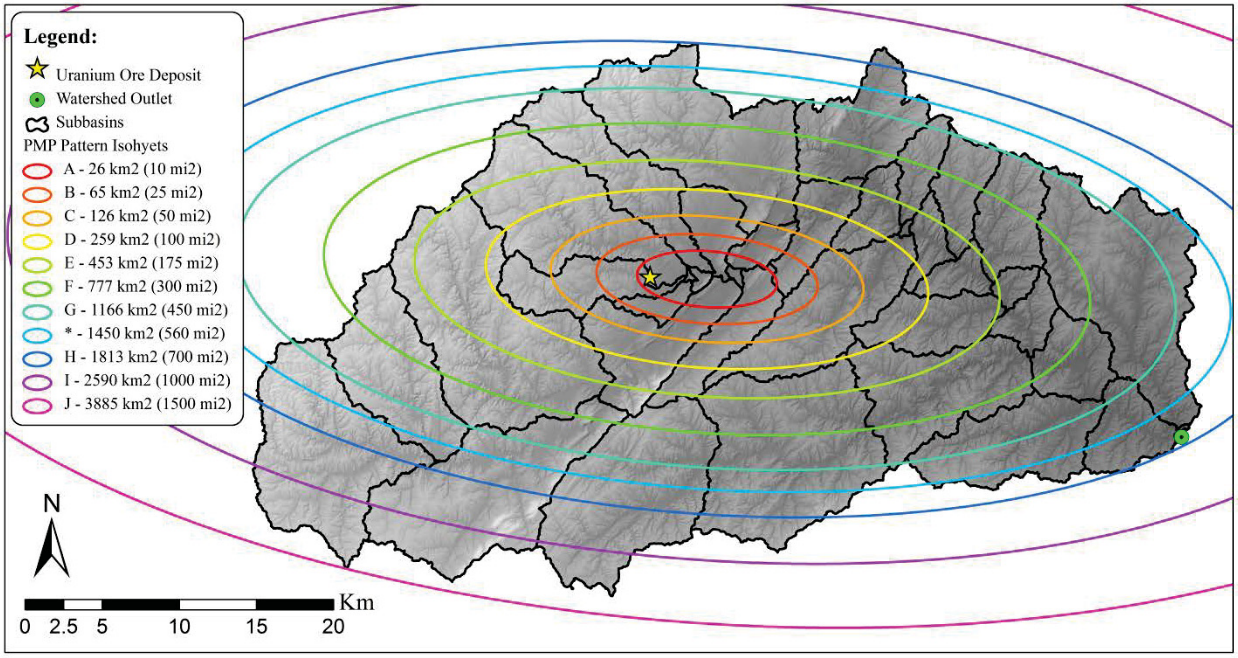

Figure 17: Selected PMS Isohyetal Distribution for the Banister River Study Watershed

With storm patterns finalized, precipitation depths associated with each isohyet were determined for each 6-hr period of the 72-hr storm. These 6-hr periods were then arranged following one of the HMR52 recommended temporal distributions. This distribution placed the most intense rainfall at the start of the third day of the storm (ninth 6-hr period), with the precipitation intensity scaling down on either side of it. The final isohyetal PMP depths for each 6-hr period of the PMS are presented in Table 5 and Table 6, corresponding to the Whitethorn Creek and Banister River analyses, respectively. A complete account of how these depths and all of the other PMP/PMS parameters were determined is presented in Appendix C.

Table 5: Isohyetal PMP Depths for Each 6-hr Period of the 72-hr PMS for the Whitethorn Creek Analysis

			Incremental PMP Depths (in.) - Whitethorn Creek Analysis											
Isohyet	Area (km^2)	Area (mi^2)	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
			0 - 6	6 - 12	12 - 18	18 - 24	24 - 30	30 - 36	36 - 42	42 - 48	48 - 54	54 - 60	60 - 66	66 - 72
A	26	10	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.55	25.91	4.91	1.62	0.81
B	65	25	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.50	24.20	4.68	1.62	0.81
C	129	50	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.47	22.49	4.50	1.62	0.81
D	259	100	0.29	0.31	0.35	0.44	0.79	0.79	0.94	1.97	16.13	3.54	1.27	0.63
E	453	175	0.23	0.24	0.28	0.35	0.63	0.63	0.75	1.58	13.20	2.91	1.02	0.51
Order of Intensity			12	11	10	9	7	6	5	3	1	2	4	8

Table 6: Isohyetal PMP Depths for Each 6-hr Period of the 72-hr PMS for the Banister River Analysis

Isohyet	Area (km^2)	Area (mi^2)	Incremental PMP Depths (in.) - Banister River Analysis											
			Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
			0 - 6	6 - 12	12 - 18	18 - 24	24 - 30	30 - 36	36 - 42	42 - 48	48 - 54	54 - 60	60 - 66	66 - 72
A	26	10	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.70	22.71	4.64	1.74	0.64
B	65	25	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.66	21.38	4.46	1.74	0.64
C	129	50	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.63	20.04	4.32	1.74	0.64
D	259	100	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.61	18.54	4.17	1.74	0.64
E	453	175	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	17.37	4.09	1.74	0.64
F	777	300	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.87	3.99	1.74	0.64
G	1165	450	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	14.86	3.91	1.74	0.64
-	1450	560	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.51	14.20	3.87	1.74	0.64
H	1813	700	0.40	0.42	0.45	0.58	0.63	0.72	0.92	2.36	12.02	3.46	1.59	0.58
I	2590	1000	0.34	0.36	0.38	0.50	0.53	0.61	0.79	2.01	9.35	2.91	1.35	0.50
J	3885	1500	0.29	0.30	0.32	0.41	0.45	0.51	0.65	1.67	7.18	2.44	1.13	0.41
Order of Intensity			12	11	10	9	7	6	5	3	1	2	4	8

4.3.3 Specified Hyetograph Meteorological Model Development

Once the incremental isohyetal PMP depths were determined, the meteorological models of the PMSs were built. For the Whitethorn analysis, a meteorological model consisting of ten individual precipitation time-series gauges was developed. Each gauge corresponded to one of the ten subbasins of the watershed and contained its own 72-hr incremental PMP hyetograph. Likewise, PMS meteorological model for the Banister analysis consisted of thirty-seven individual precipitation time-series gauges, corresponding to the thirty-seven subbasins in the Banister River Study Watershed. For both, rainfall was considered to be uniformly distributed, both spatially and temporally (6-hr periods), within each subbasin.

To distribute the incremental isohyetal PMP depths, an areally-weighted averaging approach was employed, based on the area of each isohyet that was contained within each subbasin. By summing up the products of each depth and the area to which it was applied, and then by dividing the sum by the total area of the subbasin, a subbasin-average PMP depth was obtained for each 6-hr storm period. This technique of generating separate precipitation time-series, based on proximity to the storm center, enabled the simulation of different rainfall inputs for different areas of the watershed. In this way, the PMS was modeled with greater resolution than if a single watershed-averaged approach had been taken. The final 6-hr period hyetographs used for the simulation of the PMS over the Whitethorn Creek and Banister River Study Watersheds are presented in tabular form as Table 7 and Table 8, respectively.

Table 7: Whitethorn Creek Study Watershed - PMS Specified Hyetograph Meteorological Model Input Data

Sub-WS #	Area (mi^2)	HMR52 Individual Subbasin Basin-Averaged PMP Depths (in.) for 72-hr PMP Storm - Whitethorn Creek Analysis											
		Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
		0 - 6	6 - 12	12 - 18	18 - 24	24 - 30	30 - 36	36 - 42	42 - 48	48 - 54	54 - 60	60 - 66	66 - 72
W930	0.95	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.51	24.40	4.71	1.62	0.81
W890	1.50	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.47	22.62	4.51	1.62	0.81
W850	0.14	0.34	0.36	0.42	0.52	0.93	0.93	1.11	2.30	20.37	4.18	1.50	0.75
W840	0.61	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.49	23.63	4.62	1.62	0.81
W810	1.54	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.53	25.13	4.81	1.62	0.81
W800	7.91	0.34	0.36	0.41	0.51	0.92	0.92	1.09	2.29	20.81	4.21	1.48	0.74
W780	2.69	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.48	23.07	4.56	1.62	0.81
W690	12.89	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.52	24.63	4.75	1.62	0.81
W580	12.02	0.37	0.39	0.45	0.56	0.99	0.99	1.18	2.48	23.65	4.62	1.61	0.81
W570	0.98	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.50	24.10	4.67	1.62	0.81

Table 8: Banister River Study Watershed - PMS Specified Hyetograph Meteorological Model Input Data

Subbasin Name	Subbasin Area (mi^2)	HMR52 Individual Subbasin Basin-Averaged PMP Depths (in.) for 72-hr PMP Storm - Banister River Analysis											
		Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
		0 - 6	6 - 12	12 - 18	18 - 24	24 - 30	30 - 36	36 - 42	42 - 48	48 - 54	54 - 60	60 - 66	66 - 72
W1430	34.40	0.44	0.46	0.49	0.64	0.69	0.79	1.01	2.57	15.69	3.96	1.74	0.64
W1540	27.59	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.61	18.32	4.18	1.74	0.64
W1770	38.90	0.44	0.46	0.49	0.64	0.69	0.79	1.01	2.55	14.68	3.89	1.74	0.64
W1860	11.02	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.63	19.91	4.31	1.74	0.64
W1880	15.88	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.62	19.06	4.25	1.74	0.64
W1970	22.18	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.62	19.06	4.23	1.74	0.64
W1980	45.45	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	16.61	4.04	1.74	0.64
W1990	21.90	0.44	0.46	0.49	0.64	0.69	0.78	1.01	2.55	14.85	3.90	1.74	0.64
W2090	23.21	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.97	3.99	1.74	0.64
W2100	8.95	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.19	3.94	1.74	0.64
W2190	9.02	0.42	0.44	0.47	0.61	0.66	0.75	0.97	2.43	13.06	3.65	1.66	0.61
W2300	19.34	0.44	0.46	0.49	0.63	0.68	0.78	1.00	2.52	14.17	3.83	1.72	0.63
W2310	0.18	0.40	0.42	0.45	0.58	0.63	0.72	0.92	2.36	12.02	3.46	1.59	0.58
W2320	34.98	0.39	0.41	0.43	0.56	0.60	0.69	0.89	2.26	11.85	3.37	1.53	0.56
W2420	34.98	0.36	0.37	0.40	0.52	0.56	0.64	0.82	2.09	10.21	3.07	1.41	0.52
W2430	36.09	0.36	0.38	0.41	0.53	0.57	0.65	0.84	2.12	10.64	3.14	1.44	0.53
W2520	41.00	0.43	0.45	0.48	0.62	0.67	0.76	0.98	2.49	14.42	3.79	1.68	0.62
W2800	17.34	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.60	17.21	4.09	1.74	0.64
W2830	6.31	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.63	19.92	4.32	1.74	0.64
W4490	5.90	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	17.28	4.09	1.74	0.64
W4500	17.01	0.44	0.46	0.48	0.63	0.68	0.78	1.00	2.53	14.58	3.85	1.72	0.63
W4510	8.27	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.62	18.85	4.22	1.74	0.64
W4540	5.36	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.40	3.95	1.74	0.64
W4600	0.24	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	17.37	4.09	1.74	0.64
W4620	7.68	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.53	3.96	1.74	0.64
W4630	3.99	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	17.29	4.09	1.74	0.64
W4640	10.77	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.60	17.71	4.12	1.74	0.64
W4650	11.13	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.50	3.96	1.74	0.64
W4670	4.01	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	17.41	4.09	1.74	0.64
W4680	2.14	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	15.98	4.00	1.74	0.64
W4690	4.73	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.87	3.99	1.74	0.64
W4700	2.48	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.67	21.48	4.48	1.74	0.64
W4710	0.15	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.70	22.71	4.64	1.74	0.64
W4720	0.57	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.70	22.71	4.64	1.74	0.64
W4730	9.80	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.63	19.73	4.31	1.74	0.64
W4740	0.35	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.70	22.71	4.64	1.74	0.64
W4750	3.33	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.65	20.89	4.41	1.74	0.64

4.4 Control Specifications Model

In addition to a basin model and a meteorological model, HEC-HMS requires a control specifications model to run a simulation. This model, though very simple, is one of the main components in a project, as it provides the timing information for the simulation run. In the control specifications model, the user specifies a model start date and start time, as well as an end date and end time. Additionally, the modeling time interval or time step is specified. Due to the theoretical and event-based nature of both the Whitethorn Creek and Banister River analyses, the selection of a start and end dates and times were arbitrary. For both, the model was assigned to start at time 00:00 on 01Jan2000 and end approximately a week later at time 00:00 on 08Jan2000. The modeling time frame (between start and finish) was selected so as to capture both the rising and falling limbs of the PMF hydrographs both during and after the 72-hr PMS event. For all simulations, a modeling time interval of five minutes was chosen, corresponding to the intensity duration used for the frequency storm meteorological models.

4.5 Hydrologic Simulation of PMS

After a basin model, the meteorological model, and a control specifications model have been generated, HEC-HMS can begin to run hydrologic simulations. In the case of the study watersheds, the basin models were first calibrated with the 24-hr frequency design storm data to ensure they appropriately mimicked the hydrologic response for each of the watersheds. Once calibrated, the PMS meteorological models were simulated and PMF discharge hydrographs were generated at each node in the models.

5. RESULTS AND DISCUSSION

5.1 Frequency Storm Comparison Results – Whitethorn Creek Analysis

After all of the pertinent parameters were determined and the HEC-HMS basin model was generated for the Whitethorn Creek Study Watershed, an evaluation was conducted to test that the hydrologic basin model functioned as anticipated. For this, a statistical regional regression approach was adopted, due to the lack of actual gauge-collected data within the study watershed. Analytically, eight different meteorological models, each corresponding to a different 24-hr PF recurrence interval (2, 5, 10, 25, 50, 100, 200, and 500-yr), were simulated in the Whitethorn Creek hydrologic model (storm data in Table 3). The resulting peak flow rates from these design storms were compared to frequency peak discharge estimates obtained through the use of the area-based single-parameter Southern Piedmont regional regression equations presented in the Bisese report. As discussed in Section 3.3.1, the Bisese report provides guidance on how to estimate the magnitude of peak discharges at specific recurrence intervals for rural, unregulated streams in Virginia. Using these equations, probabilistic peak discharge estimates were obtained at two locations in the watershed (depicted in Figure 18): (1) the watershed outlet at the confluence of Whitethorn Creek and Dry Branch (contributing area = 107 km^2 (41.2 mi^2)) (Table 9), and (2) a point roughly 0.5 miles upstream of the Chalk Level Rd. bridge crossing on Whitethorn Creek (at the division of the "Whitethorn Middle" and "Whitethorn Down" subbasins) (contributing area = 64.5 km^2 (24.9 mi^2)) (Table 10). In addition to these estimates, upper and lower confidence limit discharges were computed for each return period based on the discharge estimate and the Bisese-specified standard errors of prediction.

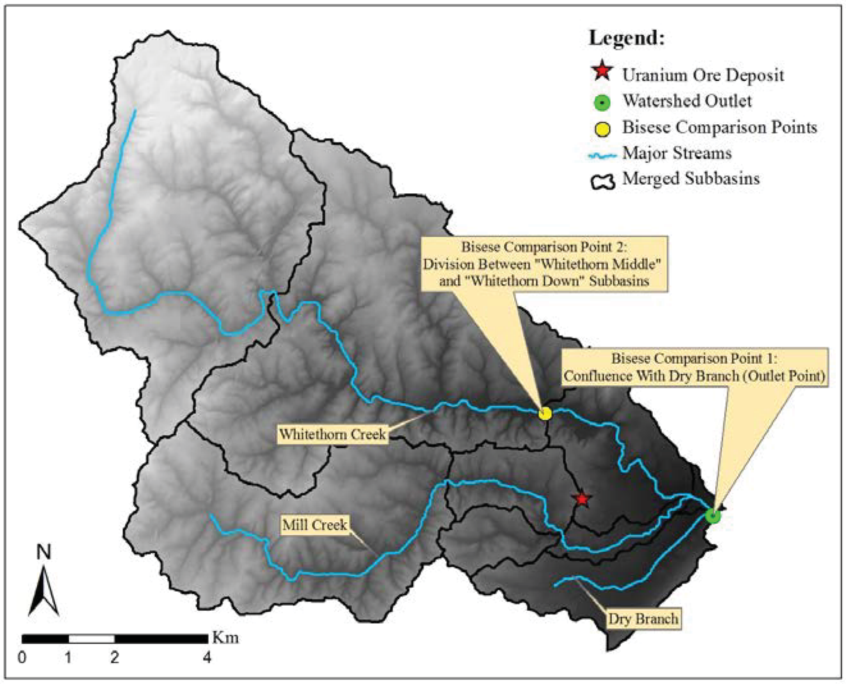

Figure 18: Map Showing the Two Selected Bisese Comparison Points Used for the Whitethorn Creek Analysis

Table 9: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Whitethorn Creek Analysis - Comparison Point 1

Single-Parameter Regional Regression Equation for the Southern Piedmont	Standard Error of Prediction (%)	Equivalent Years of Record	Whitethorn Creek Discharge Estimate (cfs)	Bisese Standard Error of Prediction	
				Lower Limit (cfs)	Upper Limit (cfs)
$Q_{(2)} = 122\ (A)^{0.635}$	40.2	2.8	1.29E+03	7.74E+02	1.81E+03
$Q_{(5)} = 233\ (A)^{0.610}$	38.7	5.4	2.25E+03	1.38E+03	3.12E+03
$Q_{(10)} = 335\ (A)^{0.596}$	38.5	8.0	3.07E+03	1.89E+03	4.26E+03
$Q_{(25)} = 504\ (A)^{0.581}$	40.8	10.9	4.37E+03	2.59E+03	6.16E+03
$Q_{(50)} = 661\ (A)^{0.570}$	43.8	12.3	5.51E+03	3.09E+03	7.92E+03
$Q_{(100)} = 849\ (A)^{0.559}$	47.7	13.2	6.79E+03	3.55E+03	1.00E+04
$Q_{(200)} = 1{,}070\ (A)^{0.549}$	52.2	13.7	8.24E+03	3.94E+03	1.25E+04
$Q_{(500)} = 1{,}418\ (A)^{0.538}$	59.0	13.9	1.05E+04	4.30E+03	1.67E+04
Area (sq. mi.) 41.2					

Table 10: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Whitethorn Creek Analysis – Comparison Point 2

Single-Parameter Regional Regression Equation for the Southern Piedmont	Standard Error of Prediction (%)	Equivalent Years of Record	Whitethorn Creek Discharge Estimate (cfs)	Bisese Standard Error of Prediction	
				Lower Limit (cfs)	Upper Limit (cfs)
$Q_{(2)} = 122\ (A)^{0.635}$	40.2	2.8	9.40E+02	5.62E+02	1.32E+03
$Q_{(5)} = 233\ (A)^{0.610}$	38.7	5.4	1.66E+03	1.02E+03	2.30E+03
$Q_{(10)} = 335\ (A)^{0.596}$	38.5	8.0	2.28E+03	1.40E+03	3.15E+03
$Q_{(25)} = 504\ (A)^{0.581}$	40.8	10.9	3.26E+03	1.93E+03	4.59E+03
$Q_{(50)} = 661\ (A)^{0.570}$	43.8	12.3	4.13E+03	2.32E+03	5.94E+03
$Q_{(100)} = 849\ (A)^{0.559}$	47.7	13.2	5.12E+03	2.68E+03	7.56E+03
$Q_{(200)} = 1{,}070\ (A)^{0.549}$	52.2	13.7	6.25E+03	2.99E+03	9.51E+03
$Q_{(500)} = 1{,}418\ (A)^{0.538}$	59.0	13.9	8.00E+03	3.28E+03	1.27E+04
Area (sq. mi.) 24.9					

With respect to the modeled discharges, output from each of the eight frequency storm simulation runs was analyzed to obtain the comparison discharge values at each point. For this, the simulated hydrographs at each location (presented in Appendix F) were evaluated and the peak discharge value was identified for each recurrence interval. These HEC-HMS flow values are shown in Table 11 and Table 12 for the first and second comparison points, respectively. These values reflect the basin model assumption of ARC II (average conditions) and subbasin lag times were obtained using the NRCS Watershed Lag Equation, as discussed in Chapter 4.

Table 11: HEC-HMS Simulated Discharges for the Whitethorn Creek Study Watershed – Comparison Point 1

HEC-HMS Flowrate Comparison			
Return Period (yrs)	Exceedance Probability (%)	ARCII - NRCS Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})
2	50	1.08E+03	-16.8%
5	20	2.20E+03	-2.4%
10	10	3.36E+03	9.4%
25	4	5.30E+03	21.2%
50	2	7.09E+03	28.7%
100	1	9.15E+03	34.7%
200	0.5	1.15E+04	39.1%
500	0.2	1.49E+04	42.5%

***Based on Outlet Point of the Whitethorn Creek Study Watershed (J126)**

Table 12: HEC-HMS Simulated Discharges for the Whitethorn Creek Study Watershed – Comparison Point 2

HEC-HMS Flowrate Comparison			
Return Period (yrs)	Exceedance Probability (%)	ARCII - NRCS Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})
2	50	6.42E+02	-31.7%
5	20	1.36E+03	-18.0%
10	10	2.11E+03	-7.3%
25	4	3.37E+03	3.3%
50	2	4.53E+03	9.7%
100	1	5.87E+03	14.6%
200	0.5	7.37E+03	18.0%
500	0.2	9.61E+03	20.2%

***Based on Point at the division between "Whitethorn Middle" and "Whitethorn Down" (J121)**

For comparison purposes, a calculation of percent error was done for each of the simulated flows presented in the previous two tables, holding the HEC-HMS output value as the experimental value and the Bisese value as the theoretical value (Table 11 and Table 12). Comparing these error percentages to the standard errors of prediction, all are less than their respective standard errors of prediction.

In addition, these results are presented graphically in Figure 19 and Figure 20. These plots contain points corresponding to the HEC-HMS modeled flow rates, as well as lines representing the Bisese estimates and their associated upper and lower confidence limits, as determined from the standard errors of prediction. In both figures, the HEC-HMS simulated flows all plot within the envelope of +/- one standard error of prediction of the Bisese estimates.

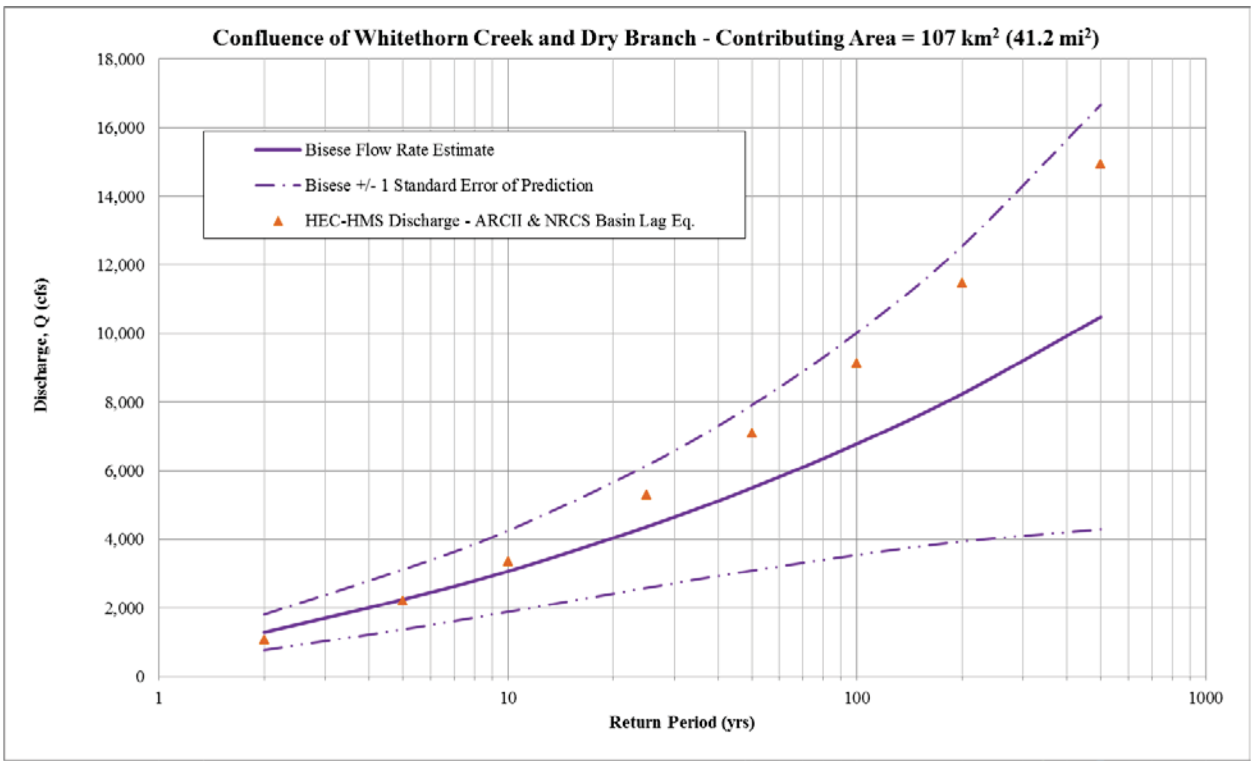

Figure 19: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 1

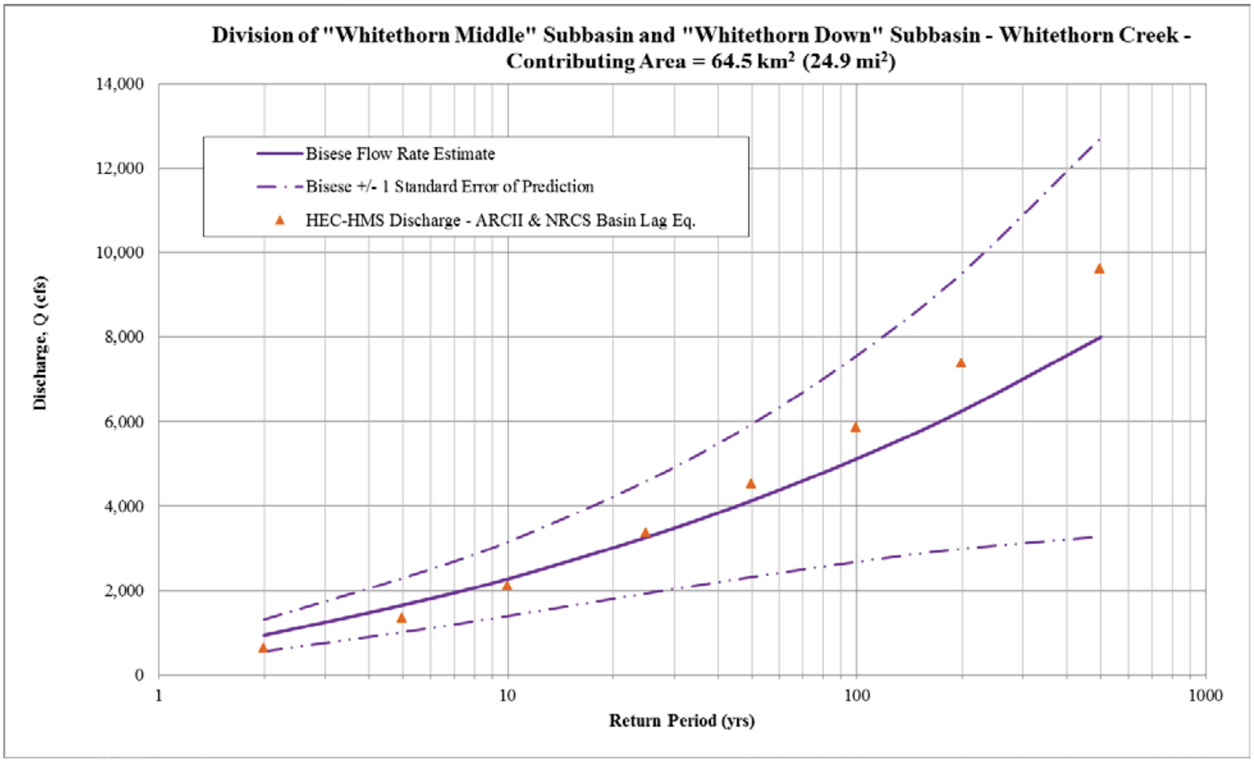

Figure 20: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 2

5.2 Frequency Storm Comparison Discussion – Whitethorn Creek Analysis

As a calibration criterion for the Whitethorn Creek analysis, the hydrologic model was deemed acceptable if the simulated flow rates for each evaluated recurrence interval fell within the bounds of +/- one standard error of prediction of the Bisese generated regional regression peak discharge estimates. Despite there being a large uncertainty associated with these estimates, as denoted by the large standard errors of prediction (approximately thirty-nine to fifty-nine percent), this benchmark was adopted due to the lack of any other viable stream discharge data for the Whitethorn Creek Study Watershed.

Based on the data presented in the previous four tables and two figures, it was concluded that the model was appropriate to be used for the PMS simulation, as the stated testing criterion had been met. For each recurrence interval evaluated (2-yr to 500-yr return periods) for each of the two comparison points used, the HEC-HMS simulated flow rates fell within the envelope of +/- one standard error of prediction of the Bisese estimates. These HEC-HMS discharges were obtained using modeling parameters representing best estimates of real-world basin characteristics and with available methodologies deemed most appropriate for this type of simulation. Current and standard best engineering practices were followed in each step of the parameter selection and model development procedures, resulting in a model that appropriately captured the rainfall-runoff response exhibited in the study watershed.

This comparison was carried out under the assumption that the frequency storms occurred under average antecedent conditions (ARC II). However, at the recommendation of the U.S. Army Corps of Engineers (1994), the model was updated to assume wet antecedent conditions (ARC III) for the PMP/PMS simulation. When modeling very extreme events, the U.S. Army Corps of Engineers (1994) suggest selecting the antecedent conditions to be the most severe that can reasonably exist at the commencement of the storm, as this assumption will lead to a worst-case runoff and flooding condition. Therefore, before the calibrated model was used to simulate the PMP/PMS, the Weighted CN, I_a, and the basin lag time (Loss and Transform Method parameters dependent on assumed ARC) for each of the subbasins was changed to reflect the new ARC.

5.3 Frequency Storm Comparison Results – Banister River Analysis

Similar to the Whitethorn Creek analysis, the hydrologic basin model of the Banister River Study Watershed was first compared to statistically generated data before it was employed to simulate the PMS event. This was done to ensure that selected basin characteristics aptly represented real-world conditions and that the model would exhibit the anticipated precipitation-runoff response. Like the first model, the Banister River model was first used to simulate a number of 24-hr PF events (2, 5, 10, 25, 50, 100, 200, 500, and 1000-yr) (storm data in Table 4). However, in addition to the Bisese regional regression approach taken for the Whitethorn Creek study, a second comparison technique was employed for the Banister River model, involving a Bulletin 17B FFA.

Regarding the first comparison method, the Bisese regional regression approach, a similar procedure to that explained in Section 5.1 was followed. For the Banister River analysis, three comparison points were selected for evaluation (depicted in Figure 21): (1) a point at the confluence of Banister River and Polecat Creek (contributing area = 1291 km^2 (499 mi^2)), (2) a point at the confluence of Banister River and Elkhorn Creek (contributing area = 846 km^2 (327 mi^2)), and (3) a point at the confluence of Banister River and Whitethorn Creek (contributing area = 569 km^2 (220 mi^2)). Unlike the first analysis, however, the watershed outlet was not selected as a Bisese comparison point because of its location downstream of the Banister Lake Dam. As the Bisese methodology is intended only for estimating peak discharges in rural, unregulated streams, the most downstream comparison point was located upstream of the influence of both the Banister Lake Dam and the reservoir behind it. For these three points, the associated Bisese regional regression peak flow estimates and upper and lower standard error of prediction confidence discharges are presented in Table 13, Table 14, and Table 15, respectively.

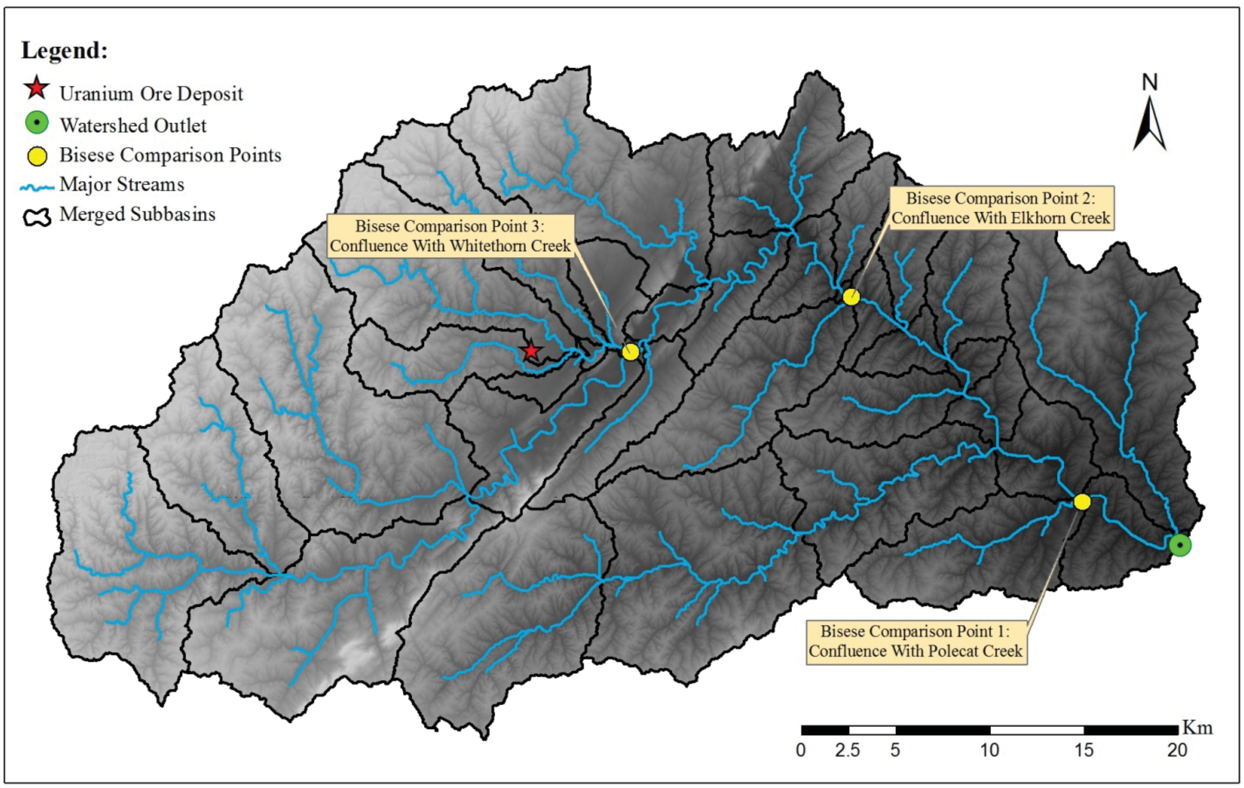

Figure 21: Map Showing the Three Selected Bisese Comparison Points Used for the Banister River Analysis

Table 13: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Banister River Analysis – Comparison Point 1

Single-Parameter Regional Regression Equation for the Southern Piedmont	Standard Error of Prediction (%)	Equivalent Years of Record	Banister River Discharge Estimate (cfs)	Bisese Standard Error of Prediction	
				Lower Limit (cfs)	Upper Limit (cfs)
$Q_{(2)} = 122\,(A)^{0.635}$	40.2	2.8	6.30E+03	3.77E+03	8.83E+03
$Q_{(5)} = 233\,(A)^{0.610}$	38.7	5.4	1.03E+04	6.32E+03	1.43E+04
$Q_{(10)} = 335\,(A)^{0.596}$	38.5	8.0	1.36E+04	8.35E+03	1.88E+04
$Q_{(25)} = 504\,(A)^{0.581}$	40.8	10.9	1.86E+04	1.10E+04	2.62E+04
$Q_{(50)} = 661\,(A)^{0.570}$	43.8	12.3	2.28E+04	1.28E+04	3.28E+04
$Q_{(100)} = 849\,(A)^{0.559}$	47.7	13.2	2.73E+04	1.43E+04	4.04E+04
$Q_{(200)} = 1{,}070\,(A)^{0.549}$	52.2	13.7	3.24E+04	1.55E+04	4.93E+04
$Q_{(500)} = 1{,}418\,(A)^{0.538}$	59.0	13.9	4.01E+04	1.64E+04	6.37E+04
Area (sq. mi.) 499					

Table 14: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Banister River Analysis – Comparison Point 2

Single-Parameter Regional Regression Equation for the Southern Piedmont	Standard Error of Prediction (%)	Equivalent Years of Record	Banister River Discharge Estimate (cfs)	Bisese Standard Error of Prediction	
				Lower Limit (cfs)	Upper Limit (cfs)
$Q_{(2)} = 122\,(A)^{0.635}$	40.2	2.8	4.82E+03	2.88E+03	6.75E+03
$Q_{(5)} = 233\,(A)^{0.610}$	38.7	5.4	7.96E+03	4.88E+03	1.10E+04
$Q_{(10)} = 335\,(A)^{0.596}$	38.5	8.0	1.06E+04	6.49E+03	1.46E+04
$Q_{(25)} = 504\,(A)^{0.581}$	40.8	10.9	1.46E+04	8.62E+03	2.05E+04
$Q_{(50)} = 661\,(A)^{0.570}$	43.8	12.3	1.79E+04	1.01E+04	2.58E+04
$Q_{(100)} = 849\,(A)^{0.559}$	47.7	13.2	2.16E+04	1.13E+04	3.19E+04
$Q_{(200)} = 1{,}070\,(A)^{0.549}$	52.2	13.7	2.57E+04	1.23E+04	3.91E+04
$Q_{(500)} = 1{,}418\,(A)^{0.538}$	59.0	13.9	3.19E+04	1.31E+04	5.08E+04
Area (sq. mi.) 327					

Table 15: Bisese Single-Parameter Discharge Estimates with Confidence Limits for the Banister River Analysis – Comparison Point 3

Single-Parameter Regional Regression Equation for the Southern Piedmont	Standard Error of Prediction (%)	Equivalent Years of Record	Banister River Discharge Estimate (cfs)	Bisese Standard Error of Prediction	
				Lower Limit (cfs)	Upper Limit (cfs)
$Q_{(2)} = 122\,(A)^{0.635}$	40.2	2.8	3.75E+03	2.24E+03	5.25E+03
$Q_{(5)} = 233\,(A)^{0.610}$	38.7	5.4	6.25E+03	3.83E+03	8.67E+03
$Q_{(10)} = 335\,(A)^{0.596}$	38.5	8.0	8.33E+03	5.13E+03	1.15E+04
$Q_{(25)} = 504\,(A)^{0.581}$	40.8	10.9	1.16E+04	6.85E+03	1.63E+04
$Q_{(50)} = 661\,(A)^{0.570}$	43.8	12.3	1.43E+04	8.03E+03	2.06E+04
$Q_{(100)} = 849\,(A)^{0.559}$	47.7	13.2	1.73E+04	9.05E+03	2.56E+04
$Q_{(200)} = 1{,}070\,(A)^{0.549}$	52.2	13.7	2.07E+04	9.88E+03	3.14E+04
$Q_{(500)} = 1{,}418\,(A)^{0.538}$	59.0	13.9	2.58E+04	1.06E+04	4.10E+04
Area (sq. mi.) 220					

For the Banister River Study Watershed, two basin models were constructed and evaluated during the comparison process. Both basin models were identical, with the exception of the subbasin lag time used in the SCS Unit Hydrograph Transform Method. As discussed in Section 4.2.3, two different widely-accepted NRCS methodologies for estimating lag time (NRCS Watershed Lag Equation Method and NRCS Segmental Velocity T_c Lag Equation Method) were employed for the Banister River analysis to assess whether one seemed more appropriate than the other for this model. For both evaluations, the same set of 24-hr frequency storms (2-yr to 500-yr) was simulated and peak flows were gathered for each at the three selected comparison points. These discharge results are presented for each of the three points in Table 16, Table 17, and Table 18, respectively. These values were compared to the Bisese peak discharge estimates in the same fashion as that detailed in Section 5.1.

Table 16: HEC-HMS Simulated Discharges for the Banister River Study Watershed – Comparison Point 1

HEC-HMS Flowrate Comparison					
Return Period (yrs)	Exceedance Probability (%)	ARCII - NRCS Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})	ARCII - Tc Segmental Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})
2	50	3.50E+03	-44.4%	3.71E+03	-41.1%
5	20	6.93E+03	-32.7%	7.58E+03	-26.4%
10	10	1.05E+04	-22.6%	1.17E+04	-13.6%
25	4	1.69E+04	-9.0%	1.90E+04	2.0%
50	2	2.31E+04	1.2%	2.59E+04	13.6%
100	1	3.03E+04	10.8%	3.40E+04	24.4%
200	0.5	3.87E+04	19.6%	4.35E+04	34.2%
500	0.2	5.18E+04	29.2%	5.81E+04	44.8%

***Based on Point at Confluence of Banister River and Polecat Creek (J575)**

Table 17: HEC-HMS Simulated Discharges for the Banister River Study Watershed - Comparison Point 2

HEC-HMS Flowrate Comparison					
Return Period (yrs)	Exceedance Probability (%)	ARCII - NRCS Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})	ARCII - Tc Segmental Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})
2	50	2.88E+03	-40.3%	3.06E+03	-36.5%
5	20	5.93E+03	-25.5%	6.27E+03	-21.3%
10	10	9.14E+03	-13.4%	9.62E+03	-8.9%
25	4	1.46E+04	0.1%	1.53E+04	5.1%
50	2	1.97E+04	10.1%	2.07E+04	15.4%
100	1	2.58E+04	19.5%	2.70E+04	25.1%
200	0.5	3.29E+04	28.0%	3.44E+04	34.0%
500	0.2	4.39E+04	37.3%	4.58E+04	43.5%

***Based on Point at Confluence of Elkhorn Creek and Banister River (J613)**

Table 18: HEC-HMS Simulated Discharges for the Banister River Study Watershed - Comparison Point 3

HEC-HMS Flowrate Comparison					
Return Period (yrs)	Exceedance Probability (%)	ARCII - NRCS Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})	ARCII - Tc Segmental Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{Bisese}) / (Q_{Bisese})
2	50	2.57E+03	-31.4%	2.86E+03	-23.5%
5	20	5.38E+03	-14.0%	5.96E+03	-4.6%
10	10	8.34E+03	0.0%	9.22E+03	10.6%
25	4	1.33E+04	15.4%	1.47E+04	27.4%
50	2	1.81E+04	26.7%	2.00E+04	39.7%
100	1	2.37E+04	37.0%	2.61E+04	50.8%
200	0.5	3.02E+04	46.1%	3.32E+04	60.6%
500	0.2	4.02E+04	55.8%	4.41E+04	70.8%

***Based on Point at Confluence of Whitethorn Creek and Banister River (J668)**

Similar to the Whitethorn Creek analysis, percent error was computed for each of the simulated flows, holding the HEC-HMS output value as the experimental value and the Bisese value as the theoretical value (Table 16, Table 17, and Table 18). Comparing these error percentages to the standard errors of prediction, it can be noted that almost all are less than their respective standard errors of prediction. For the first two comparison points (the confluences of the Banister River with Polecat and Elkhorn Creeks) all of simulated discharges with the exception of three out of the four 2-yr simulated flow rates (denoted in red) fall within the range of the Bisese standard errors of prediction. However, for the most upstream comparison point (the confluence of Banister River with Whitethorn Creek), the three highest frequency discharges using the NRCS Segmental Velocity T_c Lag Equation Method (denoted in red) fall outside of the standard error of prediction ranges.

In addition to the tabulated data, the results at the three comparison points are presented graphically in Figure 22, Figure 23, and Figure 24, respectively. These plots contain data points associated with each of the two HEC-HMS modeled flow rate series, as well as lines representing the Bisese estimates and their corresponding upper and lower confidence limits, as determined from the standard errors of prediction. The same trends described above are seen in the graphs, with the majority of the HEC-HMS points falling within the envelope of +/- one standard error of prediction of the Bisese estimates.

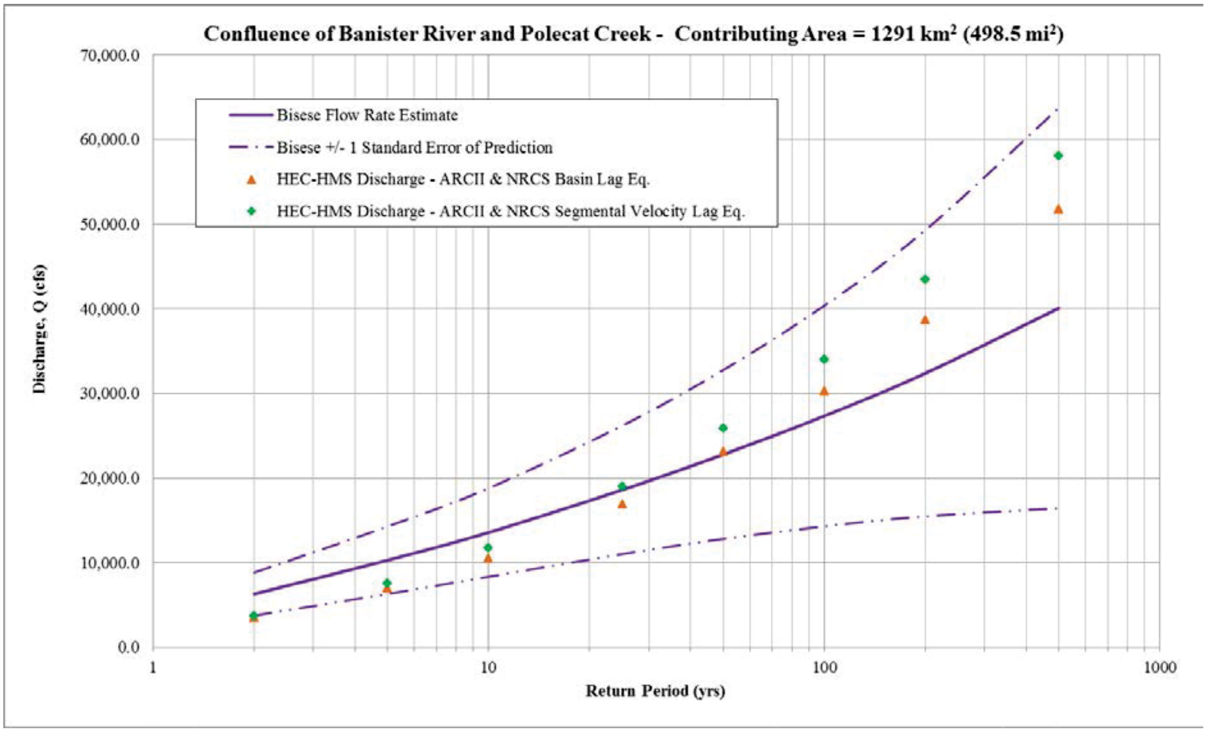

Figure 22: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 1

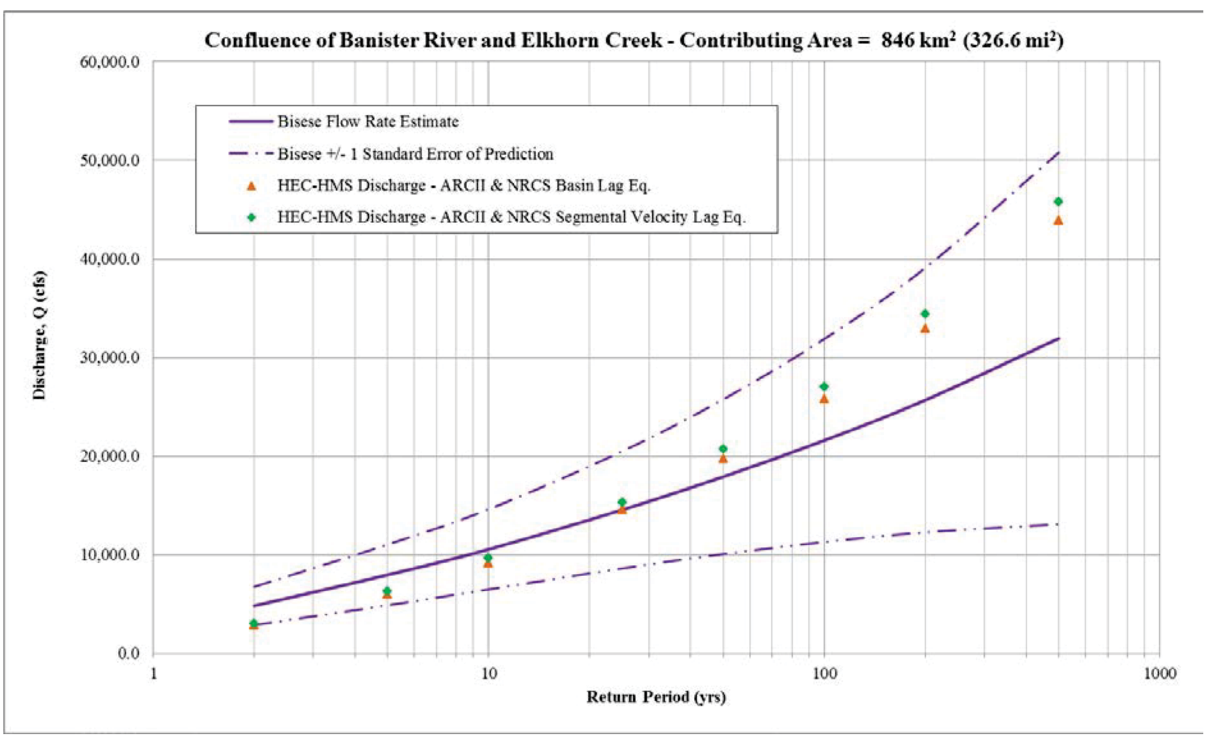

Figure 23: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 2

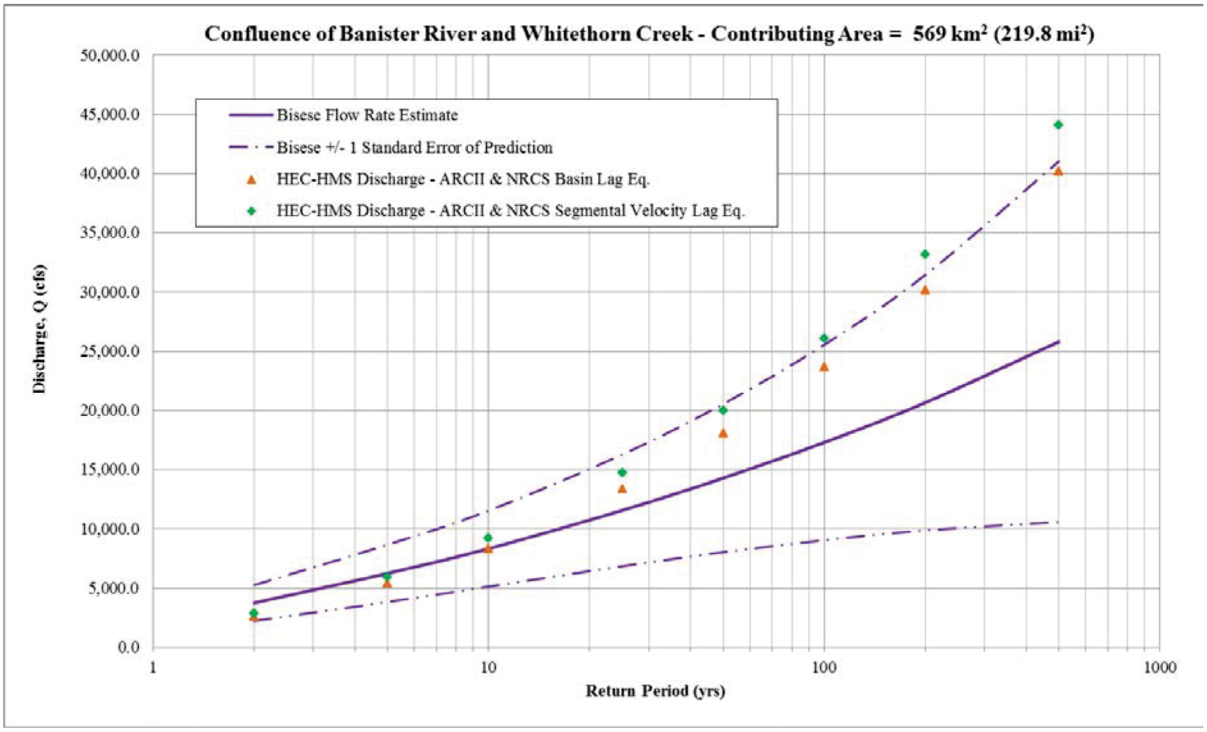

Figure 24: HEC-HMS Simulated Discharges vs. Bisese Single-Parameter Regional Regression Peak Discharge Estimates - 2-yr to the 500-yr 24-hr Frequency Storms – Comparison Point 3

After the Bisese regional regression evaluation was conducted, a second comparison was carried out for the Banister River model, this time utilizing results from a Bulletin 17B FFA. This process involved comparing the HEC-HMS simulated peak flows to peak frequency discharges obtained from a statistical analysis of observed annual peak flows. This second approach was employed to further test the model and provide greater confidence in the overall results.

As described in Section 3.3.2, a Bulletin 17B FFA examines an annual peak flow rate series from a specific stream gauging station to develop a frequency distribution of discharges as a function or recurrence intervals. For the Banister River FFA, the analytical comparison point was selected as the watershed outlet, coinciding with the USGS-operated stream gauging station on the Banister River in Halifax, VA (USGS 02077000). This gauge possessed an eighty-two year annual peak flow record (Table 19), which began after the construction of the Banister Lake Dam in 1921. Because of this, and because of the assumption that the watershed has remained relatively stable with regard to land use change and urbanization, the entire gauge record was used for the FFA.

Table 19: Annual Maximum Discharge Record for the USGS Stream Gauage on the Banister River in Halifax, VA (USGS 02077000)

Water Year/ Record #	Observation Date	Discharge (cfs)	Water Year/ Record #	Observation Date	Discharge (cfs)	Water Year/ Record #	Observation Date	Discharge (cfs)
1	17-Apr-29	6,430	29	10-Apr-57	5,400	57	19-Aug-85	7,140
2	3-Oct-29	10,100	30	7-May-58	7,330	58	6-Nov-85	7,320
3	24-Jun-31	3,530	31	30-Dec-58	11,000	59	8-Sep-87	13,400
4	7-Mar-32	8,310	32	6-Apr-60	5,800	60	21-Jan-88	2,510
5	18-Oct-32	7,270	33	24-Feb-61	4,600	61	3-May-89	6,170
6	5-Mar-34	6,570	34	8-Jan-62	5,350	62	3-Oct-89	6,310
7	2-Dec-34	7,270	35	13-Mar-63	7,640	63	31-Mar-91	10,000
8	18-Mar-36	10,200	36	2-Sep-64	6,800	64	23-Apr-92	6,180
9	26-Apr-37	9,110	37	9-Feb-65	5,800	65	5-Mar-93	11,000
10	22-Jun-38	19,000	38	2-Mar-66	5,250	66	29-Mar-94	8,480
11	20-Aug-39	6,360	39	26-Aug-67	4,040	67	24-Jun-95	10,100
12	16-Aug-40	34,000	40	15-Jan-68	2,890	68	7-Sep-96	23,900
13	16-Nov-40	3,690	41	26-Mar-69	2,030	69	29-Apr-97	5,230
14	10-Aug-42	7,750	42	17-Feb-70	1,820	70	29-Jan-98	9,900
15	31-Dec-42	4,750	43	12-Sep-71	10,800	71	30-Sep-99	4,650
16	20-Sep-44	50,000	44	22-Jun-72	16,000	72	16-Jun-00	5,190
17	19-Sep-45	11,100	45	3-Feb-73	7,120	73	23-May-01	3,470
18	8-Jan-46	7,800	46	8-Sep-74	9,360	74	4-May-02	2,230
19	25-Sep-47	6,420	47	31-Mar-75	12,600	75	21-Mar-03	12,700
20	15-Feb-48	6,100	48	2-Jan-76	4,290	76	8-Feb-04	5,980
21	29-Nov-48	7,530	49	8-Dec-76	3,100	77	15-Jan-05	5,090
22	31-Oct-49	7,260	50	27-Apr-78	17,000	78	15-Sep-06	2,810
23	5-Dec-50	3,320	51	26-Feb-79	12,900	79	2-Jan-07	14,000
24	2-Sep-52	6,740	52	3-Oct-79	7,170	80	10-May-08	8,360
25	21-Nov-52	3,500	53	21-Feb-81	2,650	81	12-Dec-08	5,280
26	24-Jan-54	5,260	54	4-Feb-82	5,820	82	13-Nov-09	12,200
27	19-Aug-55	10,100	55	4-Apr-83	7,850			
28	12-Apr-56	3,450	56	15-Feb-84	8,800			

To carry out the Bulletin 17B FFA, the computer program HEC-SSP (Statistical Software Package) was employed. In addition to a Bulletin 17B analysis, this program has the capabilities to perform a number of statistical analyses of hydrologic data, including generalized frequency analyses on not only flow data but other hydrologic data as well, volume frequency analyses on high and low flows, duration analyses, coincident frequency analyses, and curve combination analyses (Brunner & Fleming, 2010). Concerning the FFA that was done for this study, HEC-SSP was used to organize and evaluate the USGS annual peak flow data using a Log-Pearson Type III (LP3) distribution, as is recommended in the Bulletin 17B document (U.S. Interagency Advisory Committee on Water Data, 1982). In this, the generalized station skew (0.412) was adopted, as was the Weibull plotting position. This distribution is shown graphically in Figure 25. From the expected probability distribution curve computed for the data, flow rates corresponding to nine recurrence intervals (2, 5, 10, 25, 50, 100, 200, 500, and 1000-yr) were obtained and are presented in Table 20. It should be acknowledged that even though the eighty-two year record that was used for the FFA is in itself a fairly long record when compared against other USGS gauge records, it is short in relation to the storms that it is being used to extrapolate data for. Because of this, the values presented for the higher return interval storms (greater than 100-yr) carry with them greater uncertainty, as is expected when trying to extrapolate hydrologic data for conditions above what has historically been observed.

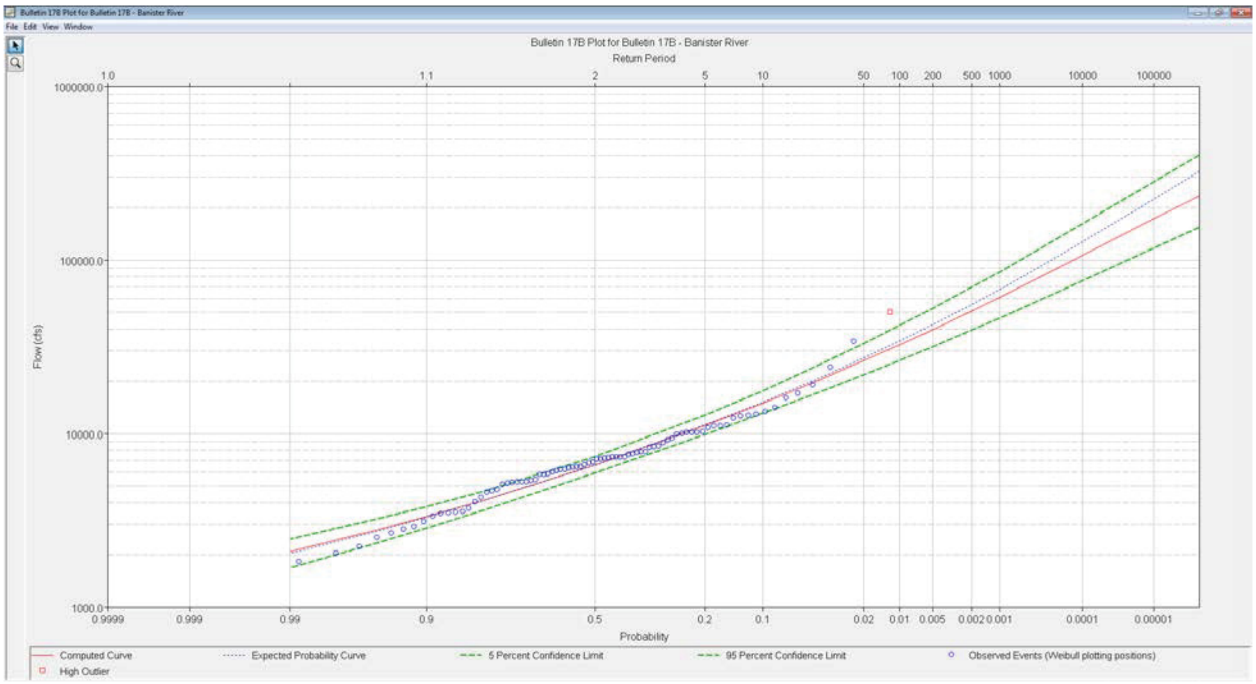

Figure 25: Graphical HEC-SSP Bulletin 17B FFA Results for the Banister River USGS Stream Flow Gauge at Halifax, VA (USGS 02077000) - 82-yr Period of Record (1929-2010)

Additionally, Table 20 displays discharges corresponding to the 0.05 (five percent chance exceedance) and 0.95 (ninety-five percent chance exceedance) confidence limits of each of the expected probability flow rates. It should be noted that this analysis determined the highest recorded discharge (1416 cms (50,000 cfs) from September of 1944) to be a high outlier. This high outlier was not eliminated from the analysis, as it is a valuable piece of the flow record. Brunner and Fleming (2010) state that the existence of a high outlier suggests that the event might actually be the largest event in a much longer period of record, and that the analyst should attempt to locate and incorporate historic information to define a longer record and improve the quality of the frequency analysis. However, for the Banister River, historic data could not be located and therefore no historic period data were included in the analysis.

Table 20: Tabulated HEC-SSP Bulletin 17B FFA Results for the Banister River USGS Stream Flow Gauge at Halifax, VA (USGS 02077000) - 82-yr Period of Record (1929-2010)

Flood Frequency Analysis (LP3) Results for the USGS Stream Gage in Halifax, VA				
Return Period (yrs)	Exceedance Probability (%)	Bulletin 17B Expected Probability Q (cfs)	Bulletin 17B 0.95 Confidence Limit Q (cfs)	Bulletin 17B 0.05 Confidence Limit Q (cfs)
2	50	6.61E+03	5.92E+03	7.36E+03
5	20	1.12E+04	9.91E+03	1.27E+04
10	10	1.52E+04	1.31E+04	1.76E+04
25	4	2.15E+04	1.78E+04	2.56E+04
50	2	2.72E+04	2.19E+04	3.31E+04
100	1	3.41E+04	2.65E+04	4.20E+04
200	0.5	4.22E+04	3.16E+04	5.26E+04
500	0.2	5.54E+04	3.95E+04	6.98E+04
1000	0.1	6.76E+04	4.64E+04	8.56E+04

Regarding the HEC-HMS simulated discharges, both basin models were again modeled concurrently, each identical with the exception of subbasin lag time. For both simulation sets, the same nine 24-hr PF meteorological models (data for which are presented in Table 4) were employed to drive the simulations. Similar to the Bisese evaluation, resulting peak flows were identified for each recurrence interval from the outflow hydrographs at the watershed outlet (displayed in Appendix F). These data, presented in Table 21, are what were utilized for comparison to the FFA generated results in Table 20.

Table 21: HEC-HMS Simulated Discharges for the Banister River Study Watershed – Watershed Outlet Point at the USGS Stream Flow Gauge at Halifax, VA (USGS 02077000)

HEC-HMS Flow Rates at the Watershed Outlet vs. Bulletin 17B Expected Probability Flow Rates					
Return Period (yrs)	Exceedance Probability (%)	ARCII - NRCS Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{FFA}) / (Q_{FFA})	ARCII - Tc Segmental Lag Eq. Q (cfs)	% Error = (Q_{HMS} - Q_{FFA}) / (Q_{FFA})
2	50	3.49E+03	-47.2%	3.76E+03	-43.1%
5	20	6.91E+03	-38.3%	7.49E+03	-33.2%
10	10	1.05E+04	-30.7%	1.15E+04	-24.3%
25	4	1.69E+04	-21.2%	1.85E+04	-13.7%
50	2	2.30E+04	-15.5%	2.53E+04	-7.3%
100	1	3.02E+04	-11.3%	3.32E+04	-2.6%
200	0.5	3.86E+04	-8.5%	4.24E+04	0.5%
500	0.2	5.17E+04	-6.6%	5.68E+04	2.5%
1000	0.1	6.31E+04	-6.5%	6.93E+04	2.6%

***Based on Watershed Outlet Point - USGS 02077000 Gauging Station (J578)**

The HEC-HMS simulated flows were again compared to the statistical flows with a percent error calculation (Table 21), holding the HEC-HMS output value as the experimental value and the FFA value as the theoretical value. It can be noted from the table that these percent errors are relatively high at the lower recurrence intervals (values denoted in red fall outside 0.05/0.95 confidence limit), but are relatively low at the higher recurrence intervals. Because the overall goal of the hydrologic model was to simulate the PMS, agreement at the higher return periods is much more important than that at the lower return periods, due to the extreme magnitude of the PMS event. On a strictly difference-based comparison, without regard to the 0.05/0.95 confidence envelope, the modeled flow rates all seem to agree reasonably well with the FFA results. Considering the NRCS Watershed Lag Equation Method results, all nine of the modeled peak flows are underestimates of the FFA values by between 88.3 cms (3120 cfs) and 132 cms (4660 cfs). For the NRCS Segmental Velocity T_c Lag Equation Method, the modeled results at the outlet fit more closely to the FFA results, ranging from 88.5 cms (3120 cfs) below an FFA value to 49.3 cms (1740 cfs) above an FFA value, with the 200-yr simulated flow being just 5.9 cms (209 cfs) above the FFA value.

These results are also presented graphically in Figure 26. This plot contains data points associated with each of the two HEC-HMS modeled flow rate series, as well as lines representing the Bulletin 17B FFA frequency discharges and their corresponding upper and lower 0.95/0.05 confidence limits. The same trends described above are seen in the figure.

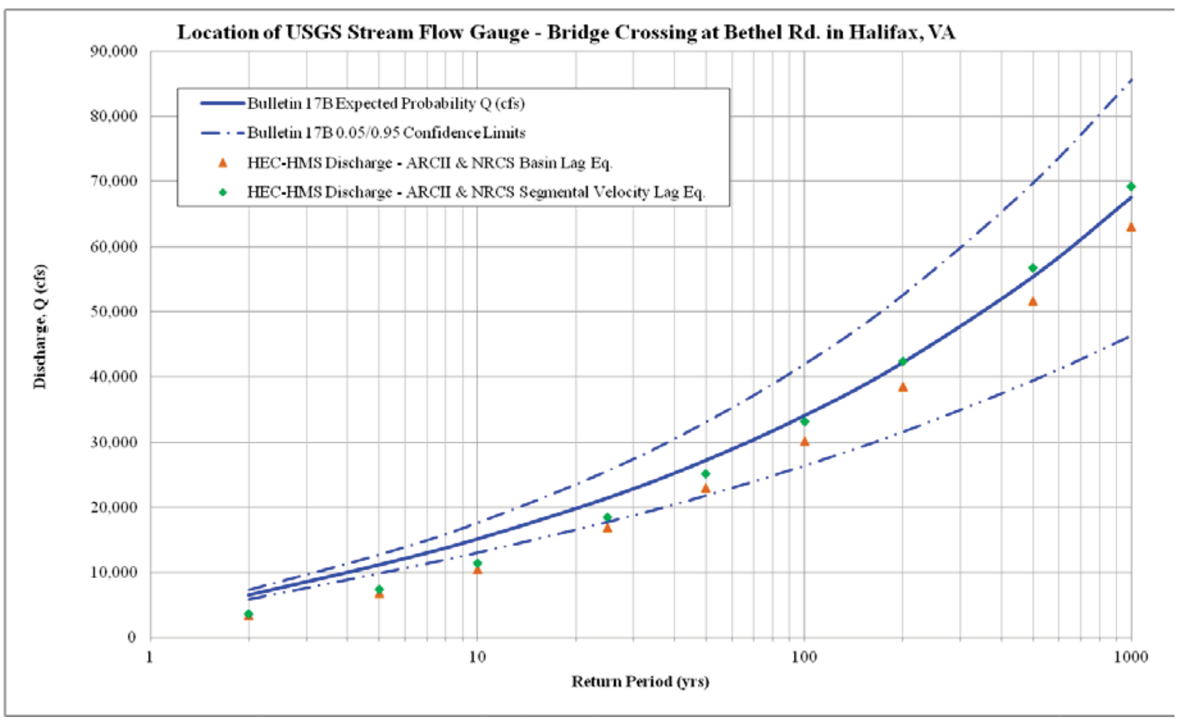

Figure 26: HEC-HMS Simulated Discharges vs. HEC-SSP FFA Expected Probability Discharges - 2-yr to the 1000-yr 24-hr Frequency Storms –Banister River at the Bethel Rd. Bridge Crossing in Halifax, VA

5.4 Frequency Storm Comparison Discussion – Banister River Analysis

Before the Banister River Study Watershed hydrologic model was used to simulate the PMS, the frequency results were analyzed to ensure that the model was acting as anticipated. As previously discussed, two basin models were developed for the Banister River analysis to determine which of the two widely employed NRCS lag time computation methodologies seemed to produce more reasonable results. A similar calibration criterion to that used for the Whitethorn Creek analysis was adopted for the Banister River study; however, it was more loosely defined. Because two basin models were compared to probabilistic flows from two separate sources at different locations, a piecewise test criterion was applied.

The first component of this piecewise assessment involved the Bisese regional regression peak discharge estimates that were calculated for the first three comparison points. For this, like with the Whitethorn Creek study, the model was examined to determine if the HEC-HMS simulated flows fell within the bounds of +/- one standard error of prediction of the Bisese estimates for the eight frequency storms that were modeled (2-yr to 500-yr). As elaborated on in the previous section, all but six out of the forty-eight simulated flow rates fell within the Bisese confidence envelope. Of these six, half corresponded to the 2-yr event (both 2-yr discharges at the first comparison point and the 2-yr discharge corresponding to the NRCS Watershed Lag Equation at the second comparison point). However, these three discharges are only slightly outside of the standard error of prediction range (with the greatest deviation being only about three percent outside of the envelope). As the overall intent of this project involves the simulation of the PMS, the theoretically most extreme event possible, the small deviations from the confidence range at the 2-yr storm level were simply neglected. However, the other three simulated flow rates that fell outside of the standard error of prediction range corresponded to the 100-yr, 200-yr, and 500-yr events at the third comparison point using the NRCS Segmental Velocity T_c Lag Equation Method. These three extreme event discharges fell above the confidence limits of the Bisese estimates, the greatest deviation of which was by about twelve percent (500-yr). Based on this observation, it was concluded that the NRCS Watershed Lag Equation Method seemed to be the more appropriate technique to use for the PMS simulation, as the NRCS Segmental Velocity T_c Lag Equation seemed to result in discharges that increased with recurrence interval at a faster rate than that anticipated through the regional regression equations.

In general, the NRCS Segmental Velocity T_c discharges are consistently higher than those developed with the NRCS Watershed Lag method at corresponding return periods. Also, it should be noted that the NRCS Segmental Velocity T_c Lag Equation Method carries with it much more uncertainty than the NRCS Watershed Lag Equation Method. This is based on the number of parameters that are necessary for each. The NRCS Watershed Lag Equation is solely based on the subbasin land slope, the weighted CN, and the hydraulically longest length in the subbasin, whereas the NRCS Segmental Velocity T_c Lag Equation requires information regarding roughness coefficients, precipitation values, surface descriptions, channel geometries, flow lengths, and land slopes for each subbasin, among other things. Because in situ data for each of the subbasins were not available and because many of the required T_c parameters were estimates of probable real-world characteristics, the greater uncertainty may have been the cause for the increased deviation from the Bisese estimates.

Concerning the second component of the piecewise assessment, involving the Bulletin 17B FFA results, two test criteria were evaluated: whether the modeled discharges fell within the 0.95/0.05 confidences limit envelope of the FFA discharges, and how the apparent trend of the modeled discharges corresponded to the apparent trend of the FFA discharges. As the FFA results were based on actual field collected data from the study watershed, it was important that the simulated flows matched relatively well to the probabilistic flows. For the first criterion, the 0.95/0.05 confidence limits were used as bounding conditions in the same fashion as the standard error of prediction limits associated with the Bisese estimates. However, the range of the FFA confidence limits (approximately eleven percent to thirty-one percent) was much smaller than that used for the Bisese values (thirty-nine percent to fifty-nine percent), reflecting the greater confidence in and less uncertainly associated with the FFA results. As previously stated, a majority of the modeled flow rates under each lag time assumption fell within the FFA confidence envelope. In general, the results display better agreement at the higher recurrence intervals, as shown in Table 21 by the relatively high percent errors at the lower return periods (forty-seven to twenty-one percent) and the relatively low percent errors at the higher return periods (eleven to one-half percent). This better agreement at the higher recurrence intervals indicates that either basin lag time methods could be used to carry out the PMS simulation, as agreement at the extreme event end of the frequency distribution is more important than agreement at the lower end of the distribution.

As both basin lag time models displayed relatively good agreement with the FFA flow rates, the second test criterion was examined to compare the data trends. On this basis, the lag time method which seemed to better imitate the trend of the observed data was deemed more appropriate for the PMS simulation. As mentioned in Section 5.3, the NRCS Segmental Velocity T_c Lag Equation results fell closer to the FFA results than the NRCS Watershed Lag Equation discharges, but followed a trend which increased at a faster rate than that of the FFA results. The T_c-based discharges started below the FFA curve, and at around the 200-yr recurrence interval, began to produce flow rates that were higher than the FFA results. If this trend continued past the highest modeled recurrence interval (1000-yr), discharges corresponding to the PMF obtained with this method could be overestimated to a high degree. In contrast, the watershed lag-based results seemed to consistently underestimate the FFA results by between 88 and 132 cms (3120 and 4660 cfs) at each of the recurrence intervals. For the larger storms (500-yr and 1000-yr), the HEC-HMS discharges only deviated from the FFA results by between six and seven percent. This data series appeared to increase at roughly the same rate as the FFA-based series, displaying the same increasing trend. It was because of this, and because of the apparent consistency in the underestimation amount, that the NRCS Watershed Lag Equation Method was selected to better meet this component of the piecewise calibration criterion.

Further, due to the attenuating nature of run-of-river reservoirs, like the Banister Lake, the effects of low recurrence interval storm events can be captured and contained in the reservoir. The additional discharge generated from these less extreme storms can be attenuated and stored in the reservoir, creating a discrepancy in the increase of flow rate observed upstream and downstream of the reservoir. For more extreme events, however, this effect is much less prominent, as the reservoir begins to act more as a wide section of river, with much of the flow bypassing the dam through primary and/or emergency spillways. This behavior can lead to a greater discrepancy between the observed and simulated flows at lower return periods, and better agreement at higher return periods when the dam and reservoir are not accounted for in the hydrologic model. This was the case for this study, as the Banister Lake was modeled as a wide river section. This was done for model simplicity, as the primary goal was to obtain flow inputs for the hydraulic model upstream of the reservoir, rather than downstream of it. This assumption, and the absence of a simulated baseflow condition, may explain the deviation between the simulated discharges and FFA results.

Considering the comparison results from both the Bisese evaluation and the Bulletin 17B FFA conducted for the Banister River Study Watershed, the basin model that utilized the NRCS Watershed Lag Equation Method was deemed most suitable for the PMP/PMS simulation. It should be noted that, contrary to the traditional calibration approach, in which parameters are adjusted to obtain better agreement with actual data, the comparison techniques employed for this study refrained from altering the parameter values. In this way, the models were evaluated to determine how accurately they could predict and reproduce the empirically-based, statistical design flows utilizing parameters representing best estimates of realistic basin characteristics/conditions. These parameters were obtained using sound engineering judgment and by following standard and best engineering practices suggested by the developers of HEC-HMS and its associated counterparts. Because these original parameters were retained, and because the modeling results showed solid agreement with the statistical flows after rather rigorous testing, it was concluded that the adopted modeling approaches and parameter estimation methodologies were satisfactory, lending confidence to the overall results. In addition, the calibration that others researchers have done in providing the various guidelines and reference values used in this work is supported in this way, further validating these results.

As with before, the calibration was carried out under the assumption of average antecedent conditions (ARC II), whereas the PMP/PMS simulation was carried out assuming wet antecedent conditions (ARC III) at the recommendation of the U.S. Army Corps of Engineers (1994). The pertinent Loss and Transform Method modeling parameters were updated before the calibrated model was used to simulate the PMS.

5.5 PMP/PMS Simulation Results

Once the hydrologic basin models were considered calibrated and the parameters were updated to reflect the new ARC III conditions the PMS meteorological models were simulated over each of their respective study watersheds to obtain discharge hydrographs corresponding to the PMF. These hydrographs (a number of which presented in Appendix F) were generated for each node (subbasin, reach, junction, etc.) in each of the models. Two of these PMF hydrographs, corresponding to the outlet points of the Whitethorn Creek and Banister River Study Watersheds, are presented in Figure 27 and Figure 28, respectively. These two hydrographs are representative of the highest peak flows experienced in the two hydrologic models, with the Whitethorn Creek model exhibiting a maximum peak discharge of 2550 cms (90,000 cfs) and the Banister River model exhibiting a maximum peak discharge of 7600 cms (268,000 cfs). To put these immense discharges into context, the HEC-HMS simulated 100-yr and 500-yr discharges at the same location for the Whitethorn Creek Study Watershed are approximately 260 cms (9150 cfs) and 425 cms (15,000 cfs), respectively. Similarly for the Banister River Study Watershed, the simulated 100-yr and 500-yr recurrence interval discharges at the outlet are approximately 855 cms (30,200 cfs) and 1460 cms (51,700 cfs), respectively. For this study watershed, the highest recorded discharge occurred in September of 1944 with a stream gauge reading of 1415 cms (50,000 cfs), placing it near the FFA estimated 500-yr event. Additionally, an extrapolation of the expected probability curve from the Banister River FFA roughly predicts a discharge of 6350 cms (224,000 cfs) for the 100,000-yr return period, which is still less than the simulated PMF discharge.

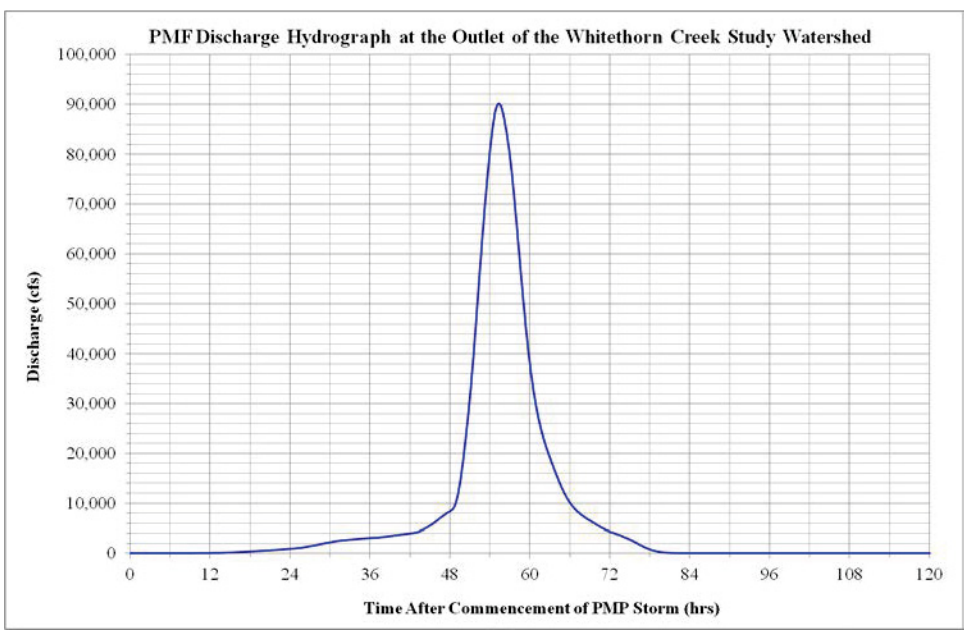

Figure 27: PMF Outflow Hydrograph at the Outlet Point of the Whitethorn Creek Study Watershed Resulting from the 72-hr PMS – ARC III & NRCS Basin Lag Equation

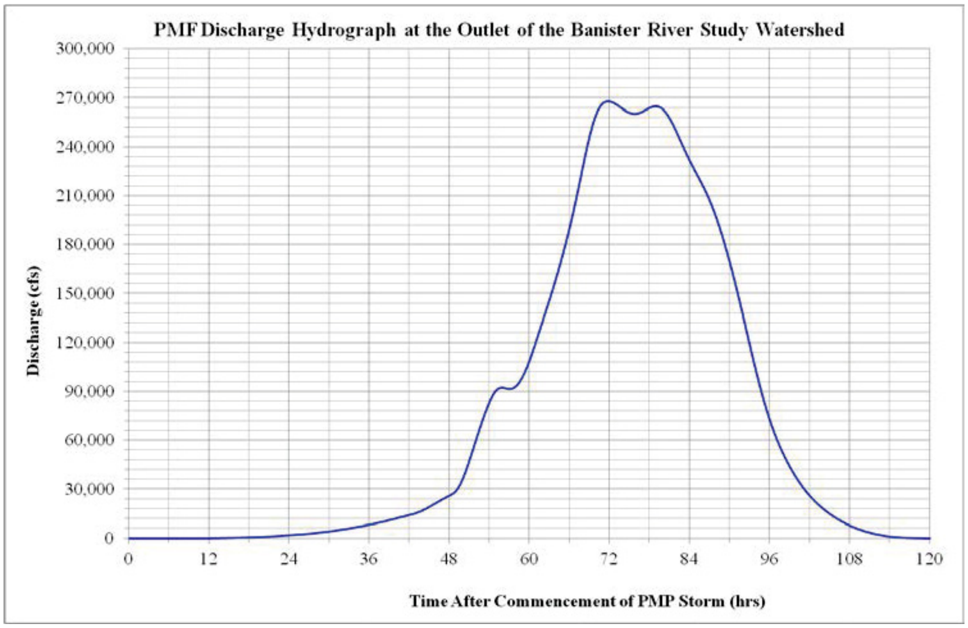

Figure 28: PMF Outflow Hydrograph at the Outlet Point of the Banister River Study Watershed Resulting from the 72-hr PMS – ARC III & NRCS Basin Lag Equation

6. CONCLUSION

6.1 Answers to Key Engineering Questions

As discussed in Section 1.4, this thesis and its associated appendices aimed to address a number of engineering questions related to the hydrologic modeling of a PMP/PMF event. By presenting information regarding the modeling theories and methodologies that were employed for this project, this document provides the reader with a deeper understanding of what is involved in this type of project, as well as with guidance on how to conduct similar studies. Each of the key questions posed in Section 1.4 is presented and addressed here:

1. *How is an event-based HEC-HMS hydrologic model developed and how can it be used to simulate a PMP/PMS event?*

An event-based HEC-HMS model can be developed a number of ways, utilizing a number of different computational tools. As demonstrated by this work, ArcHydro and HEC-GeoHMS are two tools that greatly simply the data assimilation/extraction and basin model development processes, saving both time and effort over the traditional approaches. Provided with land cover, soil, and terrain datasets, ArcHydro/HEC-GeoHMS can be used to delineate the flow network and subbasins for the a study watershed, extract the pertinent spatial information required for the HEC-HMS simulation, and generate and export a basin model file that can be opened and assessed in HEC-HMS. For the required data that cannot be obtained from the spatial data alone, such as flow velocities and travel times, industry-standard parameter estimation procedures from agencies such as the NRCS and the USACE can be followed to complete the basin model. With the basin model established, various meteorological models can be created to test the model and evaluate how well the selected parameters simulate real-world hydrologic characteristics. Once the model appears to be functioning as anticipated, it can be used to simulate the PMS event meteorological model to produce PMF outflow hydrographs at each model node.

2. *How are the theoretical PMP and PMS determined for a study watershed?*

As the PMP and PMS both represent theoretical maximum events with essentially zero percent probabilities of occurrence, there are no actual data available to accurately define them. However, the USACE and the NWS have developed a series of Hydrometeorological Reports outlining estimation methodologies for representing these events across the U.S. Based on moisture maximization, storm transposition, and envelopment techniques and on an assessment of a number of historical extreme events, these reports provide generalized storm characteristics to be applied in the determination of the PMP/PMS for a study watershed. For areas east of the 105^{th} Meridian, HMR51 provides guidance on how to determine PMP depths corresponding to certain storm durations. With these depths, HMR52 instructs a user on how to spatially and temporally distribute the PMP into a PMS, which can subsequently be simulated over the study watershed in a hydrologic model. Although these reports were developed over thirty years ago, they are still regarded as the standard references for estimating the PMP/PMS for PMF studies.

3. *How can a hydrologic model be calibrated/tested in the absence of observed rainfall or known stream discharges and what differences exist in the evaluation of a hydrologic model corresponding to an ungauged, unregulated watershed to that of a gauged, regulated watershed?*

In an ideal scenario, a watershed would contain a number of both discharge and precipitation gauges with fairly long periods of record. With a dense rainfall gauge network, observed storms can be recreated and simulated over the study watershed and a comparison can be made between modeled and observed outflow discharges. Simulation parameters can be adjusted to obtain a good agreement between the two. This approach of first calibrating a model to reproduce observed flows from an observed storm and then validating the calibration with other observed events will generally produce a model that accurately reproduces the watershed's precipitation-runoff response with the least associated uncertainty.

However, due to the lack of observed data in an ungauged, unregulated watershed, this traditional model calibration technique cannot be applied. Instead, a comparison approach must be adopted, identifying one or more reference watersheds with similar characteristics to the study watershed, but with observed data associated with them. Based on this idea, the USGS has developed a number of regional regression equations for estimating peak discharges at select recurrence intervals for rural, ungauged, unregulated watersheds. For Virginia, the Bisese report (1995) serves in this capacity, presenting regional regression equations based on an assessment of a number of gauged watersheds in each of the state's eight physiographic provinces.

Simulated discharges can be compared to these estimates to evaluate how well the hydrologic model replicates the hydrologic response exhibited by other watersheds in the same geographic region. This comparison approach carries with it a high uncertainty, as numerous site-specific factors affect the rainfall-runoff processes of a study watershed that may not be captured by the regression equations. Despite this high uncertainty, however, this rough calibration method is often the only available evaluation technique, as was the case with the Whitethorn Creek Study Watershed.

In the event that there is a stream discharge gauge in a watershed, such as in Banister River analysis, an additional resource for model evaluation is available. Through statistical analysis of a gauge record, a Bulletin 17B flood flow frequency analysis can be conducted to obtain frequency discharges at the gauge site for a number of return periods. Assuming that the gauge has a relatively long period of record, and that the watershed upstream of the gauge has remained relatively stable and unchanged over the course of that record, a FFA can generally produce frequency discharge estimates with less uncertainty than those obtained from the regional regression equations. A model producing simulated flow rates similar to the FFA discharges can lend greater confidence in the overall results, as the FFA utilizes site-specific data to develop its estimates. However, if the riverine system being studied is regulated by a dam or other hydraulic structure near to the gauge, as was the case with the Banister Lake Dam just upstream of the Halifax gauge, certain behaviors/consequences must be acknowledged. Primarily, only the gauge record after the regulation should be considered, as the addition of a dam will generally alter the discharge response of a waterway.

4. *Can a model developed following standard and best engineering practices accurately predict design discharges obtained through established statistical techniques?*

Based on the results presented in Chapter 5, it was shown that a hydrologic model developed following standard and best engineering practices can produce discharge results that correlate reasonably well with flow estimates obtained through standardized regression and statistical approaches. Through the utilization of simulation methodologies that have been widely tested and accepted by the engineering community, and with best estimates of real-world hydrologic parameters, this work has demonstrated that in the absence of observed calibration data, a viable hydrologic model can still be generated and used to simulate an extreme event.

6.2 Concluding Remarks

Whether designing a high-risk structure or planning the layout of a high-hazard site, it is imperative to consider the various worst-case failure scenarios that may impact the project over the course of its design life. With regard to uranium mining in the relatively wet and humid climate of Virginia, planning for a PMP-type event is crucial to ensure that key structures and operations are not impacted by flood waters during an extreme event. Through the simulation of the PMS and the determination of the PMF and its associated discharges and flooding extents, a newly developed site can be designed and constructed in such a way as to safeguard against a hydrologically-induced failure that may otherwise compromise the site.

As the PMS is a theoretical event with essentially a zero percent probability of occurrence, there is still a great deal of uncertainty regarding how to pinpoint a PMP depth and how to develop the storm, both spatially and temporally. However, using the methodologies developed by the NWS and USACE, best approximations of these events can be made using available data from historic storms of record. With a PMS model developed in this fashion, and with a hydrologic model acting as a simplification of the complex characteristics and interactions of a real-world watershed, a modeler can provide an indication of the potential implications of such an extreme event.

Through the development of the two PMS models presented as part of this work, and through their simulation over their respective study watersheds, the potential effect of a PMP/PMS event in the vicinity of the Coles Hill site can be assessed. Using results from these studies, the PMF can be routed through the hydraulic models of the study sites to achieve the overall project goals of inundation mapping and sediment transport. This will help to provide guidance on how to develop the Coles Hill site, and to take proactive measures to impede the highly unlikely release of mine tailings.

The body of work presented in this thesis examined the model development procedure and implementation process required to carry out a hydrologic simulation of a PMS event. It has been shown that by utilizing the analytical and parameter estimation functionalities built into ArcHydro and HEC-GeoHMS, the data extraction and basin model development routines have become greatly simplified compared to the traditional HEC-HMS model generation techniques. These software packages greatly reduced the time and effort that would have been required to assimilate and analyze the numerous spatial datasets used to extract the pertinent information and develop the basin model structure.

Regarding the storm information, details have been provided on how to gather precipitation data and develop frequency design storms for model calibration, as well as on how to determine the PMP and transform it into a PMS capable of being modeled over study basin. Using industry-standard simulation methodologies, viable models of both the study basins and the design storms were constructed and utilized to evaluate a number of rainfall-runoff scenarios. Some of these simulations served as comparison datasets to evaluate the models and determine if they functioned as anticipated. Once deemed to appropriately mimic the hydrologic response in the study watersheds, the models were finally employed to simulate the PMS events and generate the PMF hydrographs at key locations within the study areas.

The PMF hydrographs produced by these hydrologic simulations will serve as flow inputs into the corresponding HEC-RAS hydraulic models of the two study systems. It is within these hydraulic modeling simulations that the flow dynamics are evaluated and the inundation areas are defined. Knowledge of theses outcomes will not only help to assess the transport of released tailings during a catastrophic failure, but will also consequently allow for proper site planning and preparations to mitigate, if not avoid altogether, the impact of such an extreme event.

7. REFERENCES

Anderson, M. L., Chen, Z. Q., Kavvas, M. L., and Feldman, A. (2002). "Coupling HEC-HMS with atmospheric models for prediction of watershed runoff." *Journal of Hydrologic Engineering*, 7(4), 312-318.

Baker Engineering (2011). *A Preliminary Assessment of Potential Impacts of Uranium Mining in Virginia on Drinking Water Sources, Final Report*. Virginia Beach, VA

Barnes, H. H. (1967). *Characteristics of Natural Channels*. Washington, DC: U.S. Geological Survey Water-Supply Paper 1849.

Bisese, J. A. (1995). *Methods for Estimating the Magnitude and Frequency of Peak Discharges of Rural, Unregulated Streams in Virginia*. Richmond, VA: U.S. Geological Survey, and Virginia Department of Transportation.

Bonnin, G. M., Martin, D., Lin, B., Parzybok, T., Yekta, M., and Riley, D. (2006). *NOAA Atlas 14, Volume 2, Precipitation-Frequency Atlas of the United States, Version 3.0*, Silver Spring, MD: National Oceanic and Atmospheric Administration, National Weather Service.

Brunner, G. W. and Fleming, M. J. (2010). *HEC-SSP Statistical Software Package User's Manual (Version 2.0)*. Davis, CA: U.S. Army Corps of Engineers Hydrologic Engineering Center.

Chaubey, I., Haan, C. T., Grunwald, S., and Salisbury, J. M. (1999). "Uncertainty in the model parameters due to spatial variability of rainfall." *Journal of Hydrology*, 220 (1-2): 48-61.

Chow, V. T. (1959). *Open Channel Hydraulics*. McGraw-Hill, Inc., New York, NY.

Chow, V. T., Maidment, D. R., and Mays, L. W. (1988). *Applied Hydrology*. McGraw-Hill, Inc., New York, NY.

Chu, X., and Steinman, A. (2009). "Event and Continuous Hydrologic Modeling with HEC-HMS." *Journal of Irrigation and Drainage Engineering*, 135 (1): 119-124.

Cudworth, Jr., A. G. (1989). *Flood Hydrology Manual: A Water Resources Technical Publication*, Denver, CO: U.S. Department of the Interior, Bureau of Reclamation.

Dziuban, J. (2000). *Radiation Protection at EPA: The First 30 Years*. EPA 402-B-00-001, Washington, D.C.: U.S. Environmental Protection Agency (USEPA), Office of Radiation and Indoor Air (ORIA), 17 p.

Fleming, M. J., and Doan, J. H. (2010). *HEC-GeoHMS Geospatial Hydrologic Modeling Extension User's Manual (Version 5.0)*. Davis, CA: U.S. Army Corps of Engineers Hydrologic Engineering Center.

Folmar, N.D., Miller, A. C., and Woodward, D. E. (2007). "History and Development of the NRCS Lag Time Equation." *Journal of the American Water Resources Association*, 43 (3): 829-838.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011). "Completion of the 2006 National Land Cover Database for the Conterminous United States." *Photogrammetric Engineering & Remote Sensing*, Vol. 77(9):858-864.

Garcia, A., Sainz, A., Revilla, J. A., Alvarez, C., Juanes, J. A., and Puente, A. (2008). "Surface water resources assessment in scarcely gauged basins in the north of Spain." *Journal of Hydrology*, 356 (3-4): 312-326.

Gesch, D. B. (2007). The National Elevation Dataset, in Maune, D., ed., *Digital Elevation Model Technologies and Applications: The DEM User's Manual, 2nd Edition*. Bethesda, MD: American Society for Photogrammetry and Remote Sensing: 99-118.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D. (2002). The National Elevation Dataset: *Photogrammetric Engineering and Remote Sensing*, v. 68, no. 1: 5-11.

Hansen, E. M., Schreiner, L. C., and Miller, J. F. (1982). *NOAA Hydrometeorological Report No. 52: Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian*. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, and U.S. Department of the Army - Corps of Engineers.

Harrison, J. (2003). “PMPs Never Happen - Or Do They?” Proc., *Reducing Risk from Extreme Events*, United States Society on Dams, Charleston, SC.

Hawkins, R. H., Jiang, R., Woodward, D.E., Hjelmfelt, A.T., and Van Mullem, J.A. (2002). “Runoff Curve Number Method: Examination of the Initial Abstraction Ratio.” *Proc., Second Federal Interagency Hydrologic Modeling Conference*. Las Vegas, NV: U.S. Geological Survey.

Hershfield, D. M. (1961). *Technical Paper No. 40: Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years*, Washington, D.C.: U.S. Department of Commerce, Weather Bureau.

Jenson, S. K., and Domingue, J. O. (1988). "Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis." *Photogrammetric Engineering and Remote Sensing*, 54(11), 1593-1600.

Kafle, T. P., Hazarika, M. K., Karki, S., Sshrestha, R. M., Sharma, R., and Samarakoon, L. (2007). “Basin Scale Rainfall-Runoff Modeling for Flood Forecasts.” Proc., *5th Annual Mekong Flood Forum*. Ho Chi Minh City, Vietnam.

Kalyanapu, A. J., Burian, S.J., and McPherson, T. N. (2009). "Effect of land use-based surface roughness on hydrologic model output." *Journal of Spatial Hydrology*, 2009 (9): 51-71.

Knebl, M. R., Yang, Z. L., Hutchison, K., and Maidment, D. R. (2005). "Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event." *Journal of Environmental Management*, 75 (4): 325-336.

Lotspeich, R. R. (2009). *Regional Curves of Bankfull Channel Geometry for Non-Urban Streams in the Piedmont Physiographic Province, Virginia*. Reston, VA: U.S. Geological Survey, and Virginia Transportation Research Council.

Maryland Hydrology Panel. (2010). *Application of Hydrologic Methods in Maryland*. Cambridge, MD: Maryland Hydrology Panel.

McCuen, R. H. (1998). *Hydrologic Analysis and Design: Second Edition*. Prentice Hall, Upper Saddle River, NJ.

Merwade, V. (2010). "Creating SCS Curve Number Grid using HEC-GeoHMS." School of Civil Engineering, Purdue University, West Lafayette, IN. Available online at http://web.ics.purdue.edu/~vmerwade/education/cngrid.pdf.

Mockus, V. (1961). *Watershed Lag*. ES-1015, Washington, D.C.: U.S. Department of Agriculture (USDA), Soil Conservation Service (SCS).

Olivera, F. (2001). "Extracting hydrologic information from spatial data for HMS modeling." *Journal of Hydrologic Engineering*, 6 (6): 524-531.

Olivera, F., and Maidment, D. R. (2000). ‘‘GIS tools for HMS modeling support.’’ *Hydrologic and Hydraulic Modeling Support with Geographic Information Systems, Chapter 5*, San Diego, CA: ESRI Press, D. R. Maidment and D. Djokic, eds.

Razi, M. A. M., Ariffin, J., Tahir, W., and Arish, N. A. M. (2010). "Flood Estimation Studies using Hydrologic Modeling System (HEC-HMS) for Johor River, Malaysia." *Journal of Applied Sciences*, 10 (11): 930-939.

Santoy Resources LTD. (2009). *Technical Report on the Coles Hill Uranium Property Pittsylvania County, Virginia, United States of America*. NI 43-101, British Columbia, Canada: Santoy Resources.

Scharffenberg, W. A., and Fleming, M. J. (2010). *Hydrologic Modeling System HEC-HMS User’s Manual (Version 3.5)*. Davis, CA: U.S. Army Corps of Engineers Hydrologic Engineering Center.

Schreiner, L. C., and Riedel, J. T. (1978). *Hydrometeorological Report No. 51: Probable Maximum Precipitation Estimates, United States East of the 105th Meridian*. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, and U.S. Department of the Army - Corps of Engineers.

U.S. Army Corps of Engineers (USACE) (1994). *Engineering and Design – Flood-Runoff Analysis*. EM 1110-2-1417, Washington, D.C.

U.S. Army Corps of Engineers (USACE) (1979). *National Program for Inspection of Non-Federal Dams*. ER 1110-1-106, Appendix D, Washington, D.C.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2007). *Part 630 Hydrology, National Engineering Handbook, Chapter 7: Hydrologic Soil Groups*. 210-VI-NEH, Washington, D.C.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2004). *Part 630 Hydrology, National Engineering Handbook, Chapter 10: Estimation of Direct Runoff from Storm Rainfall*. 210-VI-NEH, Washington, D.C.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2010). *Part 630 Hydrology, National Engineering Handbook, Chapter 15: Time of Concentration*. 210-VI-NEH, Washington, D.C.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2009). Soil Survey Geographic (SSURGO) Database for Pittsylvania County and the City of Danville, Virginia. Available online at http://soildatamart.nrcs.usda.gov.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (1986). *Technical Release 55: Urban Hydrology for Small Watersheds*. Washington, D.C.: US Government Printing Office.

U.S. Energy Information Administration (USEIA) (2010). "Uranium Purchased by Owners and Operators of U.S. Civilian Nuclear Power Reactors," http://www.eia.gov/cneaf/nuclear/umar/summarytable1.html. (April 30, 2011).

U.S. Geological Survey (USGS) (2011). "National Water Information System: Web Interface - USGS 02077000 BANISTER RIVER AT HALIFAX, VA," http://waterdata.usgs.gov/usa/nwis/ uv?02077000. (June 6, 2011).

U.S. Interagency Advisory Committee on Water Data (1982). *Guidelines for Determining Flood-Flow Frequency, Bulletin 17B of the Hydrology Subcommittee*. Reston, VA: U.S. Geological Survey (USGS), Office of Water Data Coordination.

U.S. Nuclear Regulatory Commission (USNRC) (2002). *Design of Erosion Protection for Long-Term Stabilization: Final Report*. NUREG-1623, Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards,, Division of Fuel Cycle Safety and Safeguards.

Woodward, D.E., Hawkins, R.H., Hjelmfelt, A.T., Van Mullem, J.A., and Quan, Q.D. (2002). "Curve Number Method: Origins, Applications, and Limitations." Proc., *Second Federal Interagency Hydrologic Modeling Conference*. Las Vegas, NV: U.S. Geological Survey Advisory Committee on Water Information.

Yawson, D. K., Kongo, V. M., and Kachroo, R. K. (2005). "Application of linear and nonlinear techniques in river flow forecasting in the Kilombero River basin, Tanzania." *Hydrological Sciences Journal*, 50(5), 783-796.

Appendix A:

Development of a Hydrologic Basin Model Using HEC-GeoHMS, ArcHydro, and ArcGIS

- **Whitethorn Creek Study Watershed**
- **Banister River Study Watershed**

Appendix A

A. TABLE OF CONTENTS

Overview 101

Arc Hydro Tools 9 Steps: 101

Data Setup: 101

Terrain Preprocessing: 102

Terrain Preprocessing Steps: 104

HEC-GeoHMS Steps: 109

Creating an SCS Curve Number Grid: 109

SCS Curve Number Grid Generation Steps: 110

HEC-GeoHMS Main View 9 Processing Steps: 119

HEC-GeoHMS Project View 9 Processing Steps: 120

Basin Processing: 120

Basin Characteristics 122

HMS Inputs/Hydrologic Parameters 124

HMS 126

Opening the Model in HEC-HMS 129

References: 131

Basin Model Development Procedure using HEC-GeoHMS, ArcHydro, and ArcGIS:

HEC-GeoHMS and ArcHydro were utilized within the ArcGIS workspace to assimilate the data sources and develop the HEC-HMS-compatible basin models for the Whitethorn Creek and Banister River study watershed. For this procedure, the required input files included a digital elevation model (DEM) grid obtained from the National Elevation Dataset (NED), a land use grid from the National Land Cover Dataset (NLCD 2006), and a soil file classified by hydrologic soil group from the Soil Survey Geographic (SSURGO) database operated by the NRCS. For compatibility and geospatial referencing purposes, a common projection was adopted for both analyses: North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) Zone 17N. The following text details the step-by-step procedure that was employed to generate the final .hms file for the HEC-HMS PMF simulations. As both analyses utilized the same model development approach, step-by-step results from each procedure are presented simultaneously in this Appendix. For additional reference, the ArcHydro/HEC-GeoHMS basin model development procedure is outlined in detail in both the HEC-GeoHMS User's Manual (Fleming & Doan, 2010), as well as in a series of tutorials developed by Dr. Venkatesh Merwade, School of Civil Engineering, Purdue University (Merwade, 2010a, 2010b, and 2010c) which were both utilized for this project.

Arc Hydro Tools 9 Steps:

Arc Hydro Tools 9 is a toolkit developed for ArcGIS version 9.3 that contains many of the hydrologic processing functions necessary to gather the required information to build the .hms file. Arc Hydro Tools 9 utilizes the functionality of the Spatial Analyst, Utility Network Analyst, and editor tools in ArcGIS to carry out its terrain preprocessing and watershed processing operations.

Data Setup:

The files created with Arc Hydro Tools 9 are inherently stored in a project-specific geodatabase that the program generates automatically once the user runs one of the program's operations. All vector data created is stored in a geodatabase that has the same name as the stored project or ArcMap (ArcGIS' mapping component) document and in the same directory where the project has been saved. However, the user may override this location and select a different geodatabase in which to store the new files. For new raster data, files are stored in a subdirectory called Layers and under the directory where the project is saved.

Terrain Preprocessing:

The first step in the .hms model generation procedure involves a number of terrain-processing steps that are carried out using the tools in the Terrain Preprocessing menu on the Arc Hydro Tools 9 toolbar. These steps must be completed in sequential order, as they are listed in the menu pictured in Figure 29.

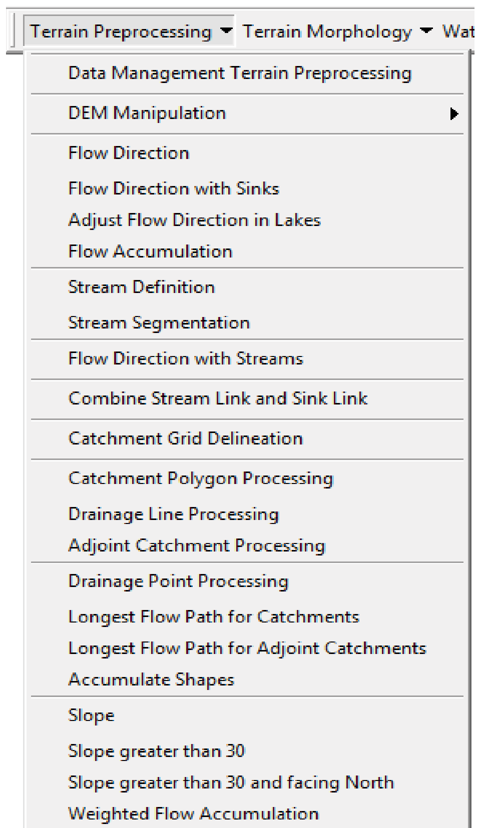

Figure 29: ArcHydro Tools 9 – Terrain Preprocessing Menu

The only required input for the terrain preprocessing operations is a DEM source grid. For this project, a 1/3 arc-second (approximately 10 m x 10 m cell size) DEM grid of each study area was obtained from the National Elevation Dataset (NED) made available from the United States Geological Society (USGS). The DEM grids used for this project, clipped to the boundaries of the Whitethorn Creek and Banister River Study Watersheds, are depicted in Figure 30 and Figure 31, respectively.

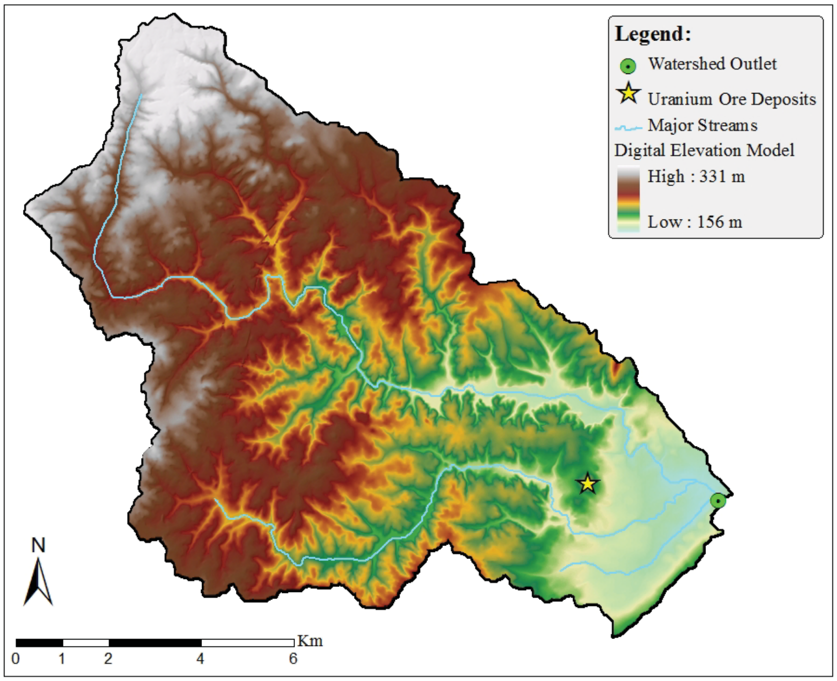

Figure 30: Digital Elevation Model for the Whitethorn Creek Study Watershed

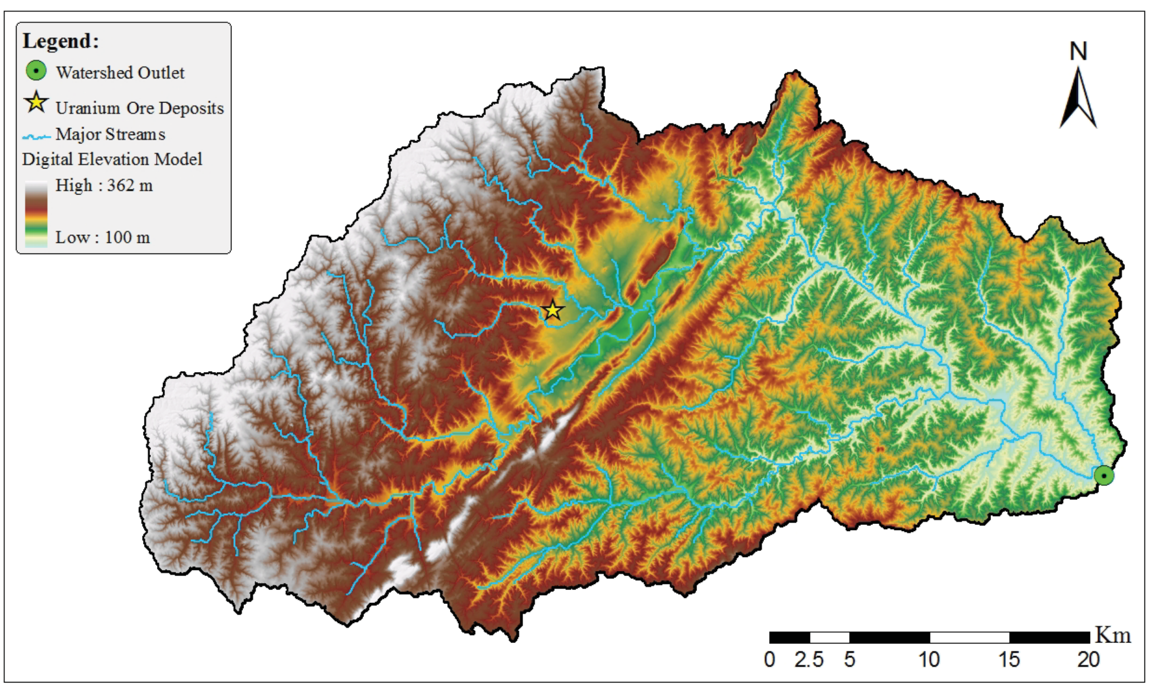

Figure 31: Digital Elevation Model for the Banister River Study Watershed

Terrain Preprocessing Steps:

1. Fill Sinks

The first step of preprocessing is to fill the sinks in the DEM. These sinks are cells or groups of cells that are of a lower elevation than all of the cells surrounding them. These cells create a problem when attempting to route flow over the landscape because the sink areas allow for flow to come in but then there is nowhere for flow to drain out of. The fill sinks command identifies these problem areas and creates a new grid with edited elevation values, assigning a new elevation value equal to the lowest surrounding cell to the sink area. This creates flat areas where the sinks are located over which the flow can be routed toward the next viable pour point. This command requires the user to input the original DEM layer and has an output of a filled "hydro DEM".

2. Flow Direction

Once the hydro DEM has been generated, a flow direction grid must be created. This grid looks at each cell and the eight cells surrounding it and determines which direction flow would travel leaving that cell. The program identifies the steepest decent from the study cell, or the surrounding cell with the lowest elevation compared to the study cell. This flow direction grid is used for determining how the flow will travel across the landscape and where stream networks will likely develop. This command requires the user to input the hydro DEM that was generated in the previous step and outputs a flow direction grid.

3. Flow Accumulation

From the flow direction grid, a flow accumulation grid is created. The value for each cell in this grid will indicate the accumulated number of cells upstream of a particular cell that drain to that cell. This calculation is done for each cell in the input grid and can later be used to define stream networks and potential discharge points for various watersheds or subbasins. This command requires the user to input the flow direction grid and outputs a flow accumulation grid.

4. Stream Definition

Once the flow accumulation grid has been generated, a stream network can be defined for a given area or watershed. This command identifies the flow accumulation grid cell values above a certain threshold and creates a new grid, assigning these cells a value of one and all other cells a value of NoData. The user must input the flow accumulation layer to be used and specify a cell threshold value from which to start the flow networks. This threshold can either be specified as a number of cells or as an area in km^2. The output of this command contains the dendritic flow network for the area as a raster grid of cells. For the Whitethorn analysis, an initiation threshold of 1 km^2 was selected, as it is approximately 1% of the total drainage area size (107 km^2). Figure 32 shows the stream grid that was generated based on this threshold for the study watershed. Similarly, Figure 33 depicts the stream grid generated for the Banister model which was based on a 6 km^2 threshold (approximately 0.4% of the total basin area). This threshold was selected to capture the smaller streams near the Coles Hill Project site.

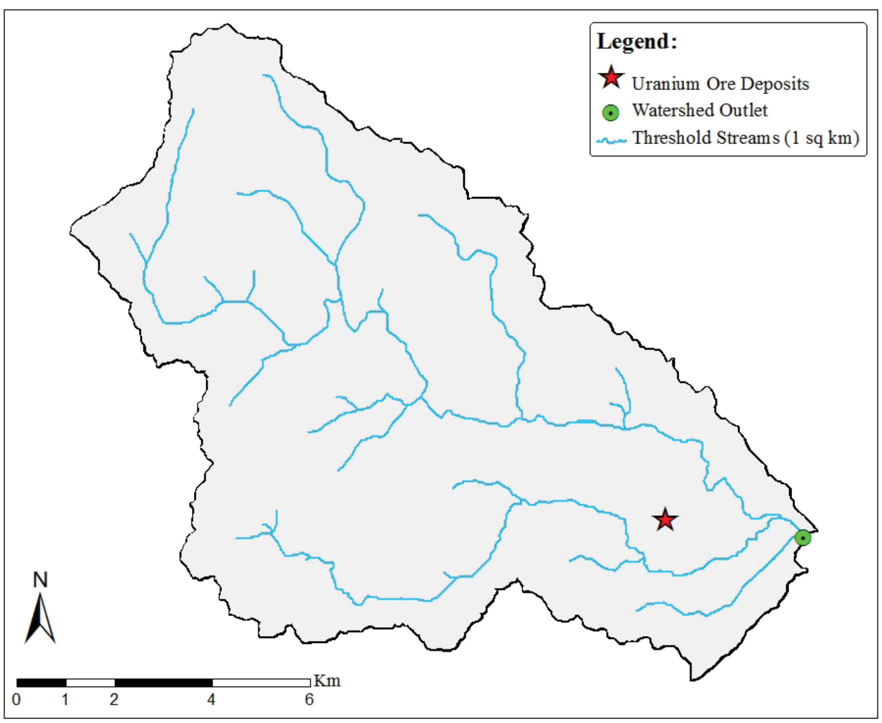

Figure 32: Threshold Stream Definition Grid for the Whitethorn Creek Study Watershed – Based on a Threshold of 1 km2

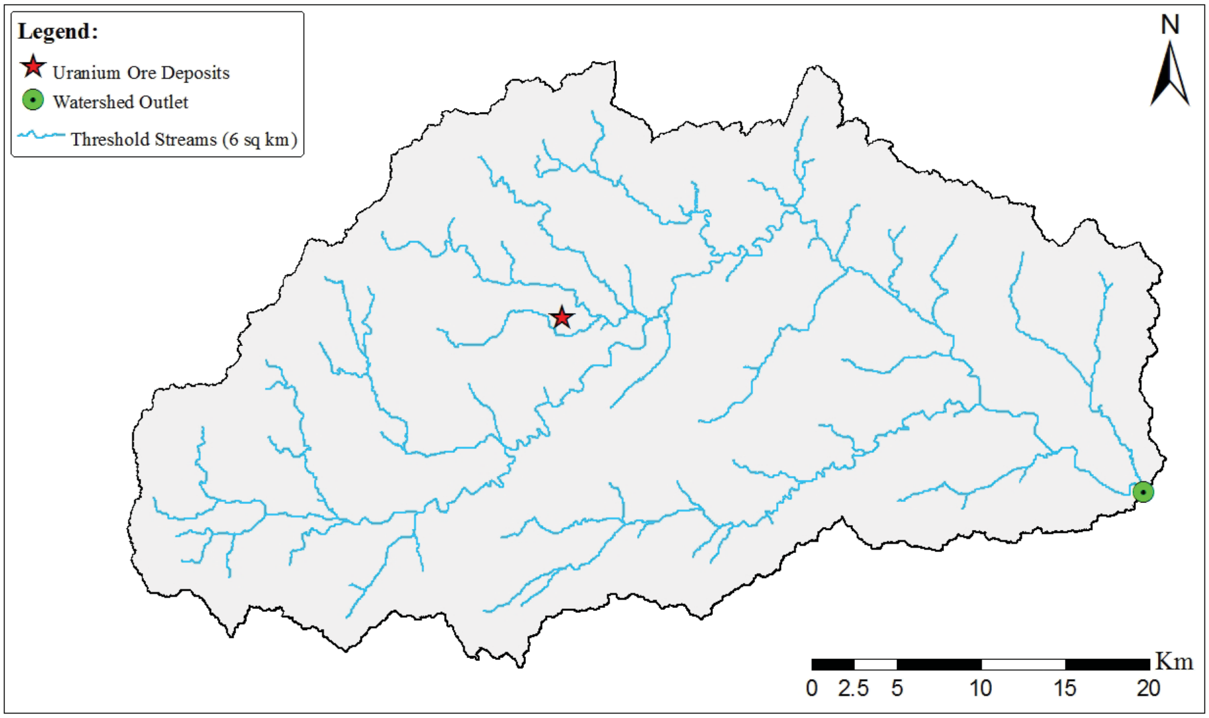

Figure 33: Threshold Stream Definition Grid for the Banister River Study Watershed – Based on a Threshold of 6 km^2

5. Stream Segmentation

Similar to the stream links command in the Spatial Analyst Hydrology toolbox in ArcGIS, the stream segmentation command examines the flow network and divides it up into individual reach segments. A break point is added each time a stream tributary connects to another tributary or anywhere that there is a fork in the stream network. This command requires the user to input the stream definition grid and the flow direction grid and outputs a new stream link grid. Based on the 1 km^2 threshold that was selected for stream initiation, 47 individual stream segments were identified for the Whitethorn basin. Likewise, 133 stream segments were found for the Banister River Study Watershed based on the selected 6 km^2 threshold.

6. Catchment Grid Delineation

Once the streams have been segmented, the catchment grid delineation command analyzes the terrain and delineates a separate watershed for each of the individual stream segments. This command requires both a flow direction grid and a stream link grid as inputs and outputs a grid with the new subbasins. As a result of the 47 threshold stream segments found for the Whitethorn model, 47 individual subbasins were delineated within the study area (Figure 34). In the same way, 133 catchments were delineated for the Banister model based on its 133 threshold streams (Figure 35). It should be noted that even though the Whitethorn study area lies within the Banister study area, their respective streams and catchments do not directly correlate due to the finer threshold that was selected for the Whitethorn model. For example, the Mill Creek watershed is represented as a single subbasin in the Banister model, whereas it is broken down into twelve smaller threshold catchments in the Whitethorn model.

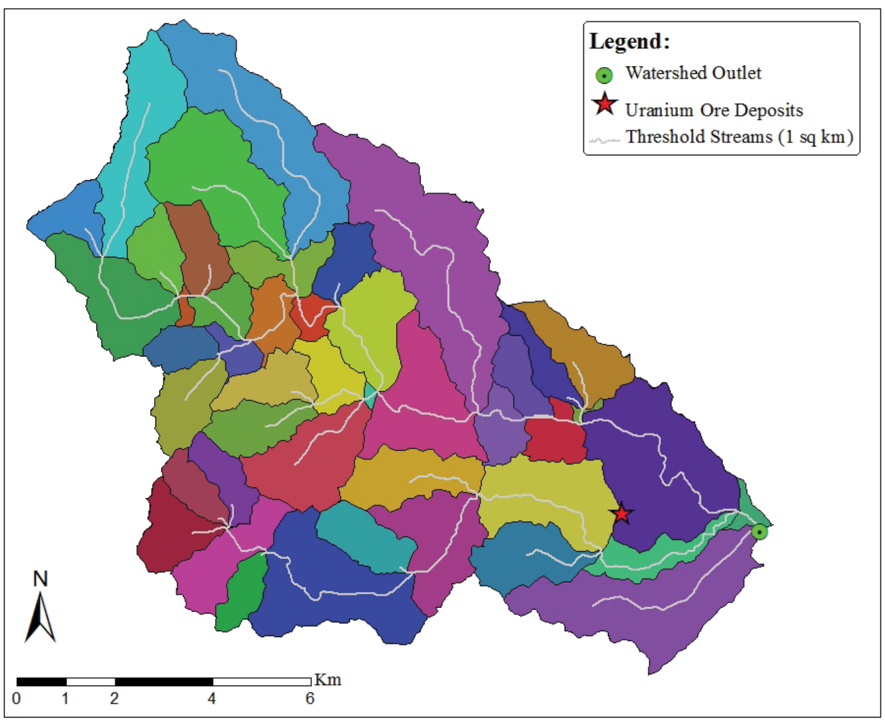

Figure 34: Threshold Stream Segment Catchment Grid for the Whitethorn Creek Study Watershed

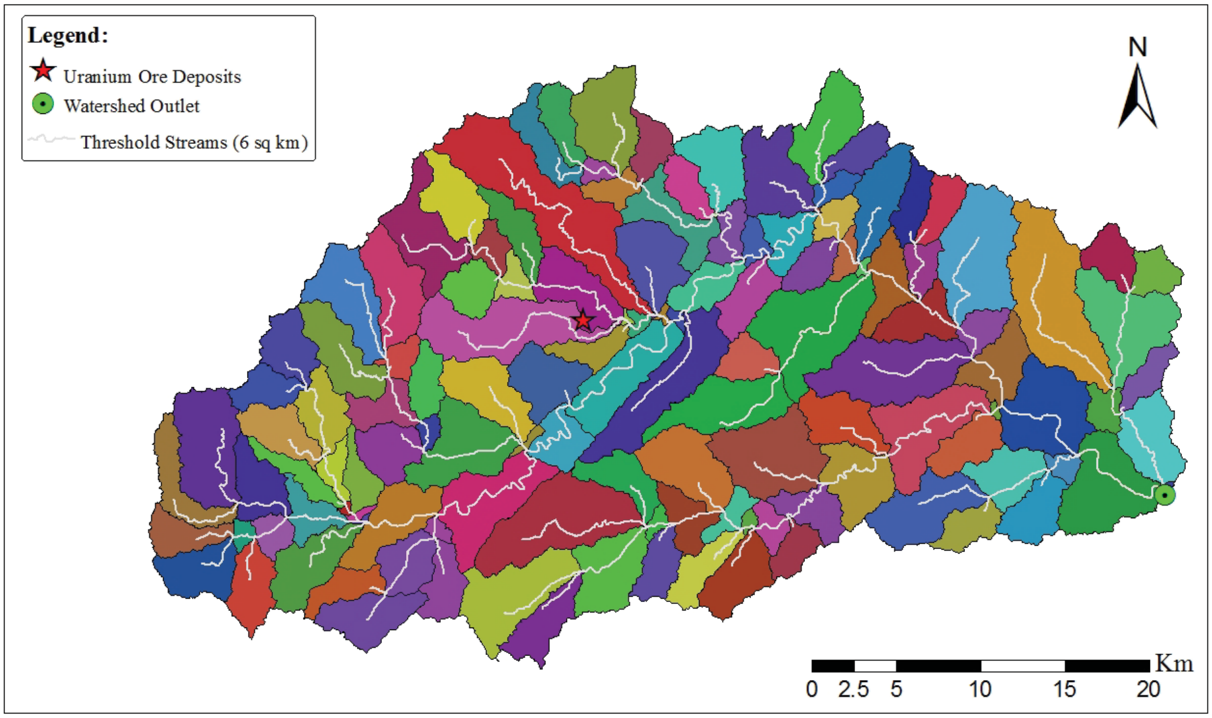

Figure 35: Threshold Stream Segment Catchment Grid for the Banister River Study Watershed

7. Catchment Polygon Processing

In order to obtain a number of basin characteristics, Arc Hydro Tools 9 and HEC-GeoHMS require polygon boundaries for the catchments generated in the previous step. Catchment polygon processing converts the raster subbasin grid into a new layer of vector polygon features. The attribute table for this new layer contains information about the area of each of the new subbasins in map units (m^2). To run this command, the only necessary input is the catchment grid and the output is a catchment polygon shapefile.

8. Drainage Line Processing

Similar to the catchment polygon processing, the drainage line processing command converts the stream segmentation raster grid into a drainage line feature class (polyline shapefile). The new feature class' attribute table will contain information on the reach lengths for each of the stream segments in map units (m). It should be noted that these segments resulted from a user defined flow accumulation threshold so the actual lengths of these new polylines are only valid under this threshold assumption. To run this command, the user must select the stream link grid and the flow direction grid to be used.

9. Adjoint Catchment Processing

This function generates aggregated upstream catchments from the catchment polygons generated in step 7. For each subbasin that is not a headwater catchment, a polygon representing the whole upstream area draining to its inlet point is constructed and stored in a feature class that has an Adjoint Catchment tag. This is used to speed up the point delineation process. The required inputs for this step are the catchment polygon and the drainage line polyline shapefiles and the output is a new adjoint catchment polygon shapefile.

10. Drainage Point Processing

The final step required in the terrain preprocessing menu is the drainage point processing command. This operation generates drainage point features associated with the individual subbasins. To create this new point shapefile, the user is required to input the flow accumulation grid, the catchment grid, and the catchment polygon feature class. These drainage points correspond to the outlets of each of the adjoint catchments.

HEC-GeoHMS Steps:

Once the ten main pre-processing steps have been carried out, a user can begin to utilize the capabilities of the HEC-GeoHMS toolbars to start generating the necessary HEC-HMS input files. The HEC-GeoHMS program makes two new toolbars available in ArcGIS: the HEC-GeoHMS Main View 9 toolbar and the HEC-GeoHMS Project View 9 toolbar.

Creating an SCS Curve Number Grid:

One very important input required for this watershed analysis was an SCS/NRCS Curve Number grid, as both the selected HEC-HMS loss method (SCS Curve Number Loss) and transform method (SCS Unit Hydrograph Transform) require it. This grid combines information regarding land use and hydrologic soil types with a tabular curve number look-up table to obtain a useable parameter for predicting direct runoff or infiltration from rainfall excess. For both analyses, two different CN grids were generated: one assuming an ARC II (average antecedent conditions) and the other an ARC III (wet antecedent conditions).The hydrologic analysis for each model was conducted with each of the CN grids to compare the effect of the assumed antecedent moisture condition in the watershed prior to the occurrence of the PMP event.

This step requires two new source grids for the study area: an NLCD 2006 (or earlier) land cover grid and a SSURGO soil feature class shapefile. The land cover grid can be obtained from the U.S. Geological Survey's (USGS) seamless data download server and the soil data can be downloaded from the Soil Survey Geographic (SSURGO) database operated by the U.S. Department of Agriculture's (USDA) Natural Resource Conservation Service (NRCS).

SCS Curve Number Grid Generation Steps:

1. Preparing the land cover data for the Curve Number Grid

   Once the land cover grid has been downloaded, the user must identify what the various land use codes correlate to, as each cell is natively assigned a number from eleven to ninety-five representing one of fifteen distinct land cover types. These codes can be obtained directly from the USGS or from a number of other websites. The NLCD 2006 grid, which has a cell resolution of 1 arc-second (approximately 30 m by 30 m), was developed through a Landsat satellite-derived remote-sensing analysis. Each cell is assigned to one of the classifications based on the predominant land cover that exists within it. Figure 36 and Figure 37 illustrate the NLCD 2006 land cover product as it applies to the Whitethorn Creek and Banister River Study Watersheds, respectively.

   In order to employ HEC-GeoHMS to create the Curve Number grid, the land cover data must first be converted into a polygon feature class so that it can be combined with the soil polygons. Using the Spatial Analyst toolbar, the Convert Raster to Feature function can be used to make this conversion. For this, the user must select the input raster (the NLCD 2006 raster) and specify the output geometry type (polygon), in addition to selecting where to save the new land cover polygon shapefile. This file can be saved into the same geodatabase as the previous data for ease of data management.

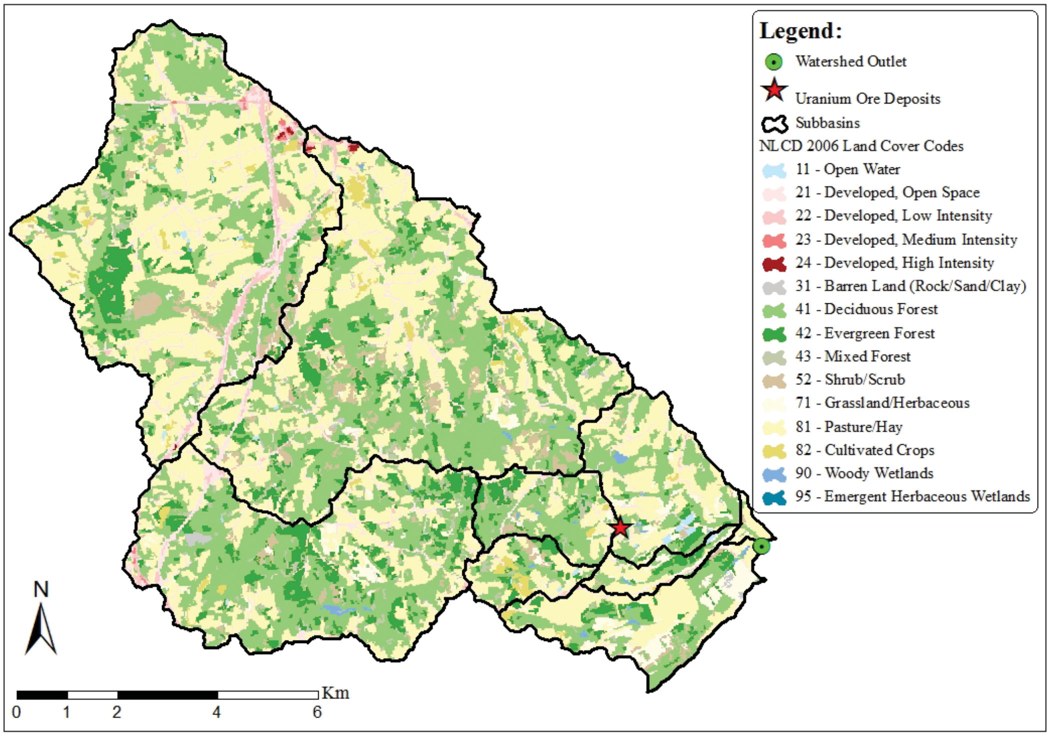

Figure 36: NLCD 2006 Land Cover for the Whitethorn Creek Study Watershed

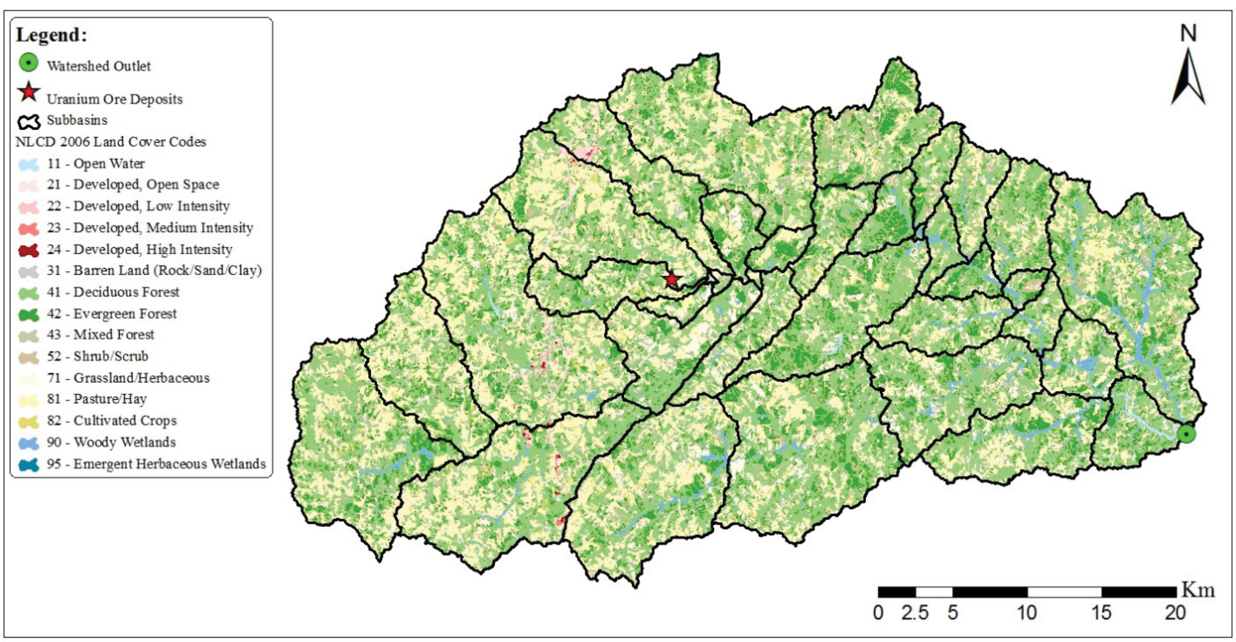

Figure 37: NLCD 2006 Land Cover for the Banister River Study Watershed

2. Preparing the SSURGO soil data for the Curve Number Grid

Once the land cover feature class has been created, the SSURGO soil data must be prepared. The soil data must include a field denoting the hydrologic soil group (HSG) for each polygon (A, B, C, D, A/D, B/D, C/D, or Unknown). This classification is based on the following factors: whether the soil freezes, whether there is a bare soil surface, the maximum swelling capacity of the expansive clays in the soil, and on the intake and transmission of water through the soil when it is thoroughly wet (USDA NRCS, 2007). In general, HSG A soils have the lowest surface runoff potentials and water is transmitted freely through the soil. In contrast, HSG D soils have high surface runoff potentials and water movement through the soil is impeded or completely restricted.

Because the HSG classification is not directly included in the data file's attribute table, it needs to be added. This can be done by joining the component table from the soil data to the polygon file to access these codes. Because not all of the soil polygons are assigned to one of the four HSG soil group types, assumptions must be made to handle the non-specific soil types. For this analysis, a conservative assumption was made about the A/D, B/D, C/D, and Unknown soil types. These polygons were considered to be D soil type, as type D soil is the least permeable and would result in the greatest surface runoff. Figure 38 shows the soil distribution for the Whitethorn Creek Study Watershed and Figure 39 shows the soil distribution for the Banister River Study Watershed.

One last step to make the soil data useable in HEC-GeoHMS is to create four data columns in the attribute table denoting the percentage of each HSG that lies within each polygon. For both analyses, soil polygons corresponded to only a single soil type (B, C, or D after the dual and unknown soils were adjusted), so the value in the percentage column corresponding to that HSG value was assigned as "100" whereas the other three columns were given a value of "0". For this, four new fields were added to the soil attribute tables (PctA, PctB, PctC, and PctD) and populated accordingly.

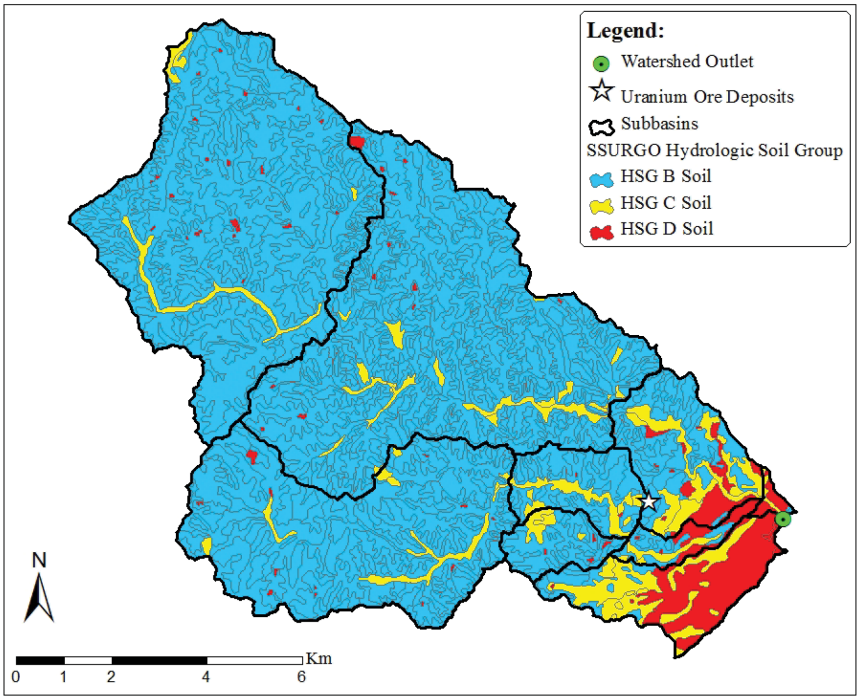

Figure 38: SSURGO Soil Data by Hydrologic Soil Group for the Whitethorn Creek Study Watershed

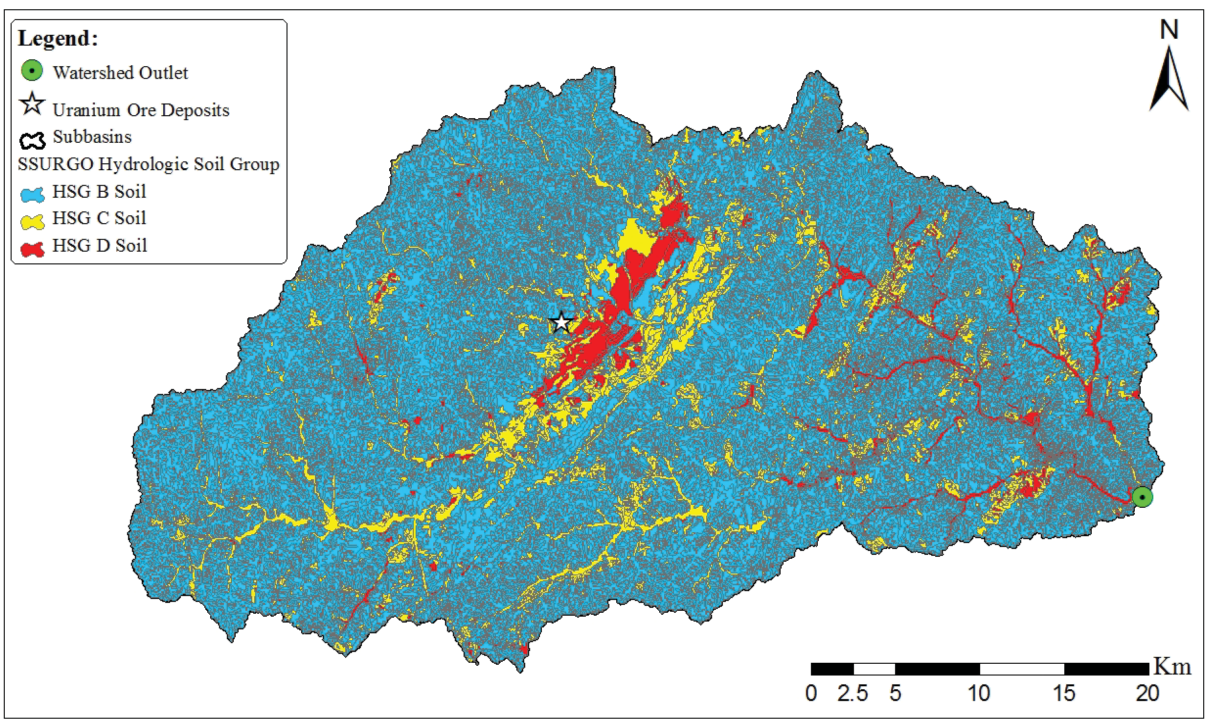

Figure 39: SSURGO Soil Data by Hydrologic Soil Group for the Banister River Study Watershed

3. Merging Soil and Land use Data

Once the land cover and soil feature classes have been prepared, they must be joined together into a single dataset. The union function in ArcGIS was used to accomplish this. This command requires the user to specify the two shapefiles to merge, as well as the destination directory and name of the output feature class. Once this new, combined polygon file is created, the "sliver polygons" that result must be addressed. These sliver polygons are areas in the new data set that only contain data from one of the two source datasets (denoted as having an FID value of -1 for one of the two layers). These sliver polygons exist around the very edges of the study watersheds and result from the raster to feature conversion not lining up exactly with the watershed polygon-defined boundaries. For both analyses, these sliver polygons were deleted due to the very small area they encompassed. However, if these areas were significant, the user could have manually assigned the missing characteristics to the respective fields in the attribute table.

One additional step that must be applied to the merged feature class is the addition of a "Landuse" field to the attribute table. This field will allow it to link up with the look-up table generated in the next step. This field can be populated by equating it to the NLCD land cover grid code field.

4. Create the Curve Number Look-up Table

In order for HEC-GeoHMS to generate the curve number grid, it must have a Curve Number look-up table with which it can reference the land uses and HSGs to and extract a curve number value from. Two tables were generated in ArcCatalog (one corresponding to CN_{II} values and the other to CN_{III} values). These were created as new tables and then imported into the map document.

For the ARC II look-up table, the CN_{II} values were selected from the Runoff Curve Number Tables found in the USDA NRCS Technical Release 55, Urban Hydrology for Small Watersheds (TR-55) document (1986). Because the cover types and land treatments do not exactly match up with the NLCD land cover types, the TR-55 values must be interpreted and a similar land use picked. For the study watersheds, the selected TR-55 cover types corresponding to the NLCD cover descriptions can be seen in Table 22. Also in this table are the curve numbers assigned to each combination of cover type and HSG from the TR-55 that were selected to develop the CN_{II} grid.

Table 22: Curve Number Look-up Table Considering Antecedent Runoff Condition II (Average Antecedent Conditions)

2006 NLCD Landuse Value	NLCD Landuse Description	HSG A	HSG B	HSG C	HSG D	TR-55 Curve Number Cover Type
11	Open Water	98	98	98	98	Impervious Areas - Paved Parking Lots, roofs, driveways, etc
21	Developed, Open Space	39	61	74	80	Open space - Good Condition (grass cover > 75%)
22	Developed, Low Intensity	54	70	80	85	Residential Districts - 1/2 acre (25% Impervious Cover)
23	Developed Medium Intensity	69	80	86	89	Residential Districts - Composite (50% Impervious Cover)
24	Developed, High Intensity	89	92	94	95	Urban Districts - Commercial and business (85% Impervious Cover)
31	Barren Land (Rock/Sand/Clay)	77	86	91	94	Fallow - Bare Soil
41	Deciduous Forest	30	55	70	77	Woods - Good
42	Evergreen Forest	30	55	70	77	Woods - Good
43	Mixed Forest	30	55	70	77	Woods - Good
52	Shrub/Scrub	30	48	65	73	Brush - Good
71	Grassland/Herbaceous	39	61	74	80	Pasture, grassland, or range - Good
81	Pasture/Hay	39	61	74	80	Pasture, grassland, or range - Good
82	Cultivated Crops	67	78	85	89	Row Crops - Straight Row - Good
90	Woody Wetlands	98	98	98	98	Impervious Areas - Paved Parking Lots, roofs, driveways, etc
95	Emergent Herbaceous Wetlands	98	98	98	98	Impervious Areas - Paved Parking Lots, roofs, driveways, etc

For the wet antecedent moisture condition (ARC III), the CN_{II} values from Table 22 were converted to CN_{III} values using the chart in Chapter 10 of the National Engineering Handbook, Part 630 Hydrology (Table 1 presented in the main body of the text). The CN_{III} look-up table that was used to generate the CN_{III} grid presented as Table 23.

Table 23: Curve Number Look-up Table Considering Antecedent Runoff Condition III (Wet Antecedent Conditions)

2006 NLCD Landuse Value	NLCD Landuse Description	HSG A	HSG B	HSG C	HSG D	TR-55 Curve Number Cover Type
11	Open Water	99	99	99	99	Impervious Areas - Paved Parking Lots, roofs, driveways, etc
21	Developed, Open Space	59	78	88	91	Open space - Good Condition (grass cover > 75%)
22	Developed, Low Intensity	73	85	91	94	Residential Districts - 1/2 acre (25% Impervious Cover)
23	Developed Medium Intensity	84	91	94	96	Residential Districts - Composite (50% Impervious Cover)
24	Developed, High Intensity	96	97	98	98	Urban Districts - Commercial and business (85% Impervious Cover)
31	Barren Land (Rock/Sand/Clay)	89	94	97	98	Fallow - Bare Soil
41	Deciduous Forest	50	74	85	89	Woods - Good
42	Evergreen Forest	50	74	85	89	Woods - Good
43	Mixed Forest	50	74	85	89	Woods - Good
52	Shrub/Scrub	50	68	82	87	Brush - Good
71	Grassland/Herbaceous	59	78	88	91	Pasture, grassland, or range - Good
81	Pasture/Hay	59	78	88	91	Pasture, grassland, or range - Good
82	Cultivated Crops	83	90	94	96	Row Crops - Straight Row - Good
90	Woody Wetlands	99	99	99	99	Impervious Areas - Paved Parking Lots, roofs, driveways, etc
95	Emergent Herbaceous Wetlands	99	99	99	99	Impervious Areas - Paved Parking Lots, roofs, driveways, etc

5. Generate the Curve Number Grid

Once the previous four steps have been completed, a curve number grid can be generated using the "Generate CN Grid" function in the Utility menu of the HEC-GeoHMS Project View 9 toolbar. This command will take the hydro DEM, the combined soil and land use polygon file, and the Curve Number look-up table and process them to generate the new curve number grid. The CN_{II} grid that was generated for the Whitethorn Creek Study Watershed is shown in Figure 40. Likewise, Figure 41 depicts the CN_{II} grid for the Banister River Study Watershed. For both, the curve numbers range from 48 to 98, with the lower curve numbers representing lower surface runoff potential and the higher numbers representing higher surface runoff potential.

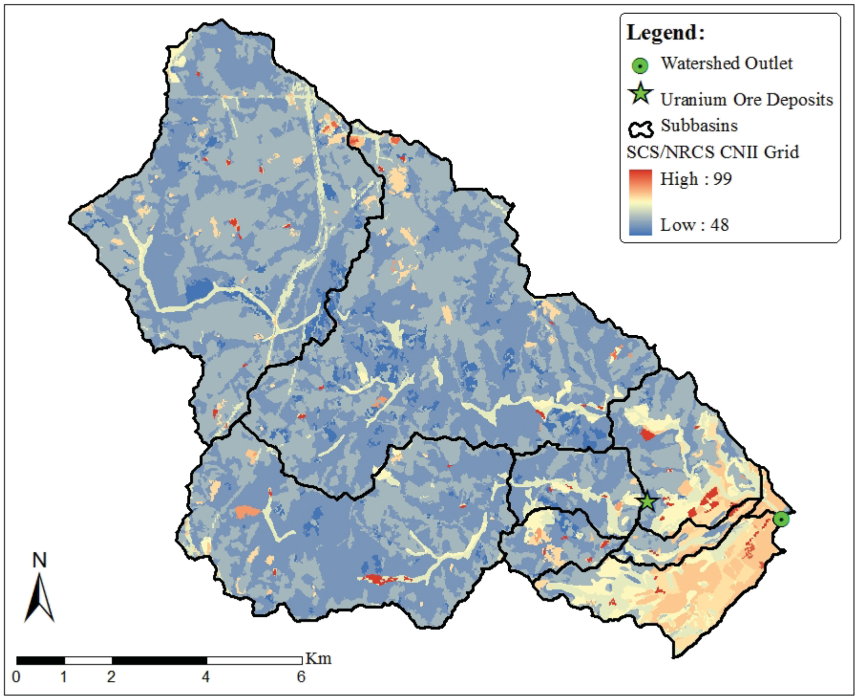

Figure 40: SCS/NRCS CN_{II} Grid for the Whitethorn Creek Study Watershed

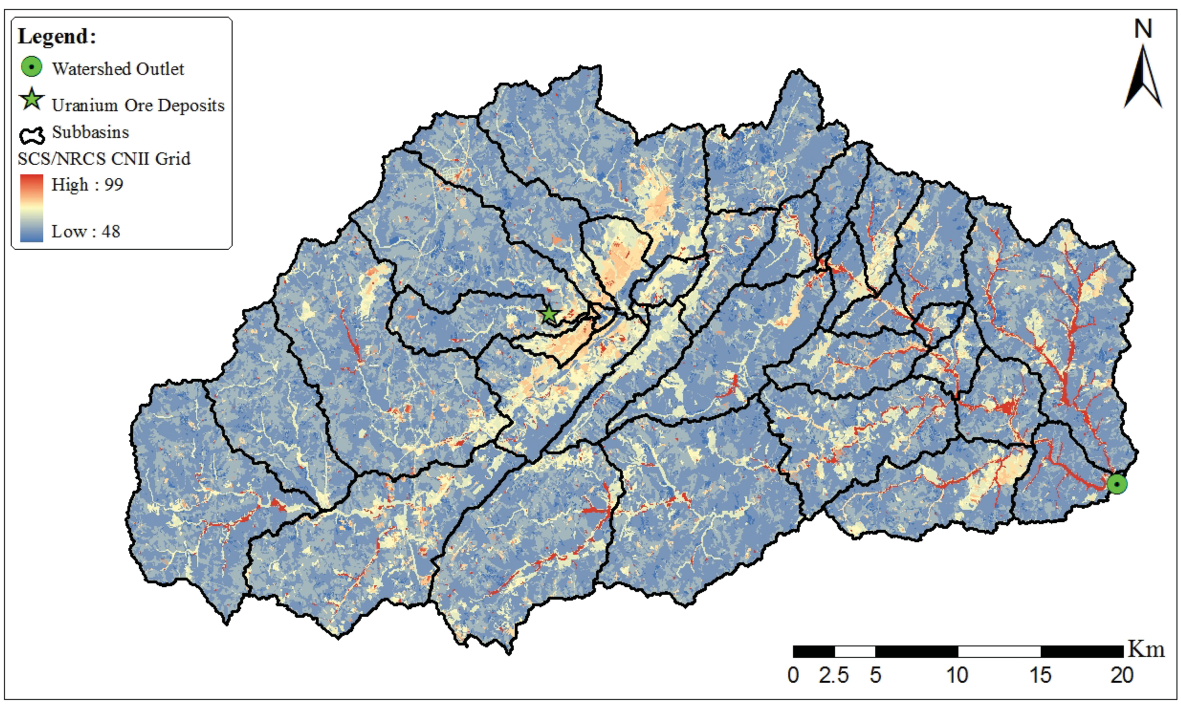

Figure 41: SCS/NRCS CN_{II} Grid for the Banister River Study Watershed

Similarly, Figure 42 and Figure 43 depict the CN_{III} grids that were generated for the Whitethorn and Banister analyses, respectively. For both, the ARC III CN results are considerably higher than those for ARC II, ranging from 68 to 99. For comparison purposes, all four CN grids are presented with the same color gradient (from 48 to 99).

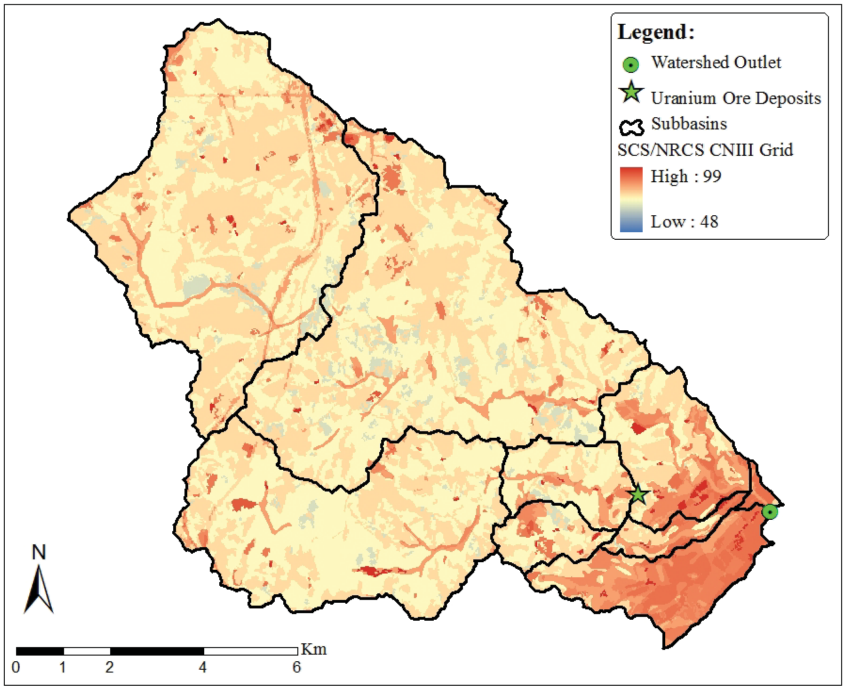

Figure 42: SCS/NRCS CN_{III} Grid for the Whitethorn Creek Study Watershed

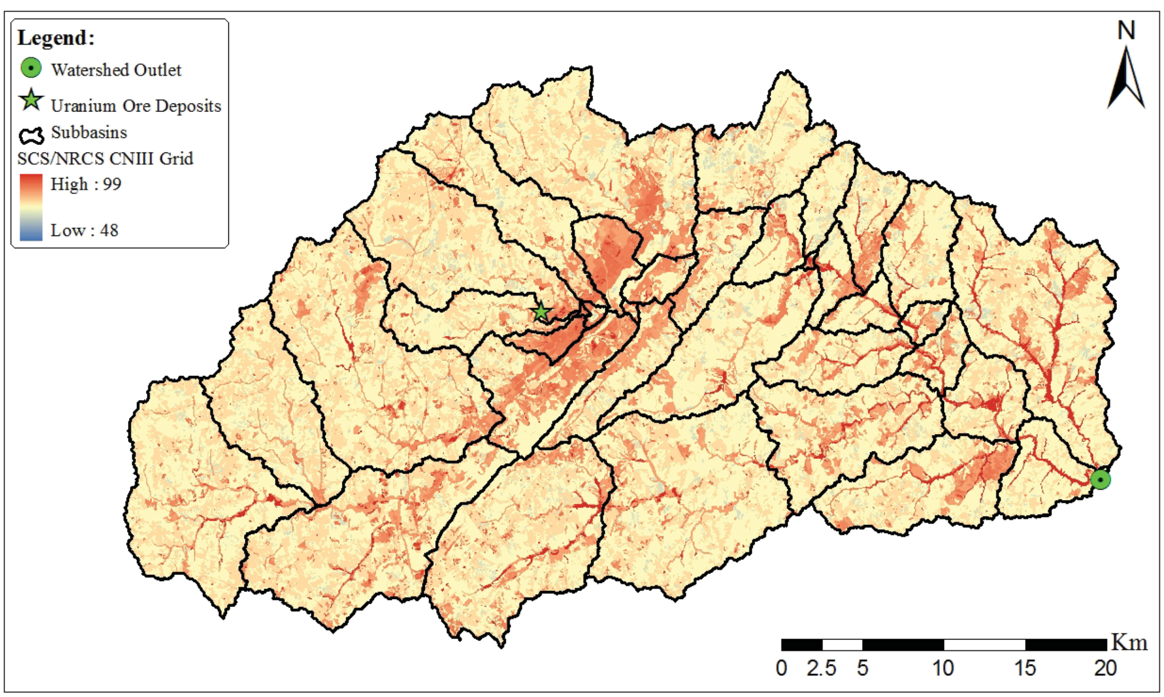

Figure 43: SCS/NRCS CN_{III} Grid for the Banister River Study Watershed

HEC-GeoHMS Main View 9 Processing Steps:

After the CN grids have been created, the procedure transitions over to utilizing the commands in the two HEC-GeoHMS toolbars. The first few steps in the construction of the .hms file involve data management and the creation of a new project.

1. Dataset Management

   The first step in the HMS Project Setup menu is Data Management. This function brings up a window in which the user must define all of the inputs that have been previously generated. The user must define the input features for: Raw DEM, Hydro DEM, Flow Direction Grid, Flow Accumulation Grid, Stream Grid, Stream Link Grid, Catchment Grid, Catchment feature class, and Adjoint Catchment feature class. Project Point and Project Area will be defined later.

2. Creating a New HMS Project

   Once the input grids have been confirmed, the next step is to start a new HMS project using the "Start New Project" function in the HMS Project Setup menu. This will bring up a window asking the user to provide a name for the project area and the project point. Once these are confirmed, a new window will appear in which the user must name the project, provide a description and the extraction method, and select where the file should be saved. For these analyses, the "Original Stream Definition" extraction method was chosen. Once the user confirms these inputs, two new feature classes are added to the map Table of Contents: Project Point and Project Area.

   Once these have been added, the watershed outlet point must be specified using the Project Point tool (denoted as the thumb tack image in the HEC-GeoHMS Main View 9 toolbar). This tool acts similar to the draw tool in editor. With this tool selected, the user must define the outlet point for the watershed of interest. For the Whitethorn analysis, the Project Point was chosen as just downstream of the confluence of Whitethorn Creek and Dry Branch, whereas for the Banister River analysis, the point was selected at the USGS stream gauging station downstream from the Banister Lake Dam. For each, the Project

Point was placed on the most downstream cell of the flow network that was just inside the study watershed boundary.

3. Generate Project

Once the Project Point has been specified, the "Generate Project" function must be selected from the HMS Project Setup menu. This function creates a mesh grid over the area corresponding to the drainage area to the Project Point specified in the previous step. Once the user confirms that this hatched area is the correct project area to use, a dialog box will appear asking the user to reconfirm all of the Terrain Preprocessing inputs. Once this step has been completed, a new data frame is added to the Table of Contents in ArcMap containing new subbasin and river files, as well as copies of all of the terrain preprocessing input files. The functions in the HEC-GeoHMS Project View 9 toolbar are utilized in this new data frame.

HEC-GeoHMS Project View 9 Processing Steps:

Similar to the Main View 9 and Arc Hydro Tools 9 toolbars, the HEC-GeoHMS Project View 9 toolbar contains a number of functions and operations which can be used to extract various basin characteristics, as well as complete the remaining processing steps needed to generate the final .hms file.

Basin Processing:

1. Merging Basins

This first step in the Project View 9 processing procedure involves the Basin Merge command in the Basin Processing menu. This command combines two or more adjacent basins into one, larger basin. This is useful if one or more of the study subwatersheds are comprised of more than one link delineated subbasins. If there is a very short stream link that has a basin associated with it, it may be desirable to combine it with one of the adjacent basins. The user must select the basins he/she wants to combine using the select tool in ArcGIS and select "Basin Merge" and the program will automatically combine them into one aggregate basin. For the

Whitethorn Creek Study Watershed, the threshold catchment method based on the 1 km^2 threshold stream segments generated 47 subbasins. Including all of these subbasins in the hydrologic model would have produced a very complex and complicated flow network. Even though a more detailed model would theoretically produce better results, the lack of actual stream or precipitation gauge data within the watershed makes it difficult to determine if all the simulated basins are performing correctly under given conditions. With so many subbasins and no accurate way to check if they are producing the desired results, there can be no assurance that the more complex model is acting any differently than a coarser model would. For this reason, the 47 subbasin configuration was simplified into the 10 subbasin configuration depicted in Figure 44. This layout of subcatchments has a finer resolution near the watershed outlet where the PMF modeling was done and a coarser resolution in the upper part of the watershed. Following the same procedure, Figure 45 shows the 37 merged subbasins that were generated from the original 133 threshold subbasins.

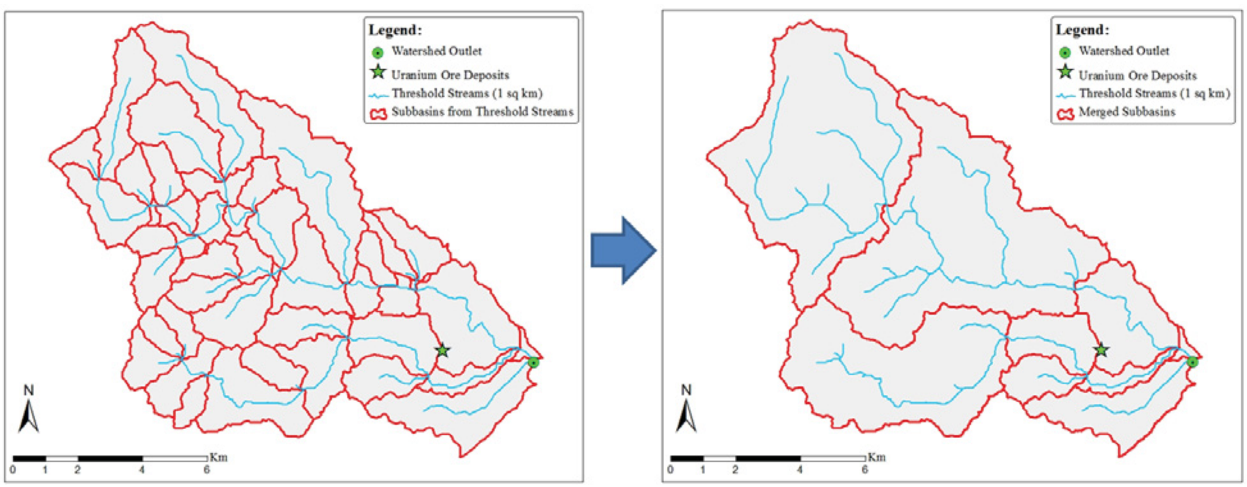

Figure 44: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Whitethorn Creek Study Watershed

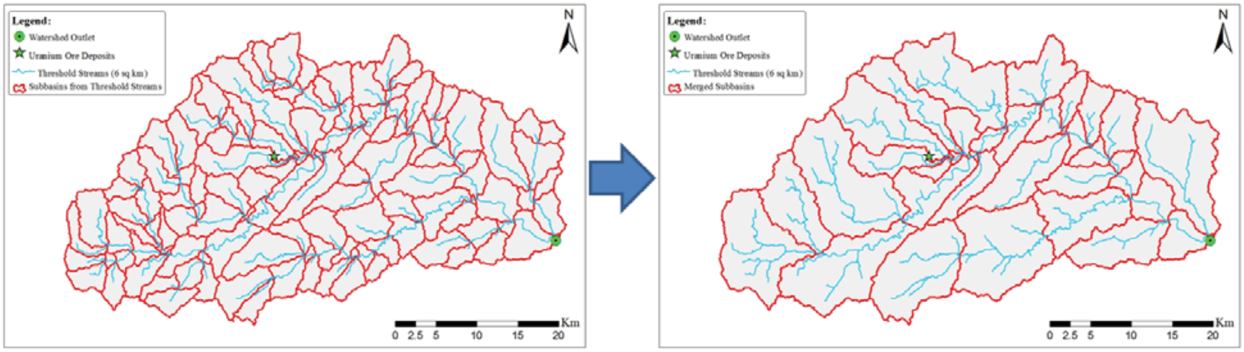

Figure 45: Threshold Stream Segment Catchments Merged into Simplified Composite Subbasins for HEC-HMS Modeling Purposes – Banister River Study Watershed

Basin Characteristics

The Basin Characteristics menu provides a number of useful analysis parameters for both the stream networks and the subwatersheds. These functions help to populate the attribute tables of both the river and subbasin feature classes used to build the HEC-HMS basin file.

1. River Length

   The first basin characteristic that can be extracted with HEC-GeoHMS is the river length in each of the subbasins. The river length function calculates the length of each stream link and adds the calculated lengths to the river attribute table (RivLen). This measurement is in map units (meters for this analysis). The only user input required is the river polyline file. It should be noted that this function does not automatically calculate the combined river length from the multiple segments in each of the merged subbasins. The user must manually merge adjacent threshold river segments from the drainage line feature class using Editor in ArcGIS. This should be done prior to calculating the river lengths using this command.

2. River Slope

   Once the river length has been calculated, the River Slope command can be run. The user must input the Raw DEM grid and the River feature class. Using the very basic slope equation *slope = (Upstream Elevation – Downstream Elevation) / River Length*, HEC-GeoHMS calculates the slope for each of the river segments in each of the watersheds.

The program then populates the attribute table of the river file with a slope, upstream elevation, and downstream elevation (Slp, ElevUP, ElevDS) for each stream segment.

3. Basin Slope

The Basin slope command calculates an average basin slope for each of the subwatersheds and uses that value to populate the BasinSlope field in the subbasin attribute table. For this command, the user must first generate a slope grid using the Surface Analysis toolbox in Spatial Analyst. This slope grid should be a percent slope grid. The inputs that must be defined for this operation are the subbasin feature class and the slope grid.

4. Longest Flow Path

The next command in the Basin Characteristics menu is the Longest Flow Path function. This command takes the raw DEM, the flow direction grid, and the subbasin feature class and creates a new output feature class that delineates the longest hydrologic flow path in each of the subwatersheds. These longest flow paths will start along one of the edges of the subwatershed and eventually run into the delineated river segment for that subbasin. This longest flow path is analogous to the Time of Concentration flow path using the NRCS segmental velocity method.

5. Basin Centroid

The Basin Centroid function will generate a basin centroid point for each of the subbasins using one of three methods. The Center of Gravity Method (used for this analysis) calculates the basin centroid as the center of gravity of each basin using an area-weighted approach. If the basin is shaped in such a way that this center of gravity lies outside of the basin, then the program moves it to the nearest edge of the basin. The Longest Flow Path Method assigns the centroid to the center point of the longest flow path. The 50% Area Method assigns the centroid to the point where there is 50 % of the area on either side of it. The subbasin feature class is the only required input file and the program outputs a centroid point file.

6. Basin Centroid Elevation

This function looks at the Raw DEM file and assigns an elevation value to each of the centroid points. HEC-GeoHMS automatically adds these elevation values to the attribute table of the centroid point file generated in the previous step.

7. Centroidal Flow Path

The Centroidal Longest Flow Path command creates a polyline feature class indicating the overland flow paths from each centroid point along the longest flow path. These lines are essentially marking the trajectory flow would travel along the longest flow path if it started at the centroid point. This command requires the user to define the subbasin feature class, the centroid point file, and the longest flow path polyline file and outputs a new polyline shape file.

HMS Inputs/Hydrologic Parameters

In order to start building the .hms file, the hydrologic parameters menu must be used to obtain the last bit of required information. These operations help populate some of the missing fields in the subbasin and river feature classes.

1. Select HMS Processes

The methods that HMS will use to transform rainfall to surface runoff, model losses and infiltration, and route flow through the system must be specified. Once the user confirms which subbasin and river feature classes to use, a new window will pop up in which the user can define the Loss Method, Transform Method, and Baseflow Method for the subbasins and the Routing Method for the reaches. The program has a number of choices for each of these fields, so the user must define which methods he/she believes to be best for the particular application. These inputs can be edited and changed later in HEC-HMS and different methods can be assigned to each element if needed. For these analyses, the SCS Curve Number Loss and the SCS Unit Hydrograph Transform were chosen as the Loss and Transform methods, respectively. In addition, the Baseflow Method was specified as “none” and the Routing Method was selected as Muskingum Routing.

Because the goal of this modeling was to determine the watershed response from a PMP event over a short period of time, baseflow was not modeled in the hydrologic models. However, a bankfull baseflow was considered as an initial condition in the HEC-RAS hydraulic models during the PMF simulations. In this way, the hydrologic models only simulated the direct runoff from the PMS.

2 & 3. River Auto Name and Basin Auto Name

These functions assign unique names to each of the river segments and each of the subbasins. The “Name” fields in the attribute tables are populated by a randomly assigned number. The river reaches will be assigned a number in the form of R## and the subbasins will be assigned a number in the form of W###. This function adds these names to the respective attribute tables. These unique identifiers are required by HEC-HMS when simulating storms over the basin file. The River file must be specified as the input file for the River Auto Name function and the Subbasin file must be specified as the input file for the Basin Auto Name function.

4. Subbasin Parameters

Each subbasin needs certain parameters for the HMS analysis based on the methods being used. For the SCS methods, the Curve Number grid must be specified as a subbasin parameter input. The only other input required for the SCS Method is the Subbasin file. All of the other input parameters can be left as the default “Null”. This function overlays the subbasin polygons over the CN grid and computes the area-weighted average curve number value for each basin. These values are automatically added to the Subbasin attribute table in the “BasinCN” field. This was done for both the CN_{II} and CN_{III} grids, however, only one can be utilized at a time. A basin file was first completed for the CN_{II} conditions and then a separate basin file was generated based on the CN_{III} conditions.

5. Curve Number Lag Method

This operation looks at the Subbasin and the Longest Flow Path feature classes and computes a basin lag in hours for each of the subbasins. These basin lags are somewhat of a weighted time of concentration measure and are generated using the NRCS Watershed Lag Equation:

$$\text{Lag} = \frac{\left(L^{0.8} * (S+1)^{0.7}\right)}{(1900 * Y^{0.5})} \tag{16}$$

Where:

- Lag = basin lag time (hrs)
- L = hydraulic length of the watershed (length of longest flow path) (ft)
- S = storage = (1000/CN) – 10 (in)
- Y = basin slope (%)

The lag times are added to the Subbasin feature class attribute table in the "BasinLag" field. As mentioned in the previous step, separate basin model analyses were carried out for the two ARCs that were considered and the lag times were calculated for each.

HMS

The HMS menu on the HEC-GeoHMS Project View 9 toolbar contains the final processing steps that must be carried out before the .hms model file is complete. These tools prepare and check the data to make sure that everything is compatible with HEC-HMS. The final conversions are made from this menu and the background maps, basin files, and meteorological files are generated here.

1. Map to HMS Units

Map to HMS Units converts units in both the River and Subbasin feature classes into the units used in the HEC-HMS model. All fields that have lengths or areas will gain a corresponding "_HMS" field in the attribute table as a result of the conversion. For this step, the user must specify the Raw DEM, the Subbasin feature class, the Longest Flow Path feature class, the Centroidal Longest Flow Path feature class, and the River and Centroid feature classes. Lastly, the user must specify the unit type for HMS Unit Conversion. For both analyses, a unit type of "English" was selected.

2. Check Data

The “Check Data” function checks to make sure that all the necessary inputs have been generated correctly to build the HMS model. A text file will be generated notifying the user if any errors were encountered. The user must confirm that the River, Subbasin, Project Points, and Centroid feature classes are correct. If any errors are detected, it is important for the user to go back and fix them before proceeding.

3. HMS Schematic

The HMS Schematic function creates a schematic network of basin elements (nodes/links or junctions/edges) and their connectivity. This is a GIS representation of the hydrologic system that will be used in HEC-HMS. The user must define the Project Points, Centroid, River, and Subbasin feature classes to be used and this command will output an HMS Link file and an HMS Node file. These files are what will be represented in HEC-HMS. The next command in the menu, Toggle HMS Legend, allows the user to preview what the system will look like once it is brought into HEC-HMS.

4. Add Coordinates

The “Add Coordinates” function attaches geographic coordinates to the components in the HMS Link and HMS Node feature classes that were created in the previous step. This preserves the geospatial information so that it is not lost when the schematic is exported to HEC-HMS or to some other program. The user must confirm the Raw DEM grid and the HMS Link and Node feature classes.

5. Prepare Data for Model Export

The purpose of this function is to prepare the HMS Link and HMS Node components to be exported. This operation must be completed before exporting the model or map file to HEC-HMS. The only inputs that the user must confirm are the Subbasin and River feature classes.

6. Background Map File

The "Background Map File" command identifies the geographic information associated with the subbasin boundaries and stream alignments and writes it into a text file that can be read and displayed in HMS. This file is saved to the same geodatabase as the rest of the project files.

7. Basin File

Once the Background Map File has been created, the next step is to generate the Basin File. The Basin File function exports the information associated with the hydrologic elements, their connectivity, and related geographic information into a text file that can be read and interpreted by HEC-HMS. This Basin File is saved in the same location as the Background Map File.

8. Meteorological Model

The final file that can be created is the Meteorological Model file which contains information on the weather and precipitation patterns that are to be used in the HEC-HMS model. There are four model options from which the user can choose: Subbasin Time Series, Design Gauge, Weighted Gauge, and Inverse Distance. For this analysis, the Subbasin Time Series was selected. The Subbasin Time Series function will create an empty meteorological model text file that will be populated later in HEC-HMS with the meteorological data for the study area. This model file is also saved in the same directory as the Basin File and Background Map File.

9. HMS Project Set-up

This function copies all of the project specific files that have been created to a specified directory and creates an .hms file that contains information from a number of input files. The user must choose a directory in which to store the .hms file. This command copies eight separate files, including the .basin, .map, and .met files, into the specified directory and uses them to build one .hms file which can be uploaded directly into HEC-HMS. Once this .hms file has been created, the model can be opened and manipulated in HEC-HMS directly without needing to interact with the GIS or HEC-GeoHMS.

Opening the Model in HEC-HMS

Once the user has installed and opened HEC-HMS, he/she can navigate to the directory containing the .hms file and open it. This should bring the Basin Models and Meteorological Models folders into the Watershed Explorer in HMS (Table of Contents window). To see the basin schematic and the characteristics of each component, the Basins Model folder must be expanded. When the user clicks on the basin model that has just been created, he/she will display the Study Watershed along with subbasins, streams, and junctions.

In order to display the background map underneath the schematic, the user can navigate to View in the top toolbar and then to Background Maps. The appropriate Background Map File can then be selected from this window and loaded into the HEC-HMS project window.

Once in the basin model, the user can click on any of the components in the watershed explorer to view or edit any of the attributes or methods that the model will use to run its routing calculations. The processes detailed above should have populated most of the fields required to run the model, however, some information, such as the reach travel times and attenuation capacity, cannot be obtained from spatial data and therefore must be manually calculated and entered. Screenshots of the Whitethorn Creek and Banister River basin files opened in HEC-HMS are shown in Figure 46 and Figure 47, respectively.

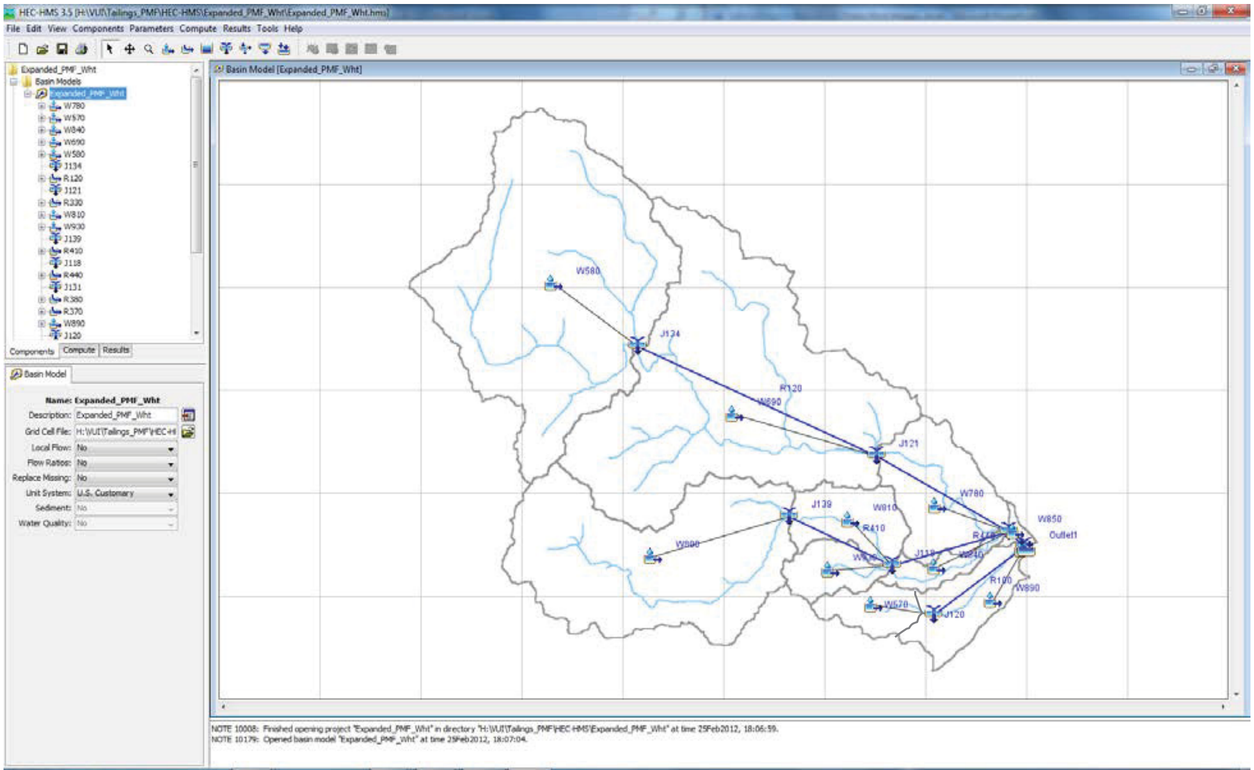

Figure 46: Whitethorn Creek Study Watershed Basin Model Open in HEC-HMS

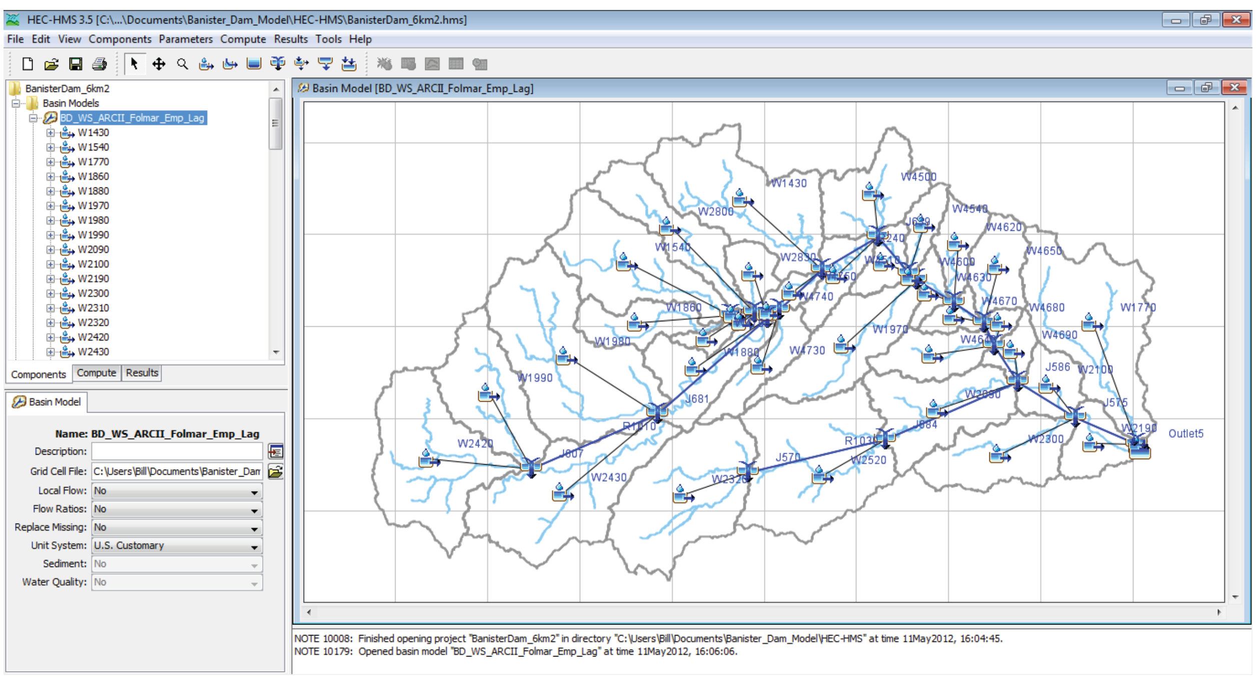

Figure 47: Banister River Study Watershed Basin Model Open in HEC-HMS

References:

Fleming, M. J., and Doan, J. H. (2010). *HEC-GeoHMS Geospatial Hydrologic Modeling Extension User's Manual (Version 5.0)*. Davis, CA: U.S. Army Corps of Engineers Hydrologic Engineering Center.

Merwade, V. (2010). "Creating SCS Curve Number Grid using HEC-GeoHMS." School of Civil Engineering, Purdue University, West Lafayette, IN. Available online at http://web.ics.purdue.edu/~vmerwade/education/cngrid.pdf.

Merwade, V. (2010). "HMS Model Development using HEC-GeoHMS." School of Civil Engineering, Purdue University, West Lafayette, IN. Available online at http://web.ics.purdue.edu/~vmerwade/ education/geohms.pdf.

Merwade, V. (2010). "Watershed and Stream Network Delineation." School of Civil Engineering, Purdue University, West Lafayette, IN. Available online at http://web.ics.purdue.edu/~vmerwade/ education/terrain_processing.pdf.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2007). *Part 630 Hydrology, National Engineering Handbook, Chapter 7: Hydrologic Soil Groups*. 210-VI-NEH, Washington, D.C.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (1986). *Technical Release 55: Urban Hydrology for Small Watersheds*. Washington, D.C.: US Government Printing Office.

Appendix B:

NOAA Atlas 14 Precipitation Frequency Data

To calibrate the basin models for these analyses, frequency storms were generated for each study watershed using available data obtained from NOAA's Atlas 14 Precipitation Frequency Data Server (PFDS). For both models, data were collected from five NOAA Atlas 14 rain gauging stations in and around the study areas. The PFDS data corresponding to the Chatham, VA, Danville, VA, Halifax, VA, Altavista, VA, and Brookneal, VA stations are presented in Table 24, Table 25, Table 26, Table 27, and Table 28, respectively. These data were obtained on April 4, 2012 and are representative of the partial duration precipitation depth series.

Table 24: Precipitation Frequency Estimates for the Chatham, VA PFDS Rain Gauging Station

PRECIPITATION FREQUENCY DEPTH ESTIMATES (in.) - CHATHAM, VA										
by duration for ARI:	1	2	5	10	25	50	100	200	500	1000 years
5-min:	0.36	0.43	0.51	0.56	0.63	0.68	0.72	0.76	0.81	0.84
10-min:	0.57	0.68	0.81	0.9	1.01	1.08	1.15	1.21	1.28	1.33
15-min:	0.71	0.86	1.03	1.14	1.28	1.36	1.45	1.52	1.61	1.67
30-min:	0.98	1.19	1.46	1.65	1.89	2.06	2.22	2.37	2.56	2.7
60-min:	1.22	1.49	1.87	2.15	2.52	2.79	3.06	3.33	3.67	3.94
2-hr:	1.45	1.77	2.24	2.6	3.08	3.46	3.86	4.25	4.79	5.21
3-hr:	1.56	1.91	2.41	2.79	3.32	3.72	4.15	4.57	5.14	5.59
6-hr:	1.93	2.34	2.95	3.44	4.13	4.69	5.28	5.9	6.78	7.48
12-hr:	2.33	2.83	3.59	4.23	5.14	5.9	6.73	7.62	8.94	10.03
24-hr:	2.8	3.4	4.33	5.13	6.3	7.29	8.38	9.59	11.37	12.88
2-day:	3.32	4.02	5.1	5.98	7.26	8.34	9.49	10.73	12.54	14.05
3-day:	3.5	4.24	5.38	6.31	7.66	8.79	9.99	11.3	13.2	14.78
4-day:	3.69	4.47	5.66	6.64	8.05	9.23	10.5	11.87	13.85	15.5
7-day:	4.23	5.08	6.34	7.38	8.86	10.08	11.39	12.79	14.79	16.44
10-day:	4.79	5.74	7.08	8.17	9.7	10.94	12.26	13.64	15.59	17.16
20-day:	6.45	7.69	9.28	10.53	12.23	13.58	14.93	16.32	18.19	19.65
30-day:	7.97	9.45	11.16	12.46	14.17	15.46	16.72	17.95	19.57	20.78
45-day:	10.03	11.84	13.82	15.31	17.21	18.64	19.99	21.3	22.98	24.2
60-day:	11.95	14.04	16.19	17.8	19.85	21.36	22.79	24.14	25.86	27.1

Table 25: Precipitation Frequency Estimates for the Danville, VA PFDS Rain Gauging Station

PRECIPITATION FREQUENCY DEPTH ESTIMATES (in.) - DANVILLE, VA										
by duration for ARI:	1	2	5	10	25	50	100	200	500	1000 years
5-min:	0.37	0.44	0.52	0.57	0.64	0.68	0.72	0.76	0.8	0.83
10-min:	0.59	0.7	0.83	0.92	1.02	1.08	1.15	1.2	1.27	1.31
15-min:	0.73	0.88	1.05	1.16	1.29	1.37	1.45	1.52	1.59	1.64
30-min:	1.01	1.22	1.49	1.68	1.91	2.07	2.22	2.36	2.54	2.66
60-min:	1.25	1.53	1.91	2.19	2.54	2.8	3.06	3.31	3.64	3.88
2-hr:	1.48	1.8	2.26	2.62	3.09	3.46	3.83	4.2	4.71	5.1
3-hr:	1.58	1.93	2.43	2.81	3.32	3.71	4.11	4.51	5.05	5.46
6-hr:	1.94	2.35	2.96	3.44	4.11	4.64	5.21	5.79	6.62	7.26
12-hr:	2.33	2.83	3.57	4.19	5.07	5.79	6.58	7.42	8.63	9.63
24-hr:	2.75	3.33	4.23	4.97	6.05	6.96	7.94	9.01	10.57	11.88
2-day:	3.25	3.92	4.94	5.77	6.94	7.91	8.95	10.06	11.64	12.96
3-day:	3.42	4.14	5.21	6.08	7.32	8.34	9.43	10.59	12.26	13.63
4-day:	3.6	4.35	5.47	6.39	7.69	8.76	9.9	11.12	12.87	14.3
7-day:	4.13	4.96	6.14	7.11	8.48	9.6	10.79	12.05	13.83	15.29
10-day:	4.68	5.59	6.85	7.87	9.29	10.44	11.64	12.89	14.65	16.05
20-day:	6.3	7.5	9.01	10.2	11.82	13.1	14.39	15.71	17.49	18.88
30-day:	7.79	9.21	10.84	12.08	13.71	14.95	16.16	17.35	18.91	20.08
45-day:	9.85	11.6	13.49	14.91	16.75	18.13	19.46	20.74	22.39	23.59
60-day:	11.77	13.81	15.85	17.37	19.33	20.77	22.14	23.45	25.09	26.27

Table 26: Precipitation Frequency Estimates for the Halifax, VA PFDS Rain Gauging Station

PRECIPITATION FREQUENCY DEPTH ESTIMATES (in.) - HALIFAX, VA										
by duration for ARI:	1	2	5	10	25	50	100	200	500	1000 years
5-min:	0.37	0.44	0.51	0.57	0.64	0.68	0.73	0.77	0.81	0.84
10-min:	0.58	0.7	0.82	0.91	1.02	1.09	1.16	1.21	1.28	1.33
15-min:	0.73	0.88	1.04	1.15	1.29	1.38	1.46	1.53	1.62	1.67
30-min:	1	1.21	1.48	1.67	1.91	2.08	2.24	2.38	2.57	2.71
60-min:	1.25	1.52	1.89	2.18	2.54	2.81	3.08	3.35	3.69	3.95
2-hr:	1.48	1.79	2.25	2.62	3.1	3.48	3.87	4.26	4.79	5.21
3-hr:	1.58	1.92	2.41	2.8	3.32	3.73	4.15	4.57	5.14	5.58
6-hr:	1.93	2.33	2.93	3.42	4.09	4.65	5.24	5.84	6.7	7.39
12-hr:	2.31	2.8	3.53	4.16	5.04	5.79	6.59	7.45	8.71	9.76
24-hr:	2.69	3.25	4.14	4.89	5.99	6.93	7.95	9.07	10.73	12.12
2-day:	3.16	3.82	4.84	5.67	6.88	7.88	8.95	10.11	11.77	13.16
3-day:	3.34	4.04	5.11	5.99	7.26	8.31	9.44	10.65	12.4	13.86
4-day:	3.52	4.25	5.38	6.31	7.64	8.74	9.93	11.2	13.03	14.55
7-day:	4.05	4.87	6.06	7.04	8.44	9.59	10.82	12.13	14	15.53
10-day:	4.6	5.51	6.78	7.81	9.26	10.45	11.68	12.98	14.81	16.28
20-day:	6.21	7.39	8.92	10.12	11.75	13.03	14.33	15.65	17.44	18.82
30-day:	7.67	9.09	10.72	11.97	13.6	14.84	16.04	17.22	18.75	19.9
45-day:	9.69	11.43	13.34	14.77	16.6	17.96	19.28	20.53	22.14	23.31
60-day:	11.56	13.59	15.66	17.21	19.18	20.63	22	23.31	24.95	26.12

Table 27: Precipitation Frequency Estimates for the Altavista, VA PFDS Rain Gauging Station

PRECIPITATION FREQUENCY DEPTH ESTIMATES (in.) - ALTAVISTA, VA										
by duration for ARI:	1	2	5	10	25	50	100	200	500	1000 years
5-min:	0.35	0.41	0.49	0.55	0.62	0.66	0.71	0.75	0.8	0.83
10-min:	0.56	0.66	0.79	0.88	0.98	1.06	1.13	1.19	1.26	1.31
15-min:	0.69	0.83	1	1.11	1.25	1.34	1.43	1.5	1.59	1.65
30-min:	0.95	1.15	1.42	1.61	1.85	2.02	2.19	2.34	2.53	2.67
60-min:	1.19	1.45	1.82	2.1	2.46	2.73	3.01	3.28	3.63	3.9
2-hr:	1.4	1.7	2.15	2.51	2.98	3.36	3.75	4.14	4.68	5.1
3-hr:	1.49	1.82	2.3	2.68	3.19	3.59	4	4.42	4.99	5.43
6-hr:	1.85	2.24	2.83	3.31	3.98	4.53	5.11	5.72	6.59	7.28
12-hr:	2.25	2.72	3.45	4.07	4.96	5.71	6.53	7.4	8.69	9.77
24-hr:	2.72	3.29	4.2	4.98	6.12	7.1	8.17	9.35	11.1	12.59
2-day:	3.22	3.89	4.94	5.81	7.07	8.12	9.25	10.48	12.25	13.73
3-day:	3.4	4.12	5.22	6.14	7.46	8.57	9.76	11.05	12.9	14.46
4-day:	3.58	4.34	5.5	6.47	7.86	9.02	10.27	11.62	13.56	15.18
7-day:	4.13	4.97	6.2	7.22	8.68	9.89	11.18	12.55	14.53	16.16
10-day:	4.69	5.62	6.93	8.01	9.51	10.74	12.04	13.4	15.32	16.87
20-day:	6.3	7.51	9.07	10.3	11.97	13.29	14.62	15.97	17.8	19.22
30-day:	7.76	9.2	10.88	12.15	13.82	15.07	16.3	17.51	19.07	20.23
45-day:	9.74	11.51	13.45	14.9	16.75	18.14	19.45	20.72	22.32	23.5
60-day:	11.6	13.65	15.74	17.32	19.32	20.8	22.19	23.52	25.18	26.36

Table 28: Precipitation Frequency Estimates for the Brookneal, VA PFDS Rain Gauging Station

PRECIPITATION FREQUENCY DEPTH ESTIMATES (in.) - BROOKNEAL, VA										
by duration for ARI:	1	2	5	10	25	50	100	200	500	1000 years
5-min:	0.35	0.42	0.5	0.55	0.62	0.67	0.72	0.76	0.81	0.85
10-min:	0.56	0.67	0.79	0.89	0.99	1.07	1.14	1.2	1.28	1.33
15-min:	0.7	0.84	1	1.12	1.26	1.35	1.44	1.52	1.61	1.68
30-min:	0.96	1.16	1.43	1.62	1.86	2.04	2.21	2.37	2.56	2.71
60-min:	1.2	1.46	1.83	2.12	2.48	2.76	3.04	3.32	3.68	3.96
2-hr:	1.42	1.72	2.17	2.54	3.02	3.4	3.8	4.21	4.75	5.19
3-hr:	1.52	1.84	2.32	2.71	3.23	3.64	4.06	4.49	5.07	5.53
6-hr:	1.87	2.26	2.85	3.34	4.01	4.58	5.17	5.8	6.68	7.4
12-hr:	2.27	2.75	3.47	4.1	5	5.76	6.6	7.49	8.79	9.9
24-hr:	2.72	3.29	4.21	4.98	6.13	7.11	8.19	9.37	11.13	12.61
2-day:	3.21	3.89	4.93	5.8	7.06	8.11	9.24	10.47	12.24	13.72
3-day:	3.4	4.11	5.22	6.14	7.46	8.57	9.76	11.05	12.92	14.47
4-day:	3.59	4.34	5.51	6.47	7.87	9.03	10.29	11.64	13.59	15.22
7-day:	4.14	4.98	6.21	7.24	8.7	9.92	11.22	12.6	14.59	16.22
10-day:	4.7	5.63	6.96	8.03	9.54	10.78	12.08	13.46	15.39	16.95
20-day:	6.33	7.54	9.11	10.34	12.03	13.35	14.68	16.05	17.89	19.32
30-day:	7.8	9.24	10.93	12.2	13.88	15.14	16.38	17.58	19.15	20.32
45-day:	9.79	11.56	13.51	14.97	16.83	18.22	19.54	20.82	22.43	23.62
60-day:	11.65	13.71	15.83	17.42	19.43	20.92	22.32	23.66	25.33	26.53

Table 29: Areally-Weighted Average PF Estimates of the Banister River Study Watershed – Obtained with Thiessen Polygon Interpolation Scheme

Areally-Averaged PFDS Precipitation Frequency Estimates (in.) - Banister RiverAnalysis										
by duration for ARI:	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	500-yr	1000-yr
5-min:	0.36	0.43	0.51	0.56	0.63	0.68	0.72	0.76	0.81	0.84
10-min:	0.57	0.68	0.81	0.90	1.01	1.08	1.15	1.21	1.28	1.33
15-min:	0.71	0.86	1.03	1.14	1.28	1.36	1.45	1.52	1.61	1.67
30-min:	0.98	1.19	1.46	1.65	1.89	2.06	2.22	2.37	2.56	2.70
60-min:	1.22	1.49	1.87	2.15	2.51	2.78	3.06	3.33	3.67	3.93
2-hr:	1.45	1.76	2.22	2.59	3.07	3.45	3.84	4.23	4.77	5.19
3-hr:	1.55	1.89	2.39	2.77	3.29	3.70	4.12	4.54	5.11	5.56
6-hr:	1.91	2.32	2.92	3.41	4.09	4.65	5.24	5.85	6.72	7.42
12-hr:	2.31	2.80	3.55	4.18	5.08	5.84	6.66	7.54	8.83	9.91
24-hr:	2.76	3.34	4.26	5.04	6.19	7.16	8.23	9.41	11.16	12.64
2-day:	3.26	3.95	5.00	5.87	7.13	8.18	9.31	10.53	12.29	13.77
3-day:	3.44	4.17	5.28	6.20	7.52	8.63	9.81	11.09	12.94	14.49
4-day:	3.63	4.39	5.56	6.53	7.91	9.07	10.31	11.66	13.59	15.20
7-day:	4.17	5.01	6.24	7.27	8.72	9.92	11.21	12.58	14.54	16.16
10-day:	4.72	5.66	6.98	8.05	9.56	10.78	12.07	13.43	15.35	16.89
20-day:	6.36	7.58	9.15	10.38	12.06	13.39	14.72	16.09	17.93	19.36
30-day:	7.86	9.31	11.00	12.28	13.96	15.23	16.47	17.69	19.27	20.46
45-day:	9.89	11.68	13.63	15.10	16.97	18.38	19.71	21.00	22.65	23.85
60-day:	11.79	13.85	15.97	17.56	19.58	21.07	22.48	23.82	25.50	26.72

Appendix C:

Development of the PMP/PMS for the Study Watershed Following the HMR Methodology

- **Whitethorn Creek Study Watershed**
- **Banister River Study Watershed**

Appendix C

C. TABLE OF CONTENTS

Overview..139

Stepwise Procedure for Determining PMP Values:..140

A. 6-Hr Incremental PMP (refer to HMR No. 51).. 140

B. Isohyetal Pattern.. 151

C. Maximum Precipitation Volume.. 158

D. Distribution of Storm-Area Averaged PMP over the Drainage.. 181

E. Temporal Distribution.. 192

Conclusion: 195

References:..196

Determination of PMP/PMS Using the Hydrometeorological Report 51 & 52 Methodology:

The Probable Maximum Storms (PMS) for both the Whitethorn Creek and Banister River studies were developed following the stepwise procedure outlined in Chapter 7 of HMR52. HMR52 (Hansen et al., 1982), created as part of the Hydrometeorological Branch studies, details the process to obtain the temporal and spatial distribution of PMP estimates derived from HMR51, "Probable Maximum Precipitation Estimates - United States East of the 105th Meridian" (Schreiner & Riedel, 1978). Included within HMR52 are discussions regarding the analysis of past major rainfalls of record. These events were used by the authors to develop generalizations about the behavior of very severe storms. From these observations, the NWS has made recommendations regarding the PMS and how to model PMP events, suggesting storm shapes, orientations, and rainfall patterns, among other things.

Unlike HMR51, which gave point PMP depths for a specific storm area and duration, HMR52 outlines how to take the point values and convert them into a spatially distributed storm pattern that covers an entire watershed. Using a series of ellipses with a common center and orientation, a storm is built, assigning each ellipse, or isohyet, a scaled value of the HMR51 point PMP depth. In this way, whole drainages can be covered and aerial reductions can be applied so as to emulate real world conditions with intense rainfall at a storm's center that dissipates as the storm extends out spatially.

The rest of this Appendix details the stepwise procedure followed for both PMP/PMS analyses. As both studies utilized the same development approach, step-by-step results from each procedure are presented simultaneously in this Appendix. For each step of the procedure, the instructional text from Chapter 7 of HMR52 has been reproduced and is written in italics. After the HMR52 text for each step is a discussion of how the step was applied to the study watersheds and what the results from each step were. In this way, a reader can see what must be done in each step and then see how it was carried out for the Whitethorn Creek and Banister River analyses. For the Banister study, four separate PMP/PMS procedures were carried out; however, this Appendix only details the final configuration that was selected (maximum 72-hr PMP out of the four storm patterns evaluated).

Stepwise Procedure for Determining PMP Values:

A. 6-Hr Incremental PMP (refer to HMR No. 51)

Step:

1. *Obtain Depth-Area-Duration (D-A-D) data from figures 18 through 47 in HMR No. 51 for the location of the drainage. Location is customarily judged at or near the center of the drainage. For particularly large drainages in which isohyetal pattern placements may be made at considerable distance from the drainage center, the location of the pattern center should be used to obtain the appropriate D-A-D data.*

For the purpose of the Whitethorn Creek study, the Depth-Area-Duration (D-A-D) data was collected for a point corresponding to the "center of gravity" (area-weighted geometric centroid) of the Whitethorn Creek Study Watershed (approximately 4.8 km (3 mi) northwest of the Coles Hill site). This point was selected so that the PMP storm would be centered over the watershed. This would theoretically generate the highest flow rates in the watershed because the most intense rainfall occurs at the storm's center.

For the Banister River Analysis, a slightly different approach was adopted. Because this study involves a worst-case sediment transport analysis resulting from a breach in a containment structure, D-A-D values were gathered for an area corresponding to the Coles Hill site. It was desired to center the storm at or near to the project site so that the cell failure and initiation of sediment transport would occur in the location receiving the most intense rainfall from the PMS.

To obtain the D-A-D amounts, the digitized HMR51 PMP gridded maps available at http://www.weather.gov/oh/hdsc/studies/pmp.html were used. As recommended in HMR51, four out of the six drainage area sizes were evaluated from these gridded maps (10, 200, 1000, and 5000 mi^2). These four area sizes represent the four closest areas to the basin size that is being evaluated (41.2 mi^2). For these four area sizes, all five temporal scales were evaluated (6-hr, 12-hr, 24-hr, 48-hr, and 72-hr). The twenty gridded maps representing the twenty combinations of drainage area and storm duration were brought into ArcGIS. This enabled the maps to be overlain on the study basins so that the all-season PMP depths could be pulled off from each. During this process, it was discovered that the NWS digitized maps for the first two combinations (10 mi^2 6-hr and 10 mi^2 12-hr) were projected incorrectly so values for these two combinations were taken by scaling/interpolating off of the original paper maps found in HMR51. The remaining eighteen PMP depths were extracted from the digital maps and checked against the paper maps to ensure consistency. The D-A-D data for these twenty combinations at the Whitethorn Creek basin centroid are shown in Table 30, whereas

Table 31 shows the D-A-D values for the Banister River study.

Table 30: D-A-D Data for Whitethorn Creek Study Watershed

Area (mi2)	PMP Depth (in.)				
	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
10	28.86	34.25	38.30	42.32	44.08
200	20.60	24.67	28.90	32.75	34.50
1000	15.07	19.34	23.97	26.73	28.07
5000	9.02	12.54	16.17	19.95	20.98

Table 31: D-A-D Data for Banister River Study Watershed

Area (mi2)	PMP Depth (in.)				
	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
10	28.86	34.25	38.31	42.36	44.12
200	20.61	24.67	28.92	32.79	34.53
1000	15.08	19.34	23.98	26.76	28.11
5000	9.02	12.54	16.18	19.96	20.99

2. *Plot the data in step A1 on semi-logarithmic paper (area on the log scale) and join points of common duration with curves. When drawing a smooth set of curves, we recommend that the curves be adjusted to assure that they are either parallel or show slight convergence with increasing area size; i.e., the largest incremental differences occur at 10 mi^2, and the smallest incremental differences occur at 20000 mi^2 in HMR No. 51.*

The data from A1 was plotted on a semi-logarithmic scale and can be seen if Figure 48 and Figure 49 for the two analyses. Each data set represents a common duration and the data points have been connected with a smooth line in Microsoft Excel.

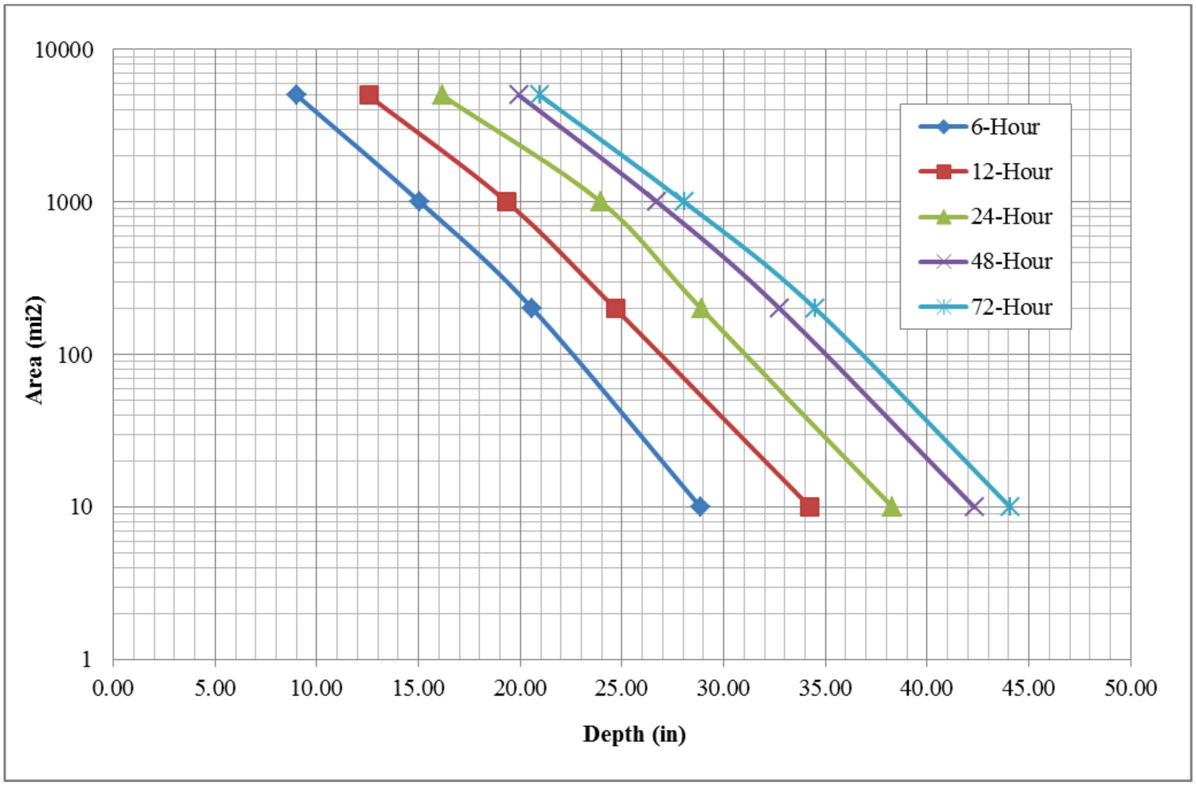

Figure 48: Depth-Area-Duration Curves for the Whitethorn Creek Study Watershed

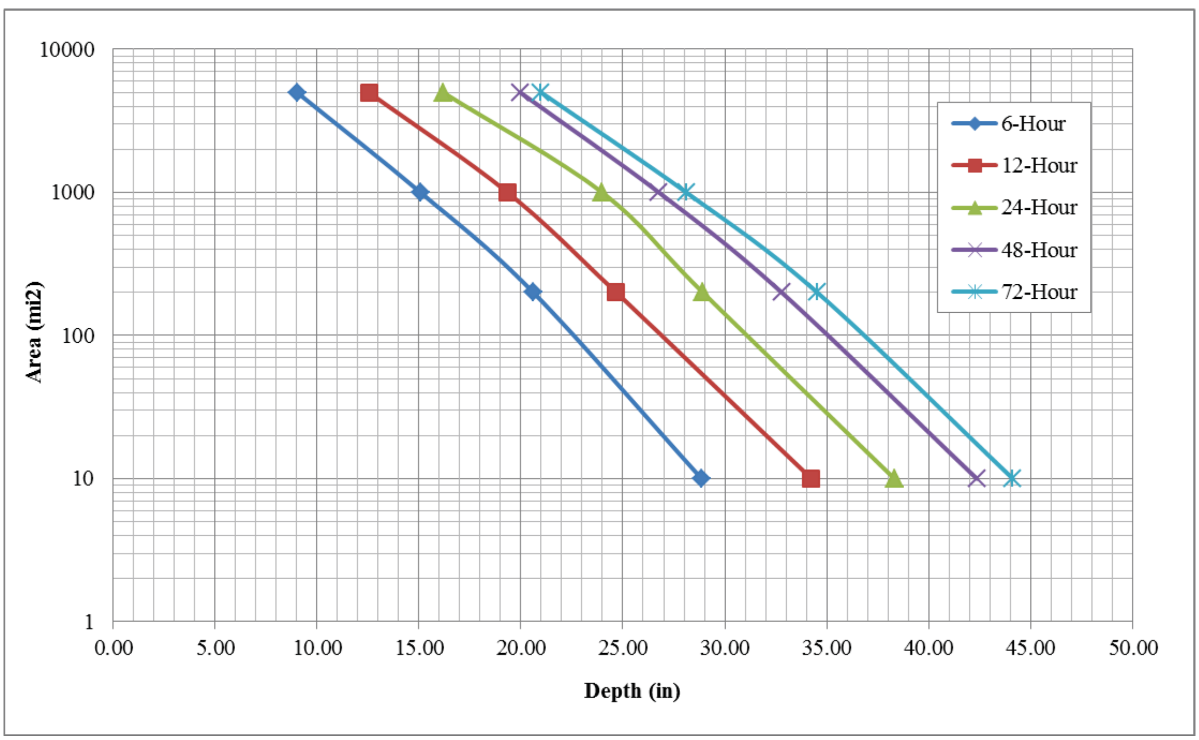

Figure 49: Depth-Area-Duration Curves for the Banister River Study Watershed

3. *From the curves in step A2, read off D-A-D values for a set of standard isohyet area sizes both larger and smaller than the area size of the specific drainage. Where possible, it is recommended that at least 4 pattern area sizes larger and smaller be used to adequately enclose the area size corresponding to maximum precipitation volume (see step C11).*

From Figure 48 and Figure 49, D-A-D values were obtained for the first six standard isohyet area sizes (10, 25, 50, 100, 175, and 300 mi^2) for the Whitethorn Creek study and for the first eleven standard isohyet area sizes (10, 25, 50, 100, 175, 300, 450, 700, 1000, 1500, and 2150 mi^2) for the Banister River study. This was accomplished by drawing horizontal lines on Figure 48 and Figure 49 corresponding to these isohyet areas and reading off the values where the standard area lines intersected the duration curves. These data can be seen in Table 32 and Table 33.

Table 32: D-A-D Values for Standard Isohyets – Whitethorn Creek Analysis

Isohyet Area (mi^2)	Storm Duration/D-A-D Values (in.)				
	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
10	28.86	34.25	38.30	42.32	44.08
25	26.40	31.34	35.43	39.43	41.23
50	24.51	29.14	33.26	37.26	39.03
100	22.57	26.91	31.09	35.06	36.80
175	21.00	25.14	29.31	33.20	34.97
300	19.3	23.4	27.7	31.4	33.1

Table 33: D-A-D Values for Standard Isohyets – Banister River Analysis

Isohyet Area (mi^2)	Storm Duration/D-A-D Values (in.)				
	6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
10	28.86	34.25	38.31	42.36	44.12
25	26.40	31.40	35.40	39.50	41.20
50	24.50	29.10	33.30	37.30	39.10
100	22.60	26.90	31.10	35.10	36.80
175	21.00	25.10	29.30	33.20	35.00
300	19.4	23.4	27.7	31.4	33.1
450	18	22.1	26.5	29.9	32.5
700	16.4	20.6	25.3	28.2	29.6
1000	15.08	19.34	23.98	26.76	28.11
1500	13.5	17.7	22.2	25.1	26.4
2150	12.2	16.2	20.5	23.5	24.7

4. *For each of the pattern area sizes selected in step A3, plot the depth-duration data (at least to 48-hr) on linear paper and fit a smooth curve to enable interpolation of values for the 18-hr duration.*

The values from Table 32 and Table 33 were plotted on a linear scale and smooth curves were fit through the data points of similar area sizes (Figure 50 and Figure 51). From these curves, values for the 18-hr duration were obtained for each area size for each analysis by reading off the depths where the 18-hr duration line crossed each of the curves. These 18-hr duration depths for both studies are shown in Table 34.

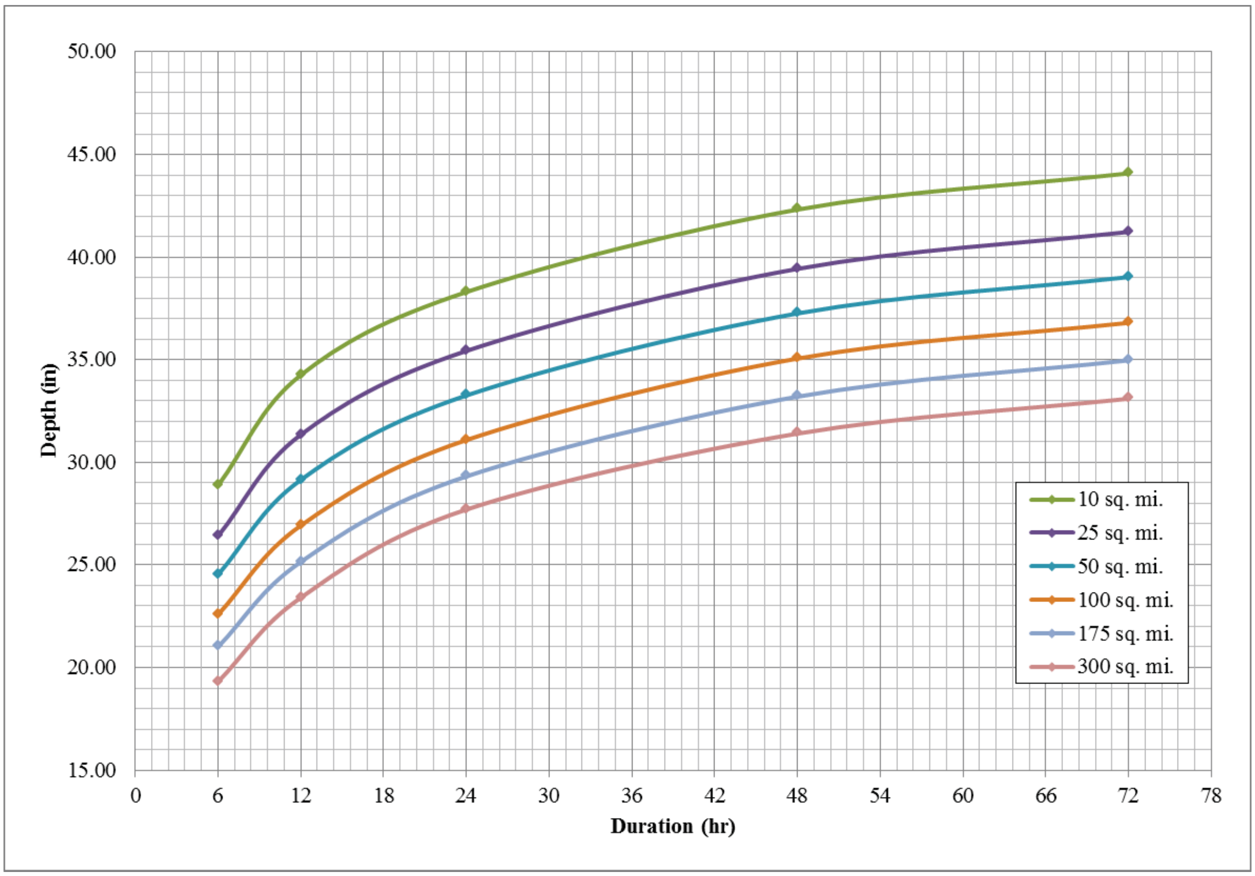

Figure 50: Depth-Duration Curves for Selected Area Sizes for the Whitethorn Creek Study Watershed

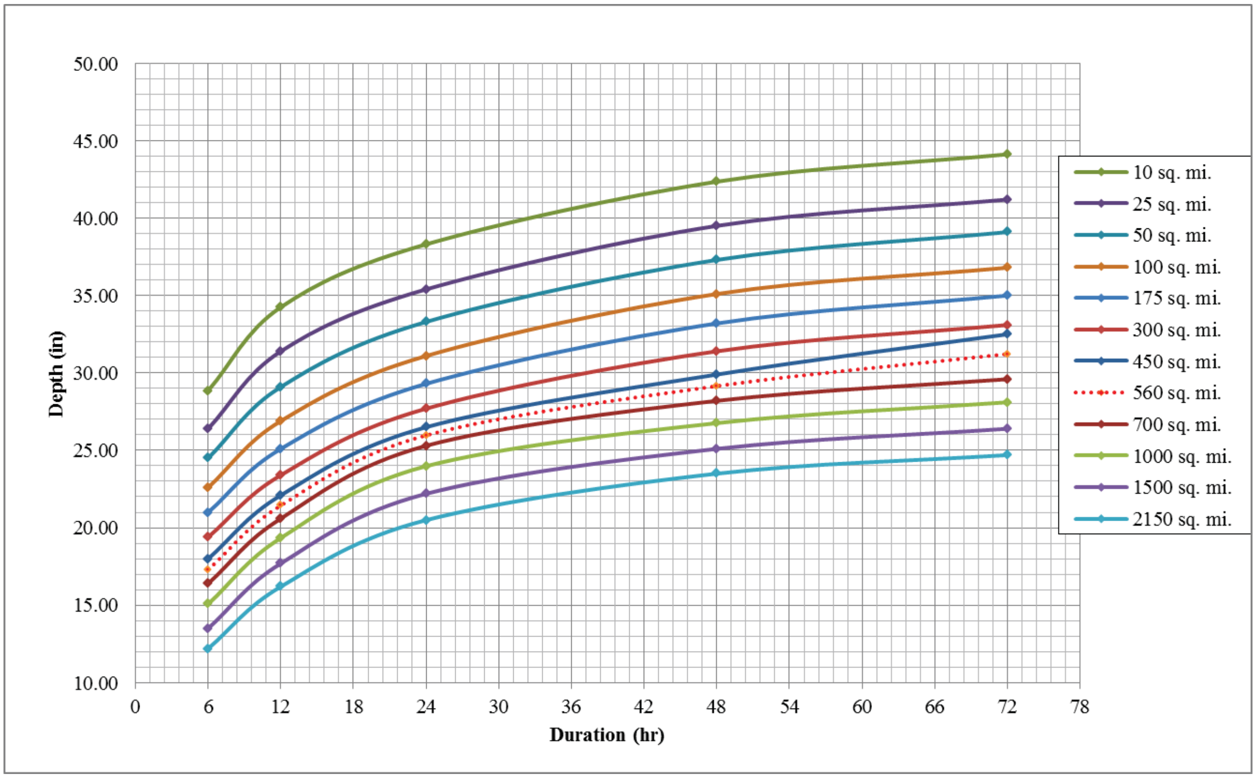

Figure 51: Depth-Duration Curves for Selected Area Sizes for the Banister River Study Watershed

Table 34: 18-hr D-A-D Data for Standard Isohyets

Isohyet Area (mi2)	Whitethorn Creek 18-Hour D-A-D Value (in.)	Banister River 18-Hour D-A-D Value (in.)
10	36.75	36.70
25	33.83	33.80
50	31.63	31.70
100	29.42	29.40
175	27.63	27.60
300	26.00	26.00
450	- - -	24.8
700	- - -	23.5
1000	- - -	22.2
1500	- - -	20.5
2150	- - -	18.8

5. *Obtain incremental differences for each of the first three 6-hr periods (0 to 6, 6 to 12, and 12 to 18-hr) through successive subtraction for each area size considered in step A4. Because of possible inaccuracies in reading the map analyses, plotting, and drawing for the data in the preceding steps, the 6-hr incremental values should also be plotted (on semi-log paper) and smoothed to insure a consistent data set. Incremental data should decrease or remain constant with increases in both duration and pattern area size. In drawing these final smoothing curves choose a scale for the abscissa (incremental depths) that allows values from curves to be read off to the nearest hundredth.*

Once the 18-hr D-A-D values were obtained, the incremental differences were calculated for the first three 6-hr periods. For the first 6-hr period (0 to 6-hr), the incremental differences are equal to the values in Table 32 and Table 33 for the 6-hr duration. For the second and third 6-hr periods, the incremental differences are obtained through successive subtraction (12-hr value from Table 32 and Table 33 minus 6-hr value from Table 32 and Table 33 and 18-hr value from Table 34 minus 12-hr value from Table 32 and Table 33, respectively).

HMR52 states that these depths should decrease in each column as area increases as well as decrease from period 1 to period 3 for constant areas. Looking at the data presented in Table 35 and Table 36, it can be seen that a few of the values do not follow this trend (denoted by the red values). To alleviate this problem, HMR52 suggest that the data be plotted on semi-logarithmic paper and then smoothing techniques be applied until the data displays the decreasing trend or remains at a constant value.

Table 35: Incremental Differences between the First Three 6-hr Periods – Whitethorn Creek Analysis

Area (mi^2)	6-Hour Periods/Incremental Differences (in.)		
	1 (0-6)	2 (6-12)	3 (12-18)
10	28.86	5.39	2.50
25	26.40	4.94	2.49
50	24.51	4.63	2.49
100	22.57	4.34	2.51
175	21.00	4.14	2.49
300	19.30	4.10	2.60

Table 36: Incremental Differences between the First Three 6-hr Periods – Banister River Analysis

Area (mi^2)	6-Hour Periods/Incremental Differences (in.)		
	1 (0-6)	2 (6-12)	3 (12-18)
10	28.86	5.39	2.45
25	26.40	5.00	2.40
50	24.50	4.60	2.60
100	22.60	4.30	2.50
175	21.00	4.10	2.50
300	19.40	4.00	2.60
450	18.00	4.10	2.70
700	16.40	4.20	2.90
1000	15.08	4.27	2.86
1500	13.50	4.20	2.80
2150	12.20	4.00	2.60

Even if the data follows the proper decreasing trend, HMR52 still recommends smoothing the data. To accomplish this, exponential trendlines were fit to the data for the first and second 6-hr periods, as can be seen in Figure 52 and in Figure 53 for the Whitethorn Creek analysis and in Figure 54 and Figure 55 for the Banister River analysis.

The equations of these lines (shown on the figures) have reasonably high coefficients of determination (R^2) and so were deemed appropriate smoothing lines. For the second 6-hr period for both analyses, the smoothing line was only applied to a portion of data: the first five area sizes for the Whitethorn and the first six area sizes for the Banister. This was done to improve the fit for the rest of the points. The new smoothed values (shown in Table 37 and Table 38) were obtained using these equations. As suggested, the smoothed values are reported to the nearest hundredth.

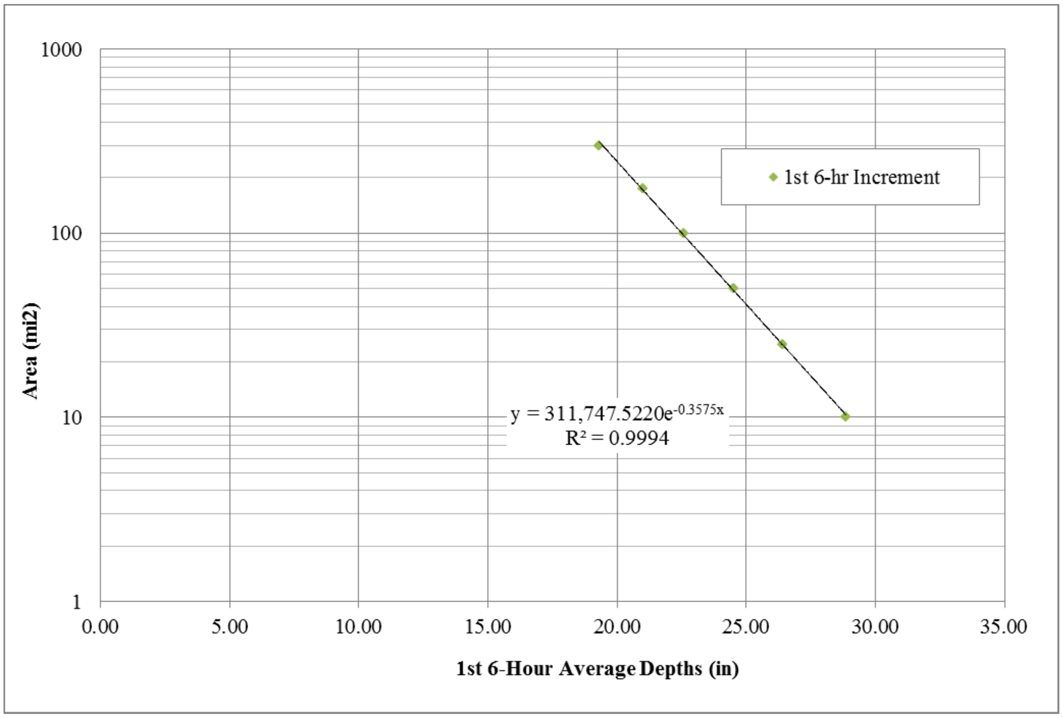

Figure 52: Smoothing Curve for First 6-Hour Incremental Values at Selected Area Sizes for the Whitethorn Creek Study Watershed

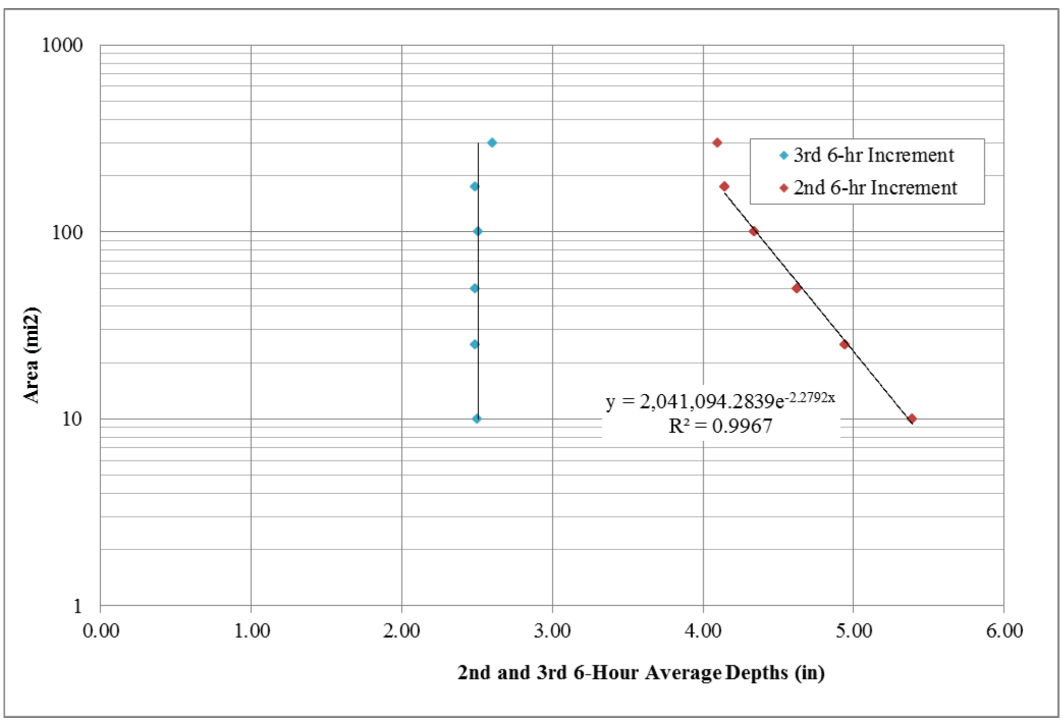

Figure 53: Smoothing Curves for Second and Third 6-Hour Incremental Values at Selected Area Sizes for the Whitethorn Creek Study Watershed

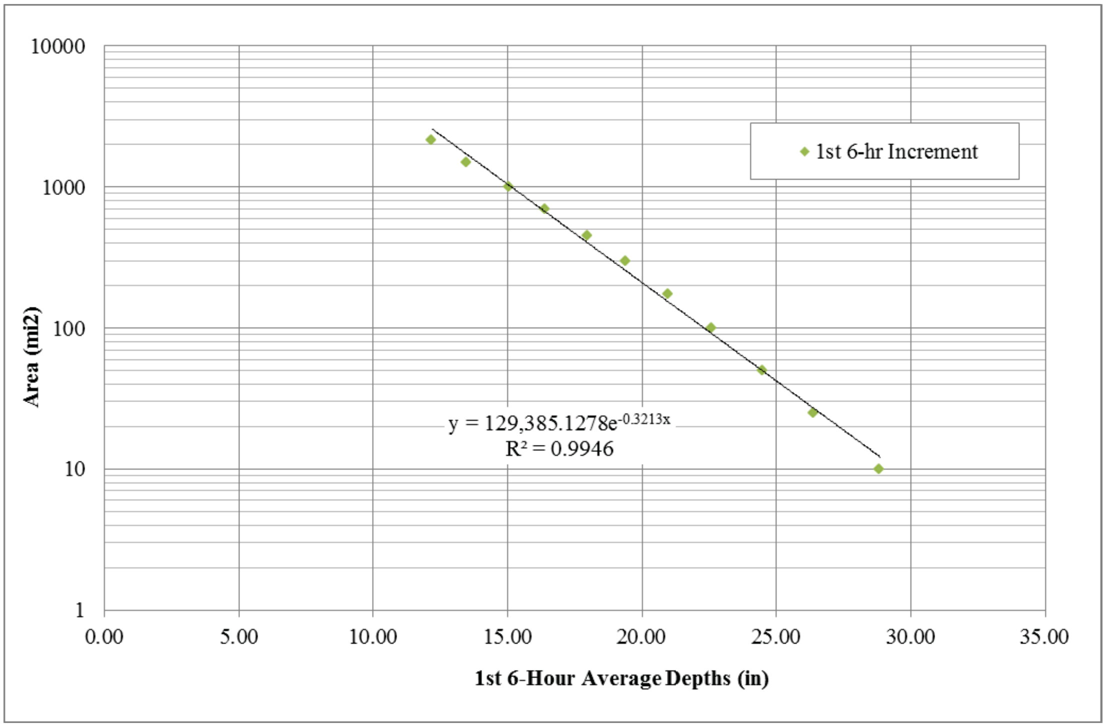

Figure 54: Smoothing Curve for First 6-Hour Incremental Values at Selected Area Sizes for the Banister River Study Watershed

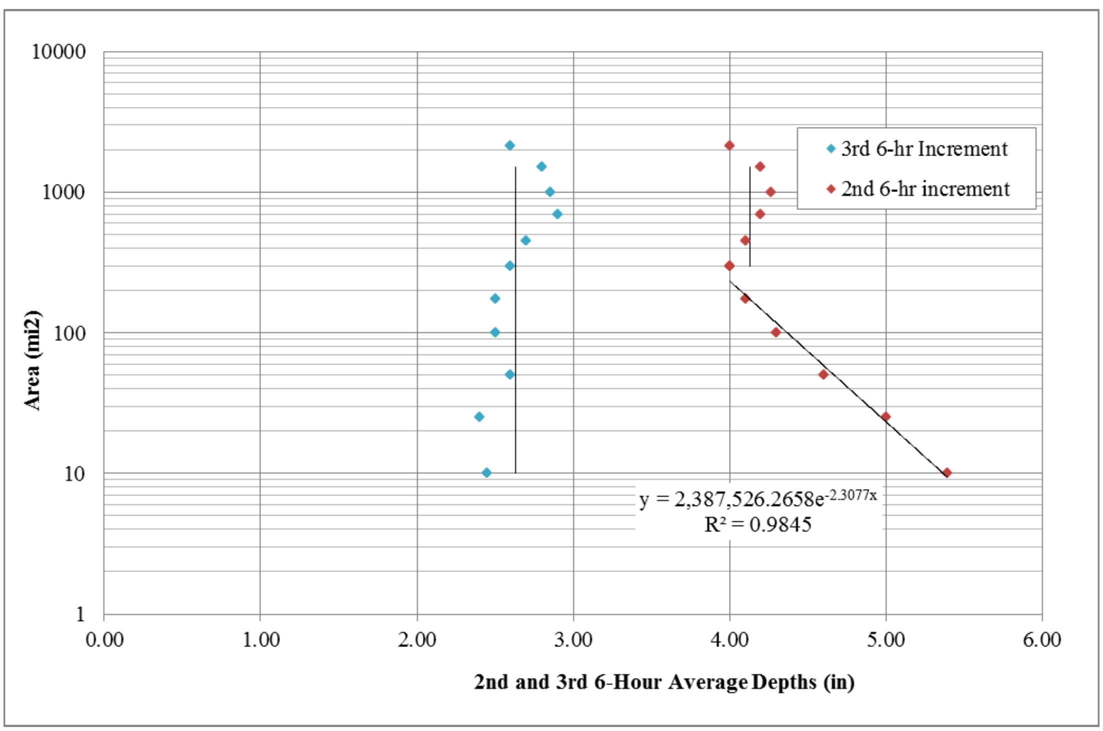

Figure 55: Smoothing Curves for Second and Third 6-Hour Incremental Values at Selected Area Sizes for the Banister River Study Watershed

For the third 6-hr period, the incremental differences did not follow any apparent decreasing or constant trend, displaying almost the opposite tendency. Because of this, the data in the third period was manually altered to have a constant value of 2.51 in for the Whitethorn Creek analysis and a constant value of 2.63 in for the Banister River analysis. These values were selected because they corresponded to the mean of the data points. The vertical black lines drawn through the blue points in Figure 53 and Figure 55 represent theses constant incremental differences that were settled upon to represent the data. The error that exists in this period is most likely due to the how the smooth curves were drawn in step A4 to obtain the 18-hr D-A-D values. Other methods of approximation were evaluated and seemed to produce similar results, leading to the conclusion that the error may just be an anomaly stemming back to the original HMR51 depths found at the selected storm centroid locations. Table 37 and Table 38 display the user-corrected incremental differences for the first three 6-hr periods for each of the studies. The grayed out boxes in these tables represent the forced values that were changed without the use of a best fit trendline.

Table 37: User-Corrected Incremental Differences between the First Three 6-hr Periods – Whitethorn Creek Analysis

Area (mi^2)	6-Hour Periods/Incremental Differences (in.)		
	1 (0-6)	2 (6-12)	3 (12-18)
10	28.95	5.36	2.51
25	26.38	4.96	2.51
50	24.44	4.66	2.51
100	22.50	4.35	2.51
175	20.94	4.11	2.51
300	19.43	4.10	2.51

Table 38: User-Corrected Incremental Differences between the First Three 6-hr Periods – Banister River Analysis

Area (mi^2)	6-Hour Periods/Incremental Differences (in.)		
	1 (0-6)	2 (6-12)	3 (12-18)
10	29.47	5.37	2.63
25	26.62	4.97	2.63
50	24.46	4.67	2.63
100	22.30	4.37	2.63
175	20.56	4.13	2.63
300	18.88	4.13	2.63
450	17.62	4.13	2.63
700	16.25	4.13	2.63
1000	15.14	4.13	2.63
1500	13.87	4.13	2.63
2150	12.75	4.13	2.63

B. Isohyetal Pattern

Step:

1. *A tracing of the drainage should be placed over the isohyetal pattern in figure 5, drawn at comparable map scales. Placement of the pattern (or adjustment of the drainage axis) is a subjective consideration. Placement is generally regarded as that which inputs the maximum precipitation to the drainage. In most cases this consideration is met by drainage-centering the isohyetal pattern, that is, the isohyetal and drainage patterns have approximately the same center and axial orientation (see section 4.4.4 for exception). Judgment is guided by trying to place the greatest number of whole isohyets completely within the drainage, since the isohyets that enclose smaller area sizes contain proportionately higher rain amounts. This guidance is subject to consideration of the relative orientations preferred for PMP-type patterns discussed in the following steps.*

To represent the spatial distribution of the PMP storm, the HMR52 suggested elliptical isohyetal pattern was adopted. This idealized spatial distribution has a shape ratio of major to minor axis of 2.5 to 1. In addition, there are standard area sizes that HMR52 suggests for each elliptical ring (isohyet), as shown in Figure 56. For the

Whitethorn Creek PMP analysis, the isohyetal pattern was centered over the study watershed, in order to maximize the rainfall depth/volume that would fall within the basin. In theory, this configuration would induce the greatest discharges in the study reaches. For the Banister River PMP analysis, the final selected isohyetal was centered near the Coles Hill site to maximize rainfall at the impoundment locations.

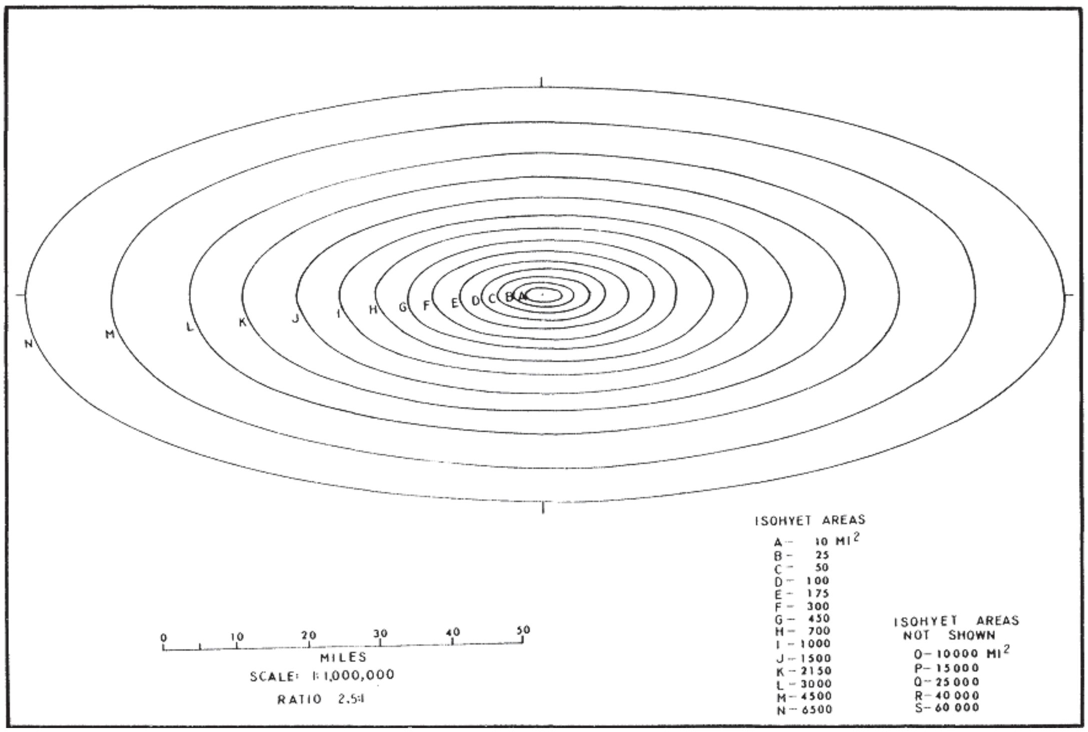

Figure 56: HMR52 Suggested Isohyetal PMP Storm Pattern (Hansen et al., 1982)

2. *Determine the orientation (to nearest whole degree) of the pattern when placed on the drainage, in terms of degrees from north. If this orientation does not fall between 135° and 315°, add 180° so that it does.*

Once the storm centers were specified, the orientations of the isohyetal patterns were determined. When selecting an orientation (clockwise rotation angle of the major axis from North), the goal is to maximize the basin coverage with the most intense rainfall possible. This means that the storm should be oriented so as to place the greatest number of whole isohyets completely within the drainage, as the smaller ellipses correspond to the higher intensities. For the Whitethorn Creek Study Watershed, a final orientation of 310° from North was selected to best cover the drainage. This orientation, with isohyets A-E, is depicted in

Figure 57. In this configuration, only the first isohyet (A) exists completely within the drainage and almost all of the second isohyet does as well. Because the watershed is contained wholly within the E isohyet, there was no need to include the F isohyet (300 mi^2) in the remainder of the analysis. It can also be noted that the major axis of the storm pattern roughly corresponds to the apparent axial orientation of the watershed.

For the Banister River Study Watershed, a final orientation of 274° from North was selected to best cover the drainage and produce the greatest precipitation depth. This orientation, with isohyets A-J, is depicted in Figure 58. In this configuration, the first five isohyets (A-E) exist completely within the drainage. Because the watershed is contained entirely within the J isohyet, there was no need to include the K isohyet (2150 mi^2) in the remainder of the analysis.

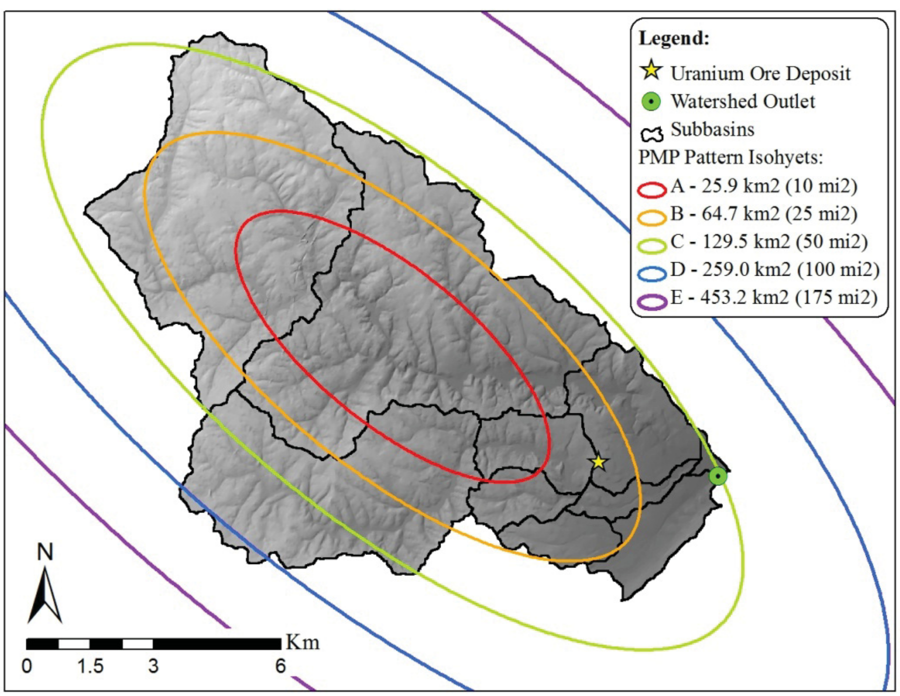

Figure 57: Selected Isohyetal Pattern and Storm Orientation for the Whitethorn Creek Study Watershed

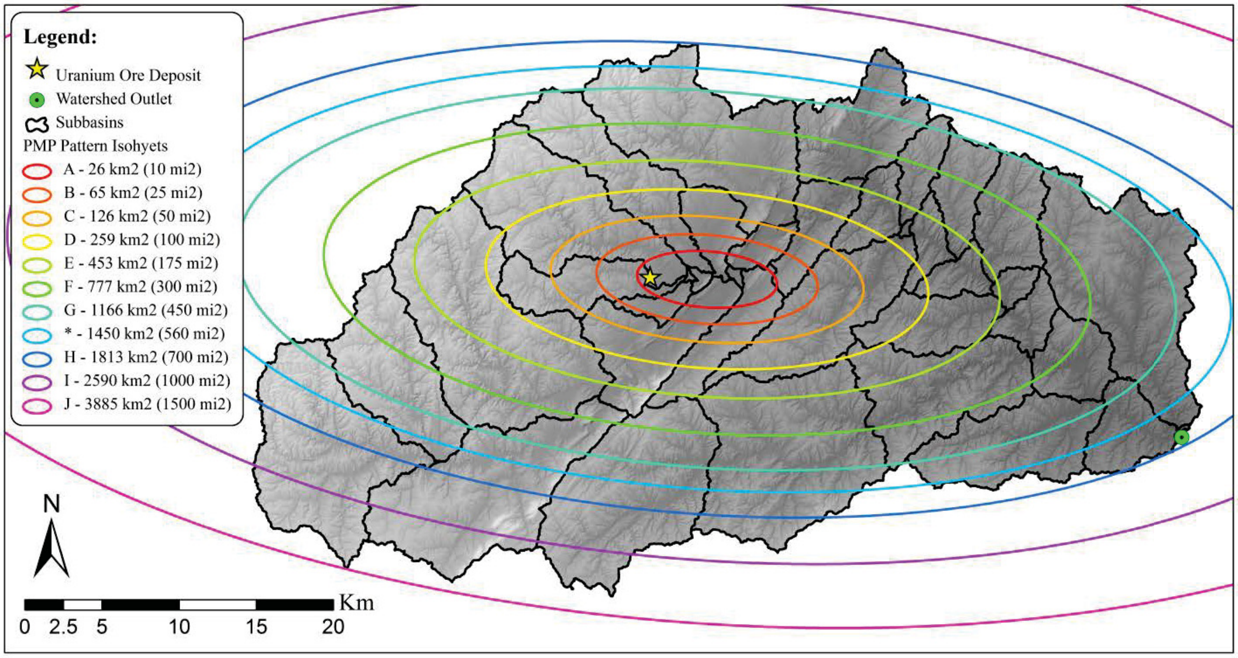

Figure 58: Selected Isohyetal Pattern and Storm Orientation for the Banister River Study Watershed

3. *Determine the orientation preferred for PMP conditions from figure 8 at the location of the pattern center. If the difference between orientations from step B3 and B2 is less than 40 degrees, then for the isohyetal pattern as placed over the drainage there is no reduction factor to consider. If the orientation differences exceed 40 degrees, then a decision must be made whether the pattern is to be placed at some angle to the drainage at which no reduction to isohyet values is required, or aligned with the drainage and a reduction made to the isohyet values. A truly objective decision on the orientation of the pattern yielding maximum volume would require numerous applications. As guidance, the area size of the drainage, the shape of the drainage, and the differences in orientations (preferred PMP and pattern placed on the drainage) have the greatest bearing on the volume of precipitation determined. Only the experience gained from numerous trials will enable the user to reduce the effort involved in making these decisions. An illustration of the effects of alternative placements is demonstrated in the examples.*

Figure 59, taken from HMR52, shows a map of recommended orientations for the isohyetal patterns located east of the 105th meridian. The report suggests that if the chosen orientation from the previous step exceeds ± 40° there must be a reduction factor applied to the data in later steps. According to Figure 59, both study areas have a recommended orientation of approximately 205° from North. Consequently, both selected orientations fall outside of the ± 40° range.

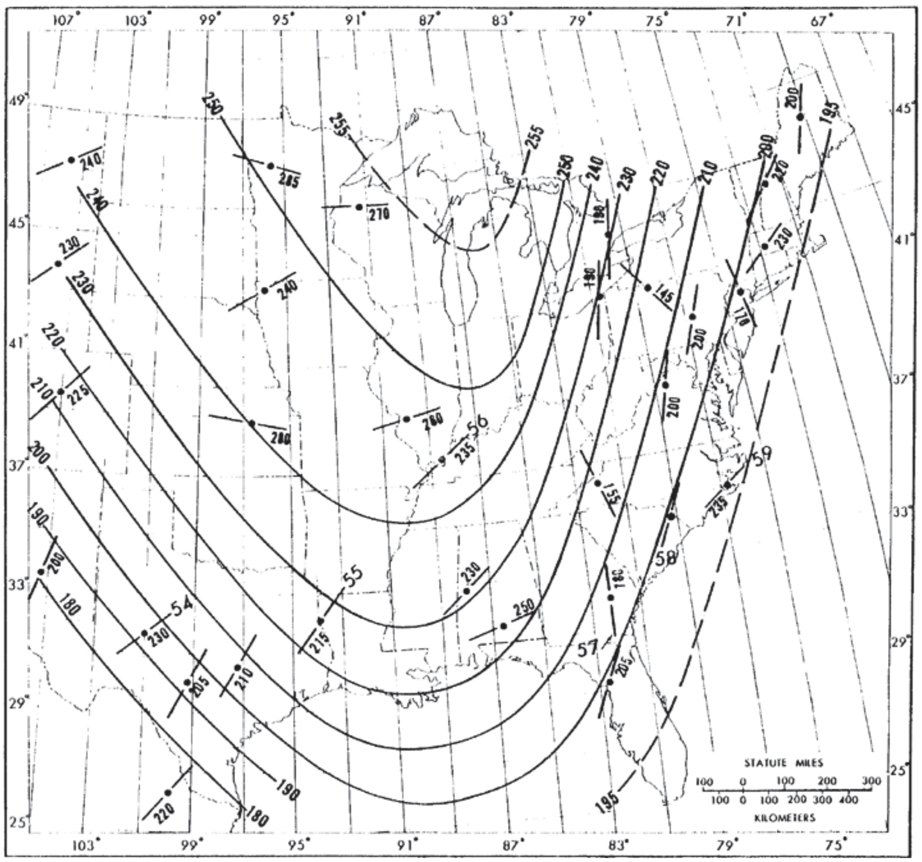

Figure 59: HMR52 Suggested Orientations ± 40° (Hansen et al., 1982)

4. *Skip this step if no adjustment for orientation is needed. Having settled on a placement of the isohyetal pattern, determine the appropriate adjustment factors due to orientation for the isohyets involved from the model shown in figure 10 (read to tenths of percent). Note that the amount of reduction is dependent upon area size (only pattern areas larger than 300 mi*^{2} *need to be reduced) and the difference between orientations. Multiply the adjustment factor times the corresponding 6-hr incremental amounts from step A5 for*

each pattern area size to obtain incremental values reduced as a result of pattern orientation.

Even though the selected orientation for the Whitethorn Creek PMS exists outside of the ± 40° range, which would normally indicate that a reduction factor is necessary, reduction factors are only applied to values with pattern areas greater than 300 mi^2. Because the Whitethorn Creek study watershed is entirely contained within the E isohyet (175 mi^2), an adjustment factor based on storm orientation is not necessary. Therefore, the values presented in Table 37 are applicable and reduction was not necessary.

For the Banister River Analysis, however, the PMS exists outside of the ± 40° range and the storm area is greater than 300 mi^2, necessitating a reduction to be applied. To find the reduction factor, HMR52 provides a figure (shown as Figure 60 here) relating the selected orientation difference from the suggested orientation to the reduction factor for a number of isohyet sizes. Based on this figure, Table 39 shows the reduction factors obtained for the provided area sizes (in black) for a 29° deviation. The red values in this table were obtained through linear interpolation of the black values from the provided lines in the figure.

Table 39: Reduction Factors Corresponding to a 29° Deviation from the HMR52 Recommended Orientation for Storm Isohyets Greater than 300 mi^2

Pattern Area (mi2)	Adjustment Factor
450	99.23%
700	97.81%
1000	96.14%
1500	93.40%

These reduction factors were then applied to the appropriate isohyets in the user-corrected incremental differences in Table 38. These new reduced, user-corrected values are presented in Table 40. The values that were changed are written in red.

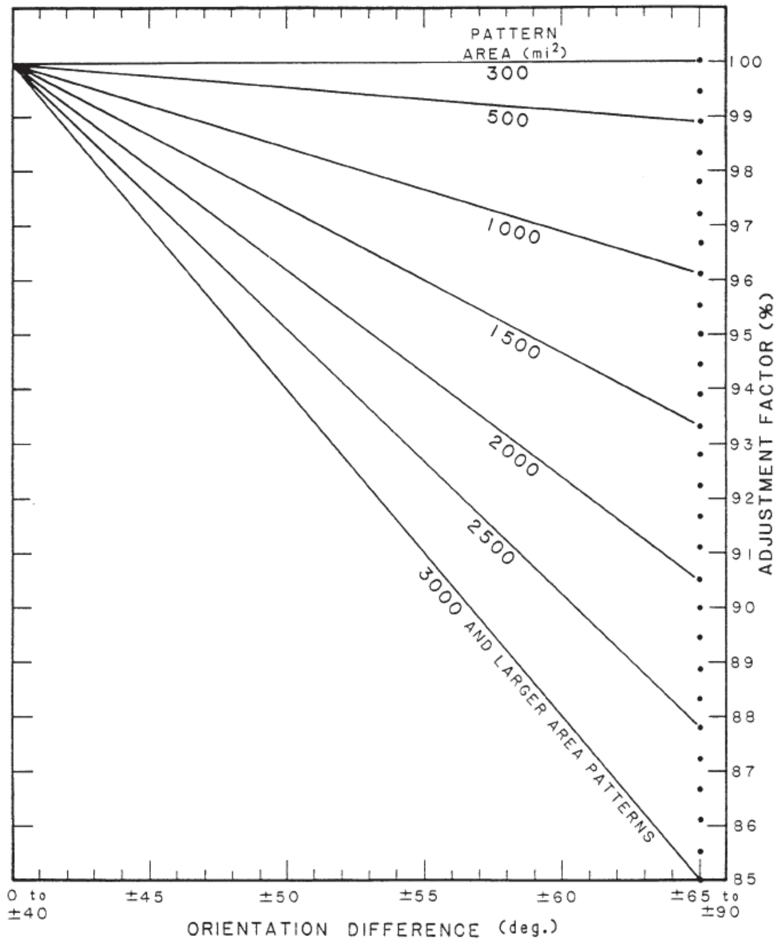

Figure 60: Model for Determining Isohyetal Pattern Reduction Factor Based on Deviation from HMR52 Suggested Orientations (Hansen et al., 1982)

Table 40: User Corrected Incremental Differences with Reduction Factors Applied – Banister River Analysis

Area (mi^2)	6-Hour Periods		
	1 (0-6)	2 (6-12)	3 (12-18)
10	29.47	5.37	2.63
25	26.62	4.97	2.63
50	24.46	4.67	2.63
100	22.30	4.37	2.63
175	20.56	4.13	2.63
300	18.88	4.13	2.63
450	17.49	4.10	2.61
700	15.89	4.04	2.57
1000	14.55	3.97	2.53
1500	12.96	3.86	2.46

C. Maximum Precipitation Volume

Step:

Determine the maximum volume of precipitation for the three largest 6-hr incremental periods resulting from placement of the pattern over the drainage. To do this, it is necessary to obtain the value to be assigned to each isohyet in the pattern that occurs over the drainage during each period. Guidance for this determination is given in the following steps related to the format presented in figure 41. It is suggested that an ample number of copies of this figure be reproduced to serve in the computation procedure.

Start by determining the maximum volume for the 1st 6-hr incremental period.

To determine the maximum precipitation volumes for the first three 6-hr increments, HMR52 suggests a tabular approach that involves filling out a computation sheet template (shown in Figure 61) to obtain the desired values. For this study, Microsoft Excel was used to reproduce this template and to carry out the numerous calculations involved.

Each computation sheet template is divided into six individual "sectors", with each one representing a specific isohyet. As discussed in Section B.2., the Whitethorn Creek study watershed PMP storm pattern consists of the first five standard isohyet sizes (A-E). This means that for each of the first three 6-hr increments, five sectors are needed to calculate the maximum values. In the same way, ten sectors were required for the Banister River analysis for the ten primary isohyets used. In addition, HMR52 recommends running the calculations for at least two intermediate isohyet sizes, one above and one below the standard isohyet size that is believed to produce the maximum volume. This means that an additional two sectors are used for each study.

The procedure followed to complete the necessary computations for each of the study watersheds is outlined below. Because there are so many steps involved, only the final versions of the computation sheets are presented in this Appendix, rather than showing the values on a step-by-step basis. The three computation sheets used in the Whitethorn Creek analysis for determining the maximum volumes for the first three 6-hr increments are presented at the end of this section in Table 47, Table 48, and Table 49. An additional sheet, Table 50, contains the calculations for the intermediate isohyet sizes for the first three 6-hr increments. Likewise, the computation sheets developed during the Banister PMP analysis are presented as Table 51, Table 52, and Table 53.

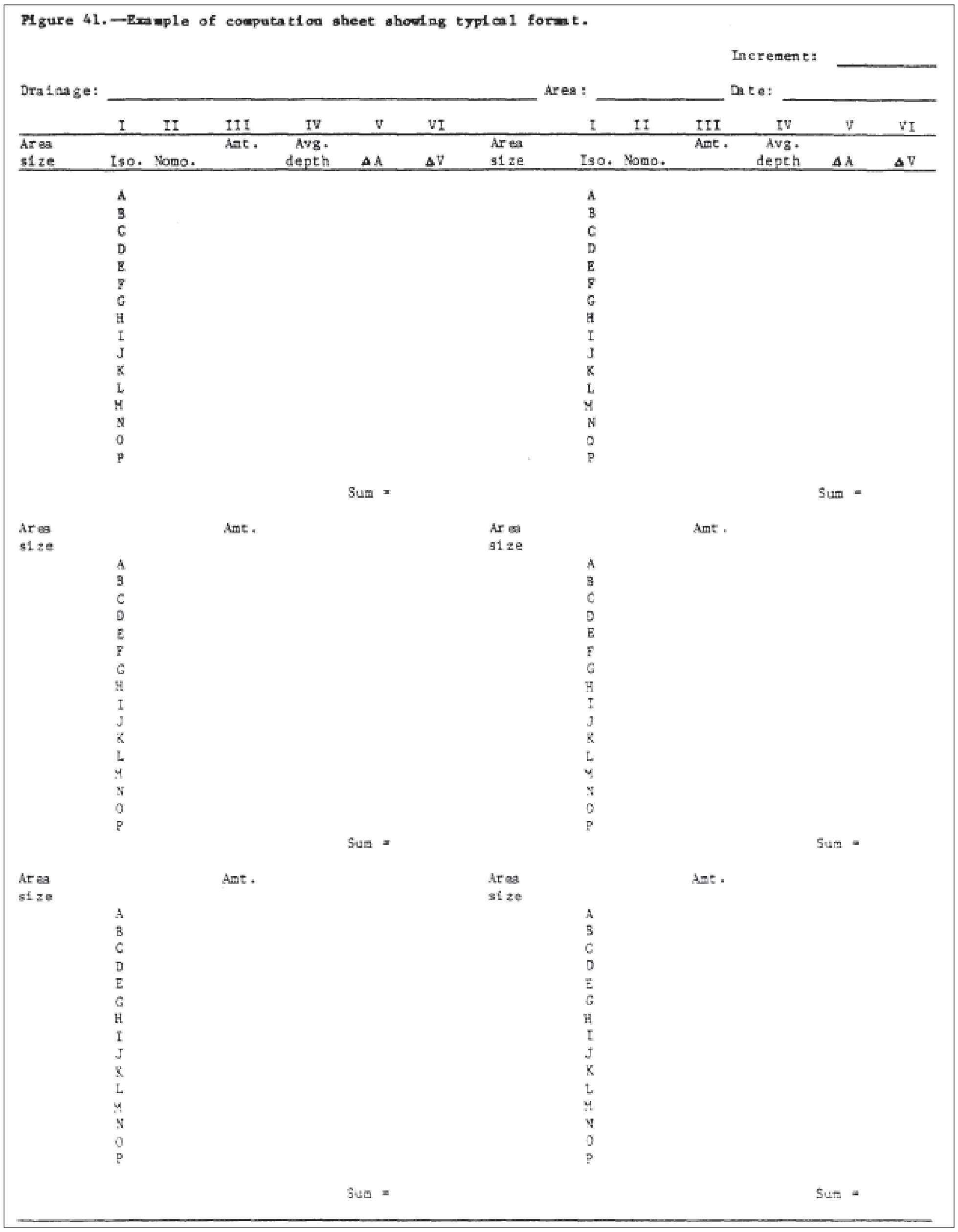

Figure 41.—Example of computation sheet showing typical format.

Increment: ____________

Drainage: ________________________ Area: ____________ Date: ____________

Area size	I Iso.	II Nomo.	III Amt.	IV Avg. depth	V ΔA	VI ΔV	Area size	I Iso.	II Nomo.	III Amt.	IV Avg. depth	V ΔA	VI ΔV
	A							A					
	B							B					
	C							C					
	D							D					
	E							E					
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =							Sum =	
Area size			Amt.				Area size			Amt.			
	A							A					
	B							B					
	C							C					
	D							D					
	E							E					
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =							Sum =	
Area size			Amt.				Area size			Amt.			
	A							A					
	B							B					
	C							C					
	D							D					
	E							E					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =							Sum =	

Figure 61: HMR52 Example Computation Sheet Showing Typical Format (Hansen et al., 1982)

1. *Fill in the name of the drainage, drainage area, date of computation, and increment (1st, 2nd or 3rd) in the appropriate boxes at top of form (fig. 41).*

The first step involved in determining the maximum precipitation volumes is to set up the template sheets and to assign the necessary identification information in the heading of each sheet. The format of the template provided in HMR52 (Figure 61) was reproduced in Excel and then copied a number of times to obtain the four computation sheets needed to run the Whitethorn calculations and the eight needed for the Banister calculations. The headings on the Whitethorn Creek templates were filled out as follows: Drainage - Whitethorn Creek Study Watershed, Area – 41.2 square miles, Date – 11/21/2011, Increment – 1st (sheet 1) or 2nd (sheet 2) or 3rd (sheet 3) or 1st - 3rd (sheet 4). In the same way, the headings on the Banister River templates were assigned the following information: Drainage – Banister River Study Watershed, Area – 546.7 square miles, Date – 3/8/2012, Increment – 1st (sheets 1 and 2) or 2nd (sheets 3 and 4) or 3rd (sheets 5 and 6).

2. *Put the area size (mi^2) from step A3 for which the first computation is made under the heading at the upper left of form.*

Under the "Area Size" column on the templates, the five areas corresponding to the first five standard isohyets (10, 25, 50, 100, and 175 mi^2) were written on the Whitethorn templates, whereas the first ten standard isohyets (10, 25, 50, 100, 175, 300, 450, 700, 1000, and 1500 mi^2) were written on the Banister ones. This was done for each of the first three 6-hr increments. The sectors representing the first 6-hr increments were symbolized as "area/1" (ex. 10/1 and 25/1 represent the 10 and 25 mi^2 isohyets for the first 6-hr increment). This was repeated for the second and third 6-hr increments represented by "area/2" and "area/3" respectively on the other template sheets.

3. *Column I contains a list of isohyet labels. Use only as many isohyets as needed to cover the drainage.*

Column I contains a list of standard isohyet letters (A-P). Because these studies are only interested in the first five and ten standard areas, the rows in the templates corresponding to isohyets F-P and K-P were neglected for the Whitethorn and Banister analyses, respectively.

4. *For the area size in step C2, list in column II the corresponding percentages read from table 15 or the nomogram in figure 16 (first 6-hr period) for those isohyets needed to cover the drainage; use table 16 or figure 18 and table 17 or figure 19 for the 2nd and 3rd 6-hr periods, respectively, when determining step C10.*

In order to apply the PMP methodology to all regions east of the 105th meridian, HMR52 developed a procedure to normalize the regional differences in PMP and scale the volumes by a percentage of the greatest 6-hr increment of PMP. Nomograms were developed to obtain these percentages for each of the first three 6-hr increments, as well as for the fourth through the twelfth 6-hr increments. In an attempt to minimize user error in reading these nomograms, HMR52 presents tabulated percentages corresponding to the standard areas as well as some intermediate areas between the standard values. These tables are presented as Tables 15-18 in HMR52. An example of one such table is shown here in Table 41.

Table 41: HMR52 Table 15a - 1st 6-hr Nomogram Values at Selected Area Sizes (Hansen et al., 1982)

	Storm Area (mi^2) size											
Isohyet	10	17	25	35	50	75	100	140	175	220	300	360
A	100*	101	102	104	106	109	112	116	119	122	126	129
B	64	78	95*	97	99	102	105	108	111	114	118	121
C	48	58	67	77	92*	95	98	101	103	106	110	113
D	38	46	52	59	66	77	90*	93	96	99	103	105
E	30	37	43	48	54	62	68	78	89*	92	96	98
F	24	30	34	39	44	50	55	61	66	73	88*	90
G	19	24	28	32	35	40	44	49	53	58	65	73
H	14	19	22	25	28	32	35	39	42	46	51	56
I	10	14	17	19	22	26	28	32	34	37	42	45
J	6	9	12	14	16	19	21	24	26	28	32	35
K	2	5	7	9	11	14	16	18	20	22	25	27
L	0	1	3	5	7	9	11	13	15	17	19	21
M		0	0	1	3	5	6	8	9	10	12	13
N				0	0	0	1	2	3	4	6	7
O							0	0	0	0	1	2
P											0	0

*Indicates cusp.

For each analysis, Column II was filled out with the corresponding percentages read from these tables. These nomogram values were only collected for isohyets used in each study, as these are the only areas of interest. This procedure for obtaining these percentages was repeated for each of the area sizes for each of the first three 6-hr increments.

5. *Under the heading amount (Amt.) in column III place the value from step B4 corresponding to area size and increment of computation. Multiply each of the percentages in column II by the Amt, at the head of column III to fill column III.*

Column III is the "Amount" column and corresponds to the volume of PMP rainfall for each isohyet and the scaled values based on the percentages in the previous step. In the heading portion of each sector, the value from Section B.4. (Table 37 and Table 38) was written, corresponding to each area size and increment of computation. The depth in the heading of each sector was then multiplied by each of the percentages in Column II and the products were entered into each of the rows in Column III.

6. *Column IV represents the average depth between adjacent isohyets. The average depth of the "A" isohyet is taken to be the value from column III. The average depth between all other isohyets which are totally enclosed by the drainage is the arithmetic average of paired values in column III. For incomplete isohyets covering the drainage, it is necessary to make a weighted estimate of the average depth if a portion of the drainage extends beyond a particular isohyet. The average depth for the extended portion of the drainage may be taken as 0.5 to 1.0 times the difference between the enclosing isohyets plus the lower isohyet. The weighting relation is given by:*

$$F\,(X-Y) + Y$$

where X and Y are adjacent isohyet values, X ≥ Y, and the weight factor, F, may be between 0.5 and 1.0. If only a small portion of the drainage extends beyond X, then the weight factor may be taken closer to 1.0, and if the drainage extends nearly to Y, then a weight factor close to 0.5 is appropriate.

As stated in HMR52, values in Column IV represent the average depths between adjacent isohyets and were calculated by taking the mean of the two adjacent values in Column III. In general, to obtain a value for one of the rows in Column IV, the average is taken of the Column III value in that row and the Column III value in the previous row. Because there is not a "previous value" for the A isohyet, the A value in Column IV is taken as the A value in Column III. This step also involves making weighted estimates for portions of the drainage that extend beyond one of the isohyets but do not fully reach the next one.

Because some of the Whitethorn Creek Study Watershed area extended beyond the D isohyet but did not touch the E isohyet, a weight factor was applied to the average depth of the E isohyet. Because only a small portion of the drainage extended beyond the D isohyet, a weight factor, F, of 0.9 was selected. Considering the Column III value for the D isohyet as X and the Column III value for the E isohyet as Y, the weighting equation $F(X - Y) + Y$ was applied to obtain the Column IV value for the E isohyet. Likewise, a weight factor of 0.7 was applied to the J isohyet in the Banister analysis, as the study watershed seemed to extend more than half the way out between the I and J isohyets.

7. *Column V lists the incremental areas between adjacent isohyets. For the isohyets enclosed by the drainage, the incremental area can be obtained from table 8. For all other isohyets it will be necessary to planimeter the area of the drainage enclosed by each isohyet and make the appropriate successive subtractions. The sum of all the incremental areas in column V should equal the area of the drainage. If the computation in step 5 results in the zero isohyets crossing the drainage, the appropriate total area is that contained within the zero isohyet, and not the total drainage area.*

Column V specifies the areas over which to apply the average depths calculated in Column IV. These areas correspond to the incremental areas of the study watershed that exist between adjacent isohyets. For the standard isohyets that exist wholly within the study watershed, the incremental area difference for each row is found by subtracting the previous isohyet area from the current one.

For the isohyets that partially extend beyond the outer watershed boundary, only the area existing within the drainage is used in the successive subtractions. For example, for the B isohyet in the Whitethorn Creek study, the standard area is 25 mi^2 but only about 24.78 mi^2 of watershed existed within the B ellipse. The successive subtraction for this isohyet therefore consisted of the 24.78 mi^2 area minus the previous 10 mi^2 area. The areas used for the successive subtraction are shown in Table 42.

The sum of the values in Column V should equal the total area of the study watershed (41.2 mi^2 and 546.7 mi^2). These values are the same for each of the evaluated template sectors on each of the computation sheets and are valid for all of the 6-hr increments.

Table 42: Cumulative Watershed Area Contained Within Each Isohyet for Each Analysis

Isohyet	Whitethorn Creek Cumulative Area (mi^2)	Banister River Cumulative Area (mi^2)
A	10.00	10.00
B	24.78	25.00
C	37.93	50.00
D	41.02	100.00
E	41.24	175.00
F	- - -	282.08
G	- - -	392.25
H	- - -	485.45
I	- - -	524.53
J	- - -	546.67

8. *Column VI gives the incremental volume obtained by multiplying values in column IV times those in column V. The incremental volumes are summed to obtain the total volume of precipitation in the drainage for the specified pattern area size in the 6-hr period.*

Column VI contains the incremental volumes of precipitation which were obtained by multiplying the areas in Column V by the depths in Column IV. Once the volumes for each isohyet were calculated in one sector, they were summed and the overall volume was reported at the bottom of each group.

9. *Steps C2 to C8 are repeated for all the other pattern area sizes selected in step A3.*

The calculations outlined from steps C.2. to C.8. were carried out for the five standard area sizes used in the Whitethorn Creek study and for the ten standard area sizes used in the Banister River study.

10. *The largest of the volumes obtained in steps C8 and C9 represents the preliminary maximum volume for the 1st 6-hr incremental period and specifies the pattern area to which such volume relates. The area of maximum volume can be used as guidance in choosing pattern areas to compute volumes for the 2nd and 3rd 6-hr incremental period. Presumably, this guidance narrows in on the range of pattern area sizes considered and possibly reduces in some degree the number of computations. Compute the 2nd and 3rd 6-hr incremental volumes by repeating steps C1 to C9, using the appropriate tables or nomograms.*

Once the volumes are found for the first 6-hr increment, the same procedure was carried out for the second and third 6-hr increments using the appropriate tables and nomograms. For the Whitethorn Creek Study Watershed, fifteen computation sets were carried out, one for each of the first five standard isohyet sizes for each of the first three 6-hr increments. In the same way, thirty computation sets were conducted for the Banister River analysis.

11. *Sum the volumes from steps C8 to C10 at corresponding area sizes and plot the results in terms of volume vs. area size (semi-log plot). Connect the points to determine the area size for the precipitation pattern that gives the maximum 18-hr volume in the drainage.*

Once the volumetric sums for each of the sectors were calculated, the area size that produced the maximum volume for the first eighteen hours of the PMP storm was identified. This was done by summing the three volumes of the first three 6-hr increments at corresponding area sizes. Table 43 shows these sums for the Whitethorn Creek analysis and ranks them from largest (1) to smallest (5). From this table, the 50 mi^2 area size produced the greatest cumulative volume out of the five sizes that were evaluated. Similarly, Table 44 displays the sums for the Banister River analysis, from which it can be seen that the 700 mi^2 area size resulted in the highest cumulative volume.

Table 43: Sum of the Volumes of the First Three 6-hr Increments for Each Isohyet – Whitethorn Creek Analysis

Area (mi^2)	Sum of Volumes (in * mi^2)	Rank
10	1138.0	5
25	1273.3	3
50	1295.9	1
100	1274.2	2
175	1253.3	4

Table 44: Sum of the Volumes of the First Three 6-hr Increments for Each Isohyet – Banister River Analysis

Area (mi^2)	Sum of Volumes (in * mi^2)	Rank
10	5930.7	10
25	7749.2	9
50	9019.1	8
100	10159.3	7
175	10993.7	6
300	11818.2	4
450	12239.1	2
700	12272.8	1
1000	12114.7	3
1500	11753.6	5

The results from Table 43 and Table 44 were plotted on a semi-logarithmic scale as recommended in HMR52 (Figure 62 and Figure 63).

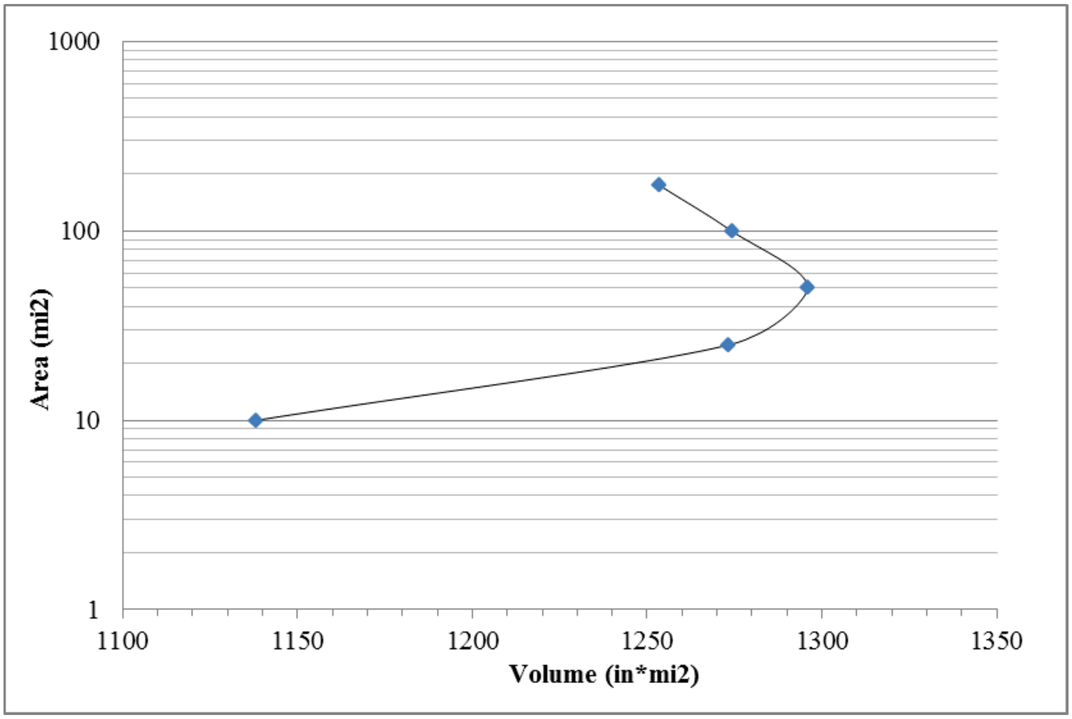

Figure 62: Area vs. Volume Curve for First Three 6-hr Increments for the Whitethorn Creek Study Watershed

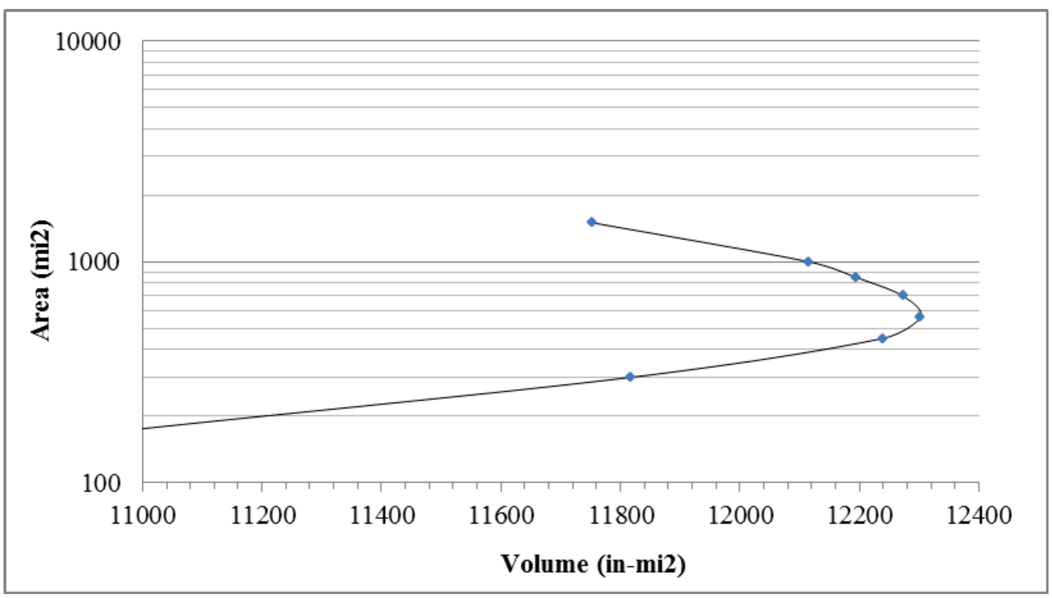

Figure 63: Area vs. Volume Curve for First Three 6-hr Increments for the Banister River Study Watershed

12. It is recommended, although not always necessary, that the user repeat steps C2 through C11 for one or two supplemental area sizes (area sizes other than those of the *standard isohyetal pattern) on either side of the area size of maximum volume in step C11. This provides a check on the possibility that the maximum volume occurs between two of the standard isohyet area sizes. To make this check, an isohyet needs to be drawn for each supplemental area size in the standard isohyetal pattern and positioned on the drainage so that the corresponding incremental areas between isohyets can be determined (planimetered). In addition, supplemental cusp points need to be determined in figures 16, 18 and 19 for each of the area sizes considered. To find the appropriate cusp position, enter the ordinate at the supplemental area size, and move horizontally to intersect a line between the two most adjacent cusps. This intermediate point will be the percentage for the supplemental isohyet when reading the other isohyet percentages in step C4; otherwise follow the computational procedure outlined.*

As discussed above, HMR52 recommends repeating steps C.2. through C.11. for two additional intermediate area sizes on either side of the area size of maximum volume (50 mi^2 for the Whitethorn Creek Study Watershed and 700 mi^2 for the Banister River Study Watershed). Based on this, the Section C procedure was repeated for area sizes of 35 mi^2 and 75 mi^2 for the Whitethorn Creek study and for area sizes of 560 mi^2 and 850 mi^2 for the Banister River study. These sizes were selected because they fall between the purported isohyet of maximum volume and its adjacent isohyets, and because they correspond to the intermediate areas that have tabulated nomogram percentages, as discussed in Section C.4. Computations for these intermediate area sizes (denoted in orange) were carried out for each of the first three 6-hr increments and are displayed in Table 50 for the Whitethorn Creek analysis, and in Table 51, Table 52, and Table 53 for the Banister River analysis. For these computations, the cusp values (nomogram percentages for Column II) were found using the nomograms from HMR52 and the procedure described above. In addition, the watershed area contained within each of these new areas was found in ArcGIS, as these were needed for the successive subtraction steps for Column V. The purpose of calculating the volumes of these intermediate area sizes is to determine if the maximum volume actually occurred between two of the standard isohyet area sizes.

13. *The largest 18-hr volume obtained from either step C11 or C12 then determines the final pattern area size of maximum volume for the pattern placement chosen in step B1.*

Similar to Table 43 and Table 44, Table 45 and Table 46 shows the sum of the volumes of the first three 6-hr increments for both the five standard area sizes and the two intermediate sizes. Because the cumulative volume for the 50 mi^2 area is greater than the cumulative volumes for the two adjacent intermediate areas, it was selected to represent the PMP pattern of maximum volume when placed over the Whitethorn Creek Study Watershed. Concerning the Banister River Study Watershed, the 560 mi^2 intermediate isohyet proved to have the greatest cumulative volume, resulting in it being selected to represent the PMP pattern of maximum volume. It should be noted that even though these areas were determined to produce the greatest volume, the 175 mi^2 and 1500 mi^2 isohyetal patterns were still used to cover the drainage. The 50 mi^2 and 560 mi^2 areas selected in this section are only used to compute rainfall depths to be assigned to the A-E isohyetal pattern. The two "patterns" represent different entities and are not to be confused with one another.

Table 45: Sum of the Volumes of the First Three 6-hr Increments for Both the Standard and Intermediate Isohyets – Whitethorn Creek Analysis

Area (mi^2)	Sum of Volumes (in * mi^2)	Rank
10	1138.0	7
25	1273.3	5
35	1295.8	2
50	1295.9	1
75	1282.6	3
100	1274.2	4
175	1253.3	6

Table 46: Sum of the Volumes of the First Three 6-hr Increments for Both the Standard and Intermediate Isohyets – Banister River Analysis

Area (mi2)	Sum of Volumes (in * mi^2)	Rank
10	5930.7	12
25	7749.2	11
50	9019.1	10
100	10159.3	9
175	10993.7	8
300	11818.2	6
450	12239.1	3
560	12302.5	1
700	12272.8	2
850	12194.0	4
1000	12114.7	5
1500	11753.6	7

Table 47: Completed Computation Sheet for the First 6-hr Increment for the Whitethorn Creek Study Watershed

Increment: 1st

Drainage: Whitethorn Creek Study Watershed *Area:* 41.2 square miles *Date:* 11/21/2011

	I	II	III	IV	V	VI		I	II	III	IV	V	VI
Area Size	Iso.	Nomo.	Amt. 28.95	Avg. Depth	Δ A	Δ V	Area Size	Iso.	Nomo.	Amt. 22.50	Avg. Depth	Δ A	Δ V
	A	100	28.95	28.95	10.00	289.46		A	112	25.20	25.20491	10.00	252.05
	B	64	18.53	23.74	14.78	350.85		B	105	23.63	24.42	14.78	360.93
10/1	C	48	13.89	16.21	13.15	213.20	100/1	C	98	22.05	22.84	13.15	300.44
	D	38	11.00	12.45	3.08	38.39		D	90	20.25	21.15	3.08	65.25
	E	30	8.68	10.77	0.22	2.34		E	68	15.30	19.76	0.22	4.30
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	894.25						Sum =	982.98

Area Size			Amt. 26.38				Area Size			Amt. 20.94			
	A	102	26.91	26.91	10.00	269.11		A	119	24.92	24.91732	10.00	249.18
	B	95	25.06	25.99	14.78	384.13		B	111	23.24	24.08	14.78	355.94
25/1	C	67	17.68	21.37	13.15	281.07	175/1	C	103	21.57	22.40	13.15	294.69
	D	52	13.72	15.70	3.08	48.42		D	96	20.10	20.83	3.08	64.27
	E	43	11.34	13.48	0.22	2.93		E	89	18.64	19.95	0.22	4.34
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	985.66						Sum =	968.42

Area Size			Amt. 24.44				Area Size			Amt.			
	A	106	25.91	25.91	10.00	259.11		A					
	B	99	24.20	25.05	14.78	370.35		B					
50/1	C	92	22.49	23.34	13.15	307.03		C					
	D	66	16.13	19.31	3.08	59.57		D					
	E	54	13.20	15.84	0.22	3.45		E					
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	999.50						Sum =	0.00

Table 48: Completed Computation Sheet for the Second 6-hr Increment for the Whitethorn Creek Study Watershed

Increment: 2nd

Drainage: Whitethorn Creek Study Watershed *Area:* 41.2 square miles *Date:* 11/21/2011

	I	II	III	IV	V	VI		I	II	III	IV	V	VI
Area Size	Iso.	Nomo.	Amt. 5.36	Avg. Depth	Δ A	Δ V	Area Size	Iso.	Nomo.	Amt. 4.35	Avg. Depth	Δ A	Δ V
	A	100	5.36	5.36	10.00	53.64		A	108	4.70	4.70	10.00	47.02
	B	64	3.43	4.40	14.78	65.02		B	103	4.48	4.59	14.78	67.90
10/2	C	48	2.57	3.00	13.15	39.51	100/2	C	99	4.31	4.40	13.15	57.84
	D	39	2.09	2.33	3.08	7.20		D	95	4.14	4.22	3.08	13.03
	E	30	1.61	2.04	0.22	0.44		E	79	3.44	4.07	0.22	0.89
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	165.82						Sum =	186.68

Area Size			Amt. 4.96				Area Size			Amt. 4.11			
	A	103	5.11	5.11	10.00	51.11		A	110	4.52	4.52	10.00	45.19
	B	98	4.86	4.99	14.78	73.72		B	105	4.31	4.42	14.78	65.29
25/2	C	72	3.57	4.22	13.15	55.48	175/2	C	101.5	4.17	4.24	13.15	55.79
	D	59	2.93	3.25	3.08	10.03		D	97.5	4.01	4.09	3.08	12.61
	E	48	2.38	2.87	0.22	0.63		E	95	3.90	4.00	0.22	0.87
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	190.96						Sum =	179.75

Area Size			Amt. 4.66				Area Size			Amt.			
	A	105.5	4.91	4.91	10.00	49.14		A					
	B	100.5	4.68	4.80	14.78	70.92		B					
50/2	C	96.5	4.50	4.59	13.15	60.35		C					
	D	76	3.54	4.02	3.08	12.39		D					
	E	62.5	2.91	3.48	0.22	0.76		E					
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	193.56						Sum =	0.00

Table 49: Completed Computation Sheet for the Third 6-hr Increment for the Whitethorn Creek Study Watershed

Increment: 3rd

Drainage: Whitethorn Creek Study Watershed *Area:* 41.2 square miles *Date:* 11/21/2011

	I	II	III	IV	V	VI		I	II	III	IV	V	VI
Area Size	Iso.	Nomo.	Amt. 2.51	Avg. Depth	Δ A	Δ V	Area Size	Iso.	Nomo.	Amt. 2.51	Avg. Depth	Δ A	Δ V
	A	100	2.51	2.51	10.00	25.10		A	102.3	2.57	2.57	10.00	25.68
	B	65	1.63	2.07	14.78	30.61		B	100.7	2.53	2.55	14.78	37.66
10/3	C	48	1.20	1.42	13.15	18.65	100/3	C	99.3	2.49	2.51	13.15	33.01
	D	39	0.98	1.09	3.08	3.37		D	98.6	2.47	2.48	3.08	7.66
	E	30	0.75	0.96	0.22	0.21		E	81.5	2.05	2.43	0.22	0.53
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	77.94						Sum =	104.54
Area Size			Amt. 2.51				Area Size			Amt. 2.51			
	A	101	2.54	2.54	10.00	25.35		A	102.8	2.58	2.58	10.00	25.80
	B	99	2.48	2.51	14.78	37.10		B	101.3	2.54	2.56	14.78	37.86
25/3	C	74.5	1.87	2.18	13.15	28.64	175/3	C	100	2.51	2.53	13.15	33.23
	D	60.5	1.52	1.69	3.08	5.23		D	99.2	2.49	2.50	3.08	7.71
	E	48.5	1.22	1.49	0.22	0.32		E	98.8	2.48	2.49	0.22	0.54
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	96.64						Sum =	105.15
Area Size			Amt. 2.51				Area Size			Amt.			
	A	101.6	2.55	2.55	10.00	25.50		A					
	B	99.8	2.50	2.53	14.78	37.36		B					
50/3	C	98.5	2.47	2.49	13.15	32.73		C					
	D	78.5	1.97	2.22	3.08	6.85		D					
	E	63	1.58	1.93	0.22	0.42		E					
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	102.87						Sum =	0.00

Table 50: Completed Computation Sheet for the Intermediate Isohyets for the Whitethorn Creek Study Watershed

Increment: 2nd

Drainage: Whitethorn Creek Study Watershed *Area:* 41.2 square miles *Date:* 11/21/2011

Area Size	I	II	III	IV	V	VI	Area Size	I	II	III	IV	V	VI
			Amt.							Amt.			
			25.44							23.31			
	A	104	26.46	26.46	10.00	264.58		A	109	25.41	25.41	10.00	254.08
	B	97	24.68	25.57	14.78	377.93		B	102	23.78	24.59	14.78	363.51
	-	92.5	23.53	24.10	7.42	178.85		C	95	22.14	22.96	13.15	302.00
35/1	C	77	19.59	21.56	5.73	123.54	75/1	-	91	21.21	21.68	2.17	47.04
	D	59	15.01	17.30	3.09	53.45		D	77	17.95	19.58	0.92	18.01
	E	48	12.21	14.73	0.22	3.21		E	62	14.45	17.60	0.22	3.83
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
					Sum =	1001.57						Sum =	988.48

Area Size	I	II	III	IV	V	VI	Area Size	I	II	III	IV	V	VI
			Amt.							Amt.			
			4.81							4.48			
	A	104	5.00	5.00	10.00	50.03		A	107	4.79	4.79	10.00	47.94
	B	99	4.76	4.88	14.78	72.17		B	102	4.57	4.68	14.78	69.20
	-	97	4.67	4.71	7.42	34.98		C	98	4.39	4.48	13.15	58.93
35/2	C	82	3.94	4.30	5.73	24.67	75/2	-	95.5	4.28	4.33	2.17	9.41
	D	66.5	3.20	3.57	3.09	11.04		D	86	3.85	4.07	0.92	3.74
	E	54.5	2.62	3.14	0.22	0.68		E	72	3.23	3.79	0.22	0.83
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
					Sum =	193.55						Sum =	190.04

Area Size	I	II	III	IV	V	VI	Area Size	I	II	III	IV	V	VI
			Amt.							Amt.			
			2.51							2.51			
	A	101.3	2.54	2.54	10.00	25.43		A	102	2.56	2.56	10.00	25.60
	B	99.4	2.49	2.52	14.78	37.23		B	100.3	2.52	2.54	14.78	37.53
	-	98.8	2.48	2.49	7.42	18.46		C	99	2.48	2.50	13.15	32.90
35/3	C	85.5	2.15	2.31	5.73	13.25	75/3	-	98.5	2.47	2.48	2.17	5.38
	D	69	1.73	1.94	3.09	5.99		D	90	2.26	2.37	0.92	2.18
	E	55.5	1.39	1.70	0.22	0.37		E	73.5	1.84	2.22	0.22	0.48
	F							F					
	G							G					
	H							H					
	I							I					
	J							J					
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
					Sum =	100.73						Sum =	104.07

Table 51: Completed Computation Sheets for the First 6-hr Increment for the Banister River Study Watershed

Increment: 1st

Drainage: Banister River Study Watershed *Area:* 546.7 square miles *Date:* 3/8/2012

	I	II	III	IV	V	VI		I	II	III	IV	V	VI
Area Size	Iso.	Nomo.	Amt. 29.47	Avg. Depth	Δ A	Δ V	Area Size	Iso.	Nomo.	Amt. 22.30	Avg. Depth	Δ A	Δ V
	A	100	29.47	29.47	10	294.71		A	112	24.98	24.98039	10	249.80
	B	64	18.86	24.17	15	362.50		B	105	23.42	24.20	15	363.00
10/1	C	48	14.15	16.50	25	412.60	100/1	C	98	21.86	22.64	25	565.96
	D	38	11.20	12.67	50	633.63		D	90	20.07	20.97	50	1048.28
	E	30	8.84	10.02	75	751.52		E	68	15.17	17.62	75	1321.51
	F	24	7.07	7.96	107.08	852.06		F	55	12.27	13.72	107.08	1468.81
	G	19	5.60	6.34	110.17	698.07		G	44	9.81	11.04	110.17	1216.33
	H	14	4.13	4.86	93.2	453.21		H	35	7.81	8.81	93.2	821.10
	I	10	2.95	3.54	39.08	138.21		I	28	6.25	7.03	39.08	274.57
	J	6	1.77	2.59	22.14	57.42		J	21	4.68	5.78	22.14	127.90
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	4653.93						Sum =	7457.24

Area Size			Amt. 26.62				Area Size			Amt. 20.56			
	A	102	27.15	27.15	10	271.51		A	119	24.47	24.46876	10	244.69
	B	95	25.29	26.22	15	393.30		B	111	22.82	23.65	15	354.69
25/1	C	67	17.83	21.56	25	539.04	175/1	C	103	21.18	22.00	25	550.03
	D	52	13.84	15.84	50	791.92		D	96	19.74	20.46	50	1022.96
	E	43	11.45	12.64	75	948.30		E	89	18.30	19.02	75	1426.49
	F	34	9.05	10.25	107.08	1097.39		F	66	13.57	15.94	107.08	1706.38
	G	28	7.45	8.25	110.17	909.11		G	53	10.90	12.23	110.17	1347.86
	H	22	5.86	6.65	93.2	620.22		H	42	8.64	9.77	93.2	910.28
	I	17	4.53	5.19	39.08	202.85		I	34	6.99	7.81	39.08	305.35
	J	12	3.19	4.13	22.14	91.35		J	26	5.35	6.50	22.14	143.86
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	5865.00						Sum =	8012.59

Area Size			Amt. 24.46				Area Size			Amt. 18.88			
	A	106	25.93	25.93	10	259.29		A	126	23.79	23.79	10	237.94
	B	99	24.22	25.07	15	376.10		B	118	22.28	23.04	15	345.58
50/1	C	92	22.50	23.36	25	584.02	300/1	C	110	20.77	21.53	25	538.20
	D	66	16.14	19.32	50	966.23		D	103	19.45	20.11	50	1005.59
	E	54	13.21	14.68	75	1100.77		E	96	18.13	18.79	75	1409.24
	F	44	10.76	11.99	107.08	1283.48		F	88	16.62	17.37	107.08	1860.35
	G	35	8.56	9.66	110.17	1064.49		G	65	12.27	14.45	110.17	1591.56
	H	28	6.85	7.71	93.2	718.14		H	51	9.63	10.95	93.2	1020.81
	I	22	5.38	6.12	39.08	238.99		I	42	7.93	8.78	39.08	343.17
	J	16	3.91	4.94	22.14	109.40		J	32	6.04	7.36	22.14	163.06
	K							K					
	L							L					
	M							M					
	N							N					
	O							O					
	P							P					
					Sum =	6700.90						Sum =	8515.49

(continued)

Increment: 1st

Drainage: Banister River Study Watershed | *Area:* 546.7 square miles | *Date:* 3/8/2012

Area Size	I Iso.	II Nomo.	III Amt. 17.49	IV Avg. Depth	V Δ A	VI Δ V
	A	132	23.08	23.08	10	230.82
	B	124	21.68	22.38	15	335.74
450/1	C	116	20.28	20.98	25	524.59
	D	108	18.89	19.58	50	979.24
	E	101	17.66	18.27	75	1370.50
	F	93	16.26	16.96	107.08	1816.27
	G	86	15.04	15.65	110.17	1724.20
	H	63	11.02	13.03	93.2	1214.15
	I	50	8.74	9.88	39.08	386.10
	J	38	6.64	8.11	22.14	179.64
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	8761.26

Area Size	I Iso.	II Nomo.	III Amt. 12.96	IV Avg. Depth	V Δ A	VI Δ V
	A	162	20.99	20.99319	10	209.93
	B	152	19.70	20.35	15	305.18
1500/1	C	142	18.40	19.05	25	476.23
	D	132	17.11	17.75	50	887.68
	E	122	15.81	16.46	75	1234.32
	F	112	14.51	15.16	107.08	1623.52
	G	105	13.61	14.06	110.17	1549.02
	H	96	12.44	13.02	93.2	1213.80
	I	88	11.40	11.92	39.08	465.91
	J	80	10.37	11.09	22.14	245.59
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	8211.18

Area Size			Amt. 15.89			
	A	140	22.25	22.25	10	222.47
	B	132	20.98	21.61	15	324.18
700/1	C	124	19.70	20.34	25	508.51
	D	115	18.27	18.99	50	949.49
	E	107	17.00	17.64	75	1322.93
	F	98	15.57	16.29	107.08	1744.15
	G	92	14.62	15.10	110.17	1663.18
	H	84	13.35	13.98	93.2	1303.32
	I	63	10.01	11.68	39.08	456.45
	J	48	7.63	9.30	22.14	205.82
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	8700.49

Area Size			Amt. 16.70			
	A	136	22.71	22.71	10	227.13
	B	128	21.38	22.05	15	330.68
560/1	C	120	20.04	20.71	25	517.73
	D	111	18.54	19.29	50	964.47
	E	104	17.37	17.95	75	1346.50
	F	95	15.87	16.62	107.08	1779.38
	G	89	14.86	15.36	110.17	1692.74
	-	85	14.20	14.53	53.74	780.83
	H	72	12.02	13.11	39.47	517.46
	I	56	9.35	10.69	39.08	417.71
	J	43	7.18	8.70	22.14	192.64
	K					
	L					
	M					
	N					
	O					
					Sum =	8767.27

Area Size			Amt. 14.55			
	A	149	21.68	21.68	10	216.83
	B	140	20.37	21.03	15	315.42
1000/1	C	131	19.06	19.72	25	492.96
	D	122	17.75	18.41	50	920.43
	E	113	16.44	17.10	75	1282.42
	F	104	15.13	15.79	107.08	1690.71
	G	97	14.12	14.63	110.17	1611.24
	H	89	12.95	13.53	93.2	1261.34
	I	82	11.93	12.44	39.08	486.24
	J	60	8.73	10.97	22.14	242.93
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	8520.53

Area Size			Amt. 15.17			
	A	145	21.99	21.99	10	219.90
	B	136	20.62	21.31	15	319.61
850/1	C	128	19.41	20.02	25	500.46
	D	119	18.05	18.73	50	936.46
	E	110	16.68	17.36	75	1302.33
	F	101	15.32	16.00	107.08	1713.22
	G	94	14.26	14.79	110.17	1629.00
	H	87	13.19	13.72	93.2	1279.14
	-	83	12.59	12.89	22.8	293.90
	I	72	10.92	11.75	16.29	191.46
	J	54	8.19	10.10	22.14	223.62
	K					
	L					
	M					
	N					
	O					
					Sum =	8609.09

Table 52: Completed Computation Sheets for the Second 6-hr Increment for the Banister River Study Watershed

Increment: 2nd

Drainage: Banister River Study Watershed *Area:* 546.7 square miles *Date:* 3/8/2012

Area Size	I Iso.	II Nomo.	III Amt. 5.37	IV Avg. Depth	V Δ A	VI Δ V
	A	100	5.37	5.37	10	53.66
	B	64	3.43	4.40	15	66.00
10/2	C	48	2.58	3.01	25	75.13
	D	39	2.09	2.33	50	116.71
	E	30	1.61	1.85	75	138.85
	F	24	1.29	1.45	107.08	155.14
	G	20	1.07	1.18	110.17	130.06
	H	14	0.75	0.91	93.2	85.02
	I	10	0.54	0.64	39.08	25.16
	J	7	0.38	0.49	22.14	10.81
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	856.55

Area Size	I Iso.	II Nomo.	III Amt. 4.37	IV Avg. Depth	V Δ A	VI Δ V
	A	108	4.72	4.72	10	47.18
	B	103	4.50	4.61	15	69.13
100/2	C	99	4.32	4.41	25	110.30
	D	95	4.15	4.24	50	211.86
	E	79	3.45	3.80	75	285.03
	F	65	2.84	3.15	107.08	336.78
	G	55	2.40	2.62	110.17	288.75
	H	47	2.05	2.23	93.2	207.63
	I	38.5	1.68	1.87	39.08	72.98
	J	31	1.35	1.58	22.14	35.06
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1664.70

Area Size			Amt. 4.97			
	A	103	5.12	5.12	10	51.18
	B	98	4.87	4.99	15	74.91
25/2	C	72	3.58	4.22	25	105.59
	D	59	2.93	3.25	50	162.74
	E	48	2.39	2.66	75	199.38
	F	39	1.94	2.16	107.08	231.46
	G	32.5	1.61	1.78	110.17	195.71
	H	26	1.29	1.45	93.2	135.46
	I	20	0.99	1.14	39.08	44.66
	J	15.5	0.77	0.93	22.14	20.52
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1221.60

Area Size			Amt. 4.13			
	A	110	4.54	4.54	10	45.38
	B	105	4.33	4.44	15	66.53
175/2	C	101.5	4.19	4.26	25	106.50
	D	97.5	4.02	4.11	50	205.26
	E	95	3.92	3.97	75	297.83
	F	79	3.26	3.59	107.08	384.36
	G	66.5	2.74	3.00	110.17	330.68
	H	56.5	2.33	2.54	93.2	236.48
	I	47	1.94	2.14	39.08	83.44
	J	38.5	1.59	1.83	22.14	40.60
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1797.05

Area Size			Amt. 4.67			
	A	105.5	4.93	4.93	10	49.25
	B	100.5	4.69	4.81	15	72.13
50/2	C	96.5	4.51	4.60	25	114.97
	D	76	3.55	4.03	50	201.34
	E	62.5	2.92	3.23	75	242.48
	F	51	2.38	2.65	107.08	283.70
	G	43.5	2.03	2.21	110.17	243.03
	H	36	1.68	1.86	93.2	172.96
	I	29	1.35	1.52	39.08	59.30
	J	23	1.07	1.27	22.14	28.11
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1467.27

Area Size			Amt. 4.13			
	A	111.5	4.60	4.60	10	46.05
	B	107	4.42	4.51	15	67.68
300/2	C	103.5	4.27	4.35	25	108.67
	D	100	4.13	4.20	50	210.11
	E	97.5	4.03	4.08	75	305.88
	F	95	3.92	3.98	107.08	425.66
	G	80	3.30	3.61	110.17	398.13
	H	67.5	2.79	3.05	93.2	283.88
	I	57	2.35	2.57	39.08	100.47
	J	47	1.94	2.23	22.14	49.38
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1995.90

(continued)

		Increment:	2nd
Drainage: Banister River Study Watershed	*Area:* 546.7 square miles	*Date:*	3/8/2012

Area Size	I Iso.	II Nomo.	III Amt. 4.10	IV Avg. Depth	V Δ A	VI Δ V
	A	113	4.63	4.63	10	46.31
	B	109	4.47	4.55	15	68.24
450/2	C	105	4.30	4.39	25	109.63
	D	102	4.18	4.24	50	212.08
	E	99.5	4.08	4.13	75	309.67
	F	97	3.98	4.03	107.08	431.16
	G	95	3.89	3.93	110.17	433.44
	H	77.5	3.18	3.53	93.2	329.43
	I	66	2.70	2.94	39.08	114.91
	J	54.5	2.23	2.56	22.14	56.75
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	2111.62

Area Size	I Iso.	II Nomo.	III Amt. 3.86	IV Avg. Depth	V Δ A	VI Δ V
	A	117	4.51	4.51	10	45.13
	B	113	4.36	4.44	15	66.54
1500/2	C	110	4.24	4.30	25	107.53
	D	107	4.13	4.19	50	209.27
	E	105	4.05	4.09	75	306.66
	F	103	3.97	4.01	107.08	429.57
	G	100.5	3.88	3.92	110.17	432.41
	H	99	3.82	3.85	93.2	358.61
	I	97	3.74	3.78	39.08	147.73
	J	95.5	3.68	3.72	22.14	82.46
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	2185.91

Area Size			Amt. 4.04			
	A	114.5	4.63	4.63	10	46.25
	B	110	4.44	4.53	15	68.02
700/2	C	107	4.32	4.38	25	109.57
	D	104	4.20	4.26	50	213.09
	E	101	4.08	4.14	75	310.54
	F	99	4.00	4.04	107.08	432.56
	G	97	3.92	3.96	110.17	436.14
	H	95	3.84	3.88	93.2	361.43
	I	78	3.15	3.49	39.08	136.55
	J	65.5	2.65	3.00	22.14	66.41
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	2180.55

Area Size			Amt. 4.07			
	A	114	4.64	4.64	10	46.41
	B	109.5	4.46	4.55	15	68.25
560/2	C	106	4.32	4.39	25	109.67
	D	102.5	4.17	4.24	50	212.22
	E	100.5	4.09	4.13	75	309.93
	F	98	3.99	4.04	107.08	432.69
	G	96	3.91	3.95	110.17	435.08
	-	95	3.87	3.89	53.74	208.95
	H	85	3.46	3.66	39.47	144.63
	I	71.5	2.91	3.19	39.08	124.50
	J	60	2.44	2.77	22.14	61.34
	K					
	L					
	M					
	N					
	O					
					Sum =	2153.68

Area Size			Amt. 3.97			
	A	116	4.61	4.61	10	46.06
	B	112	4.45	4.53	15	67.90
1000/2	C	108.5	4.31	4.38	25	109.44
	D	105	4.17	4.24	50	211.93
	E	103	4.09	4.13	75	309.71
	F	101	4.01	4.05	107.08	433.67
	G	99	3.93	3.97	110.17	437.44
	H	97	3.85	3.89	93.2	362.66
	I	95	3.77	3.81	39.08	148.96
	J	76	3.02	3.55	22.14	78.50
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	2206.27

Area Size			Amt. 4.00			
	A	115	4.60	4.60	10	46.05
	B	111	4.44	4.52	15	67.87
850/2	C	107.5	4.30	4.37	25	109.36
	D	104.5	4.18	4.24	50	212.21
	E	102	4.08	4.13	75	310.06
	F	100	4.00	4.04	107.08	433.04
	G	98	3.92	3.96	110.17	436.71
	H	96	3.84	3.88	93.2	361.98
	-	94	3.76	3.80	22.8	86.73
	I	85	3.40	3.58	16.29	58.38
	J	71	2.84	3.24	22.14	71.63
	K					
	L					
	M					
	N					
	O					
					Sum =	2194.02

Table 53: Completed Computation Sheets for the Third 6-hr Increment for the Banister River Study Watershed

Drainage: Banister River Study Watershed *Area:* 546.7 square miles *Increment:* 3rd *Date:* 3/8/2012

Area Size	I Iso.	II Nomo.	III Amt. 2.63	IV Avg. Depth	V Δ A	VI Δ V
	A	100	2.63	2.63	10	26.30
	B	65	1.71	2.17	15	32.55
10/3	C	48	1.26	1.49	25	37.15
	D	39	1.03	1.14	50	57.20
	E	30	0.79	0.91	75	68.05
	F	24	0.63	0.71	107.08	76.04
	G	20	0.53	0.58	110.17	63.74
	H	14	0.37	0.45	93.2	41.67
	I	10	0.26	0.32	39.08	12.33
	J	6.5	0.17	0.24	22.14	5.21
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	420.25

Area Size	I Iso.	II Nomo.	III Amt. 2.63	IV Avg. Depth	V Δ A	VI Δ V
	A	102.3	2.69	2.69	10	26.90
	B	100.7	2.65	2.67	15	40.04
100/3	C	99.3	2.61	2.63	25	65.75
	D	98.6	2.59	2.60	50	130.12
	E	81.5	2.14	2.37	75	177.62
	F	68	1.79	1.97	107.08	210.51
	G	59	1.55	1.67	110.17	183.99
	H	49	1.29	1.42	93.2	132.36
	I	42	1.10	1.20	39.08	46.77
	J	35.5	0.93	1.05	22.14	23.32
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1037.39

Area Size			Amt. 2.63			
	A	101	2.66	2.66	10	26.56
	B	99	2.60	2.63	15	39.45
25/3	C	74.5	1.96	2.28	25	57.04
	D	60.5	1.59	1.78	50	88.76
	E	48.5	1.28	1.43	75	107.50
	F	40	1.05	1.16	107.08	124.62
	G	34	0.89	0.97	110.17	107.21
	H	27	0.71	0.80	93.2	74.76
	I	21.5	0.57	0.64	39.08	24.92
	J	17	0.45	0.53	22.14	11.73
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	662.56

Area Size			Amt. 2.63			
	A	102.8	2.70	2.70	10	27.04
	B	101.3	2.66	2.68	15	40.26
175/3	C	100	2.63	2.65	25	66.18
	D	99.2	2.61	2.62	50	130.97
	E	98.8	2.60	2.60	75	195.28
	F	83	2.18	2.39	107.08	255.99
	G	71	1.87	2.03	110.17	223.11
	H	59.5	1.56	1.72	93.2	159.94
	I	51	1.34	1.45	39.08	56.79
	J	44	1.16	1.29	22.14	28.47
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1184.02

Area Size			Amt. 2.63			
	A	101.6	2.67	2.67	10	26.72
	B	99.8	2.62	2.65	15	39.73
50/3	C	98.5	2.59	2.61	25	65.19
	D	78.5	2.06	2.33	50	116.38
	E	63	1.66	1.86	75	139.55
	F	53.5	1.41	1.53	107.08	164.04
	G	46	1.21	1.31	110.17	144.15
	H	37.5	0.99	1.10	93.2	102.34
	I	31.5	0.83	0.91	39.08	35.46
	J	26	0.68	0.79	22.14	17.38
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	850.94

Area Size			Amt. 2.63			
	A	103.4	2.72	2.72	10	27.19
	B	101.9	2.68	2.70	15	40.50
300/3	C	100.7	2.65	2.66	25	66.60
	D	99.8	2.62	2.64	50	131.83
	E	99.3	2.61	2.62	75	196.36
	F	99	2.60	2.61	107.08	279.23
	G	86	2.26	2.43	110.17	268.02
	H	72	1.89	2.08	93.2	193.64
	I	62	1.63	1.76	39.08	68.86
	J	53	1.39	1.56	22.14	34.53
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1306.76

(continued)

							Increment:	3rd
Drainage:	Banister River Study Watershed			*Area:*	546.7 square miles		*Date:*	3/8/2012

Area Size	I Iso.	II Nomo.	III Amt. 2.61	IV Avg. Depth	V Δ A	VI Δ V
	A	103.8	2.71	2.71	10	27.09
	B	102.4	2.67	2.69	15	40.36
450/3	C	101.2	2.64	2.66	25	66.42
	D	100.3	2.62	2.63	50	131.47
	E	99.8	2.60	2.61	75	195.83
	F	99.5	2.60	2.60	107.08	278.47
	G	99.2	2.59	2.59	110.17	285.65
	H	84	2.19	2.39	93.2	222.80
	I	71	1.85	2.02	39.08	79.04
	J	60	1.57	1.77	22.14	39.12
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1366.24

Area Size	I Iso.	II Nomo.	III Amt. 2.46	IV Avg. Depth	V Δ A	VI Δ V
	A	105	2.58	2.58	10	25.79
	B	103.8	2.55	2.56	15	38.47
1500/3	C	102.7	2.52	2.54	25	63.41
	D	101.7	2.50	2.51	50	125.52
	E	101	2.48	2.49	75	186.72
	F	100.7	2.47	2.48	107.08	265.27
	G	100.3	2.46	2.47	110.17	271.98
	H	100	2.46	2.46	93.2	229.28
	I	99.7	2.45	2.45	39.08	95.85
	J	99.4	2.44	2.45	22.14	54.17
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1356.46

Area Size			Amt. 2.57			
	A	104.2	2.68	2.68	10	26.80
	B	102.9	2.65	2.66	15	39.96
700/3	C	101.7	2.62	2.63	25	65.79
	D	100.8	2.59	2.60	50	130.23
	E	100.2	2.58	2.59	75	193.89
	F	99.9	2.57	2.57	107.08	275.59
	G	99.6	2.56	2.57	110.17	282.69
	H	99.2	2.55	2.56	93.2	238.31
	I	85	2.19	2.37	39.08	92.59
	J	70.5	1.81	2.07	22.14	45.93
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1391.79

Area Size			Amt. 2.59			
	A	104	2.70	2.70	10	26.96
	B	102.7	2.66	2.68	15	40.19
560/3	C	101.5	2.63	2.65	25	66.18
	D	100.6	2.61	2.62	50	130.99
	E	100	2.59	2.60	75	195.03
	F	99.7	2.58	2.59	107.08	277.20
	G	99.4	2.58	2.58	110.17	284.35
	-	97	2.51	2.55	53.74	136.82
	H	91	2.36	2.44	39.47	96.19
	I	77.5	2.01	2.18	39.08	85.36
	J	64.5	1.67	1.91	22.14	42.25
	K					
	L					
	M					
	N					
	O					
					Sum =	1381.54

Area Size			Amt. 2.53			
	A	104.6	2.64	2.64	10	26.45
	B	103.3	2.61	2.63	15	39.43
1000/3	C	102.3	2.59	2.60	25	64.98
	D	101.3	2.56	2.57	50	128.70
	E	100.6	2.54	2.55	75	191.44
	F	100.3	2.54	2.54	107.08	271.97
	G	99.9	2.53	2.53	110.17	278.84
	H	99.6	2.52	2.52	93.2	235.07
	I	99.3	2.51	2.51	39.08	98.27
	J	82.5	2.09	2.38	22.14	52.77
	K					
	L					
	M					
	N					
	O					
	P					
					Sum =	1387.90

Area Size			Amt. 2.55			
	A	104.4	2.66	2.66	10	26.62
	B	103.2	2.63	2.65	15	39.70
850/3	C	102	2.60	2.62	25	65.40
	D	101.1	2.58	2.59	50	129.47
	E	100.4	2.56	2.57	75	192.67
	F	100.1	2.55	2.56	107.08	273.71
	G	99.7	2.54	2.55	110.17	280.63
	H	99.4	2.53	2.54	93.2	236.57
	-	98	2.50	2.52	22.8	57.38
	I	92	2.35	2.42	16.29	39.46
	J	76.5	1.95	2.23	22.14	49.31
	K					
	L					
	M					
	N					
	O					
					Sum =	1390.92

D. Distribution of Storm-Area Averaged PMP over the Drainage

<u>Steps:</u>

1. For the pattern area size for PMP determined in step C13, use the data in step A3 to extend the appropriate depth-duration curve in step A4 to 72-hr, and read off values from the smoothed curve for each 6 hr (6 to 72 hr).

Having concluded that the maximum volume occurs for a PMP pattern near 50 mi^2 for the Whitethorn Creek Study Watershed and 560 mi^2 for the Banister River Study Watershed, the next step involved assigning values to each of the isohyets used in each analysis for all twelve 6-hr increments. Using Figure 50 and Figure 51 from Section A.4., PMP depths from the lines corresponding to 50 mi^2 and 560 mi^2 area sizes from the two analyses, respectively, were read off the plots for each 6-hr increment of the 72-hr storm. These depths are shown in Table 54 and Table 55. For the Banister River analysis, this required repeating the entire procedure outlined thus far to be conducted for the new intermediate area size. Values corresponding to this area, along with their associated procedure step are displayed in Table 56.

Table 54: Cumulative Depth-Duration Values for the 50 mi2 Pattern of the Whitethorn Creek PMS

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Incremental PMP (in.)	24.51	29.14	31.64	33.26	34.45	35.45	36.45	37.26	37.82	38.27	38.64	39.03

Table 55: Cumulative Depth-Duration Values for the 560 mi2 Pattern of the Banister River PMS

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Incremental PMP (in.)	17.30	21.44	24.2	25.97	27	27.8	28.5	29.15	29.8	30.25	30.75	31.22

Table 56: Procedure Parameters Obtained for the 560 mi2 Area Size – Banister River Analysis

Procedure Step A.3: Storm Duration/D-A-D Values (in)				
6-Hour	12-Hour	24-Hour	48-Hour	72-Hour
17.30	21.44	25.97	29.15	31.22

Procedure Step A.5: User Corrected Incremental Differences (in)		
6-Hour Periods/Incremental Differences (in.)		
1 (0-6)	2 (6-12)	3 (12-18)
16.94	4.13	2.63

Procedure Step B.4: Areally-Reduced User Corrected Incremental Differences (in)		
6-Hour Periods/Incremental Differences (in.)		
1 (0-6)	2 (6-12)	3 (12-18)
16.70	4.07	2.59

2. *Obtain 6-hr incremental amounts for data in step D1 for the 4th through 12th 6-hr periods in accordance with step A5, and follow procedural steps B1 to B4 to adjust these incremental values for isohyetal orientation, if needed.*

From the values presented in Table 54 and in Table 55, incremental depths for each of the 6-hr periods were obtained. These values are a result of successive subtraction of the cumulative PMP depths of adjacent increments. Table 57 and Table 58 display these incremental depths.

Table 57: Incremental Depth-Duration Values for the 50 mi^2 Pattern – Whitethorn Creek Analysis

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Incremental PMP (in.)	24.51	4.63	2.50	1.62	1.19	1.00	1.00	0.81	0.56	0.45	0.37	0.39

Table 58: Incremental Depth-Duration Values for the 560 mi^2 Pattern – Banister River Analysis

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Incremental PMP (in.)	17.30	4.14	2.76	1.77	1.03	0.80	0.70	0.65	0.65	0.45	0.50	0.47

Due to some of the smoothing techniques that were applied in Section A.5., slightly different values are obtained for the first three 6-hr periods for each study. For consistency, the smoothed data values were substituted in for the first three incremental depths. These smoothed, substituted depths are shown in red in Table 59 and in Table 60. In addition, the incremental depths shown in blue were rearranged to maintain the ever-decreasing trend.

Table 59: Smoothed Incremental Depth-Duration Values for the 50 mi2 Pattern – Whitethorn Creek Analysis

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Incremental PMP (in.)	24.44	4.66	2.51	1.62	1.19	1.00	1.00	0.81	0.56	0.45	0.39	0.37

Table 60: Smoothed Incremental Depth-Duration Values for the 560 mi2 Pattern – Banister River Analysis

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Incremental PMP (in.)	16.94	4.13	2.63	1.77	1.03	0.80	0.70	0.65	0.65	0.50	0.47	0.45

After these smoothed values were added, the applicable areal-reduction factor was applied. As previously stated, this reduction factor is only applicable to PMS events larger than 300 mi^2. Therefore, no reduction factor was factored in to the Whitethorn Creek smoothed incremental Depth-Duration values from Table 59. However, an areal-reduction factor of 98.6 percent corresponding to a 560 mi^2 area was applied to the Banister River analysis values in Table 60, as determined from the reduction factor figure in HMR52 (Figure 60 in this Appendix). The areally-reduced smoothed incremental Depth-Duration values for the Banister River study are presented in Table 61.

Table 61: Smoothed, Areally-Reduced Incremental Depth-Duration Values for the 560 mi2 Pattern – Banister River Analysis

Duration (hr.)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60	60-66	66-72
Adjusted PMP (in.)	16.70	4.07	2.59	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44

3. *Steps D1 and D2 give incremental average depths for each of the 12 6-hr periods in the 72-hr storm. To obtain the values for the isohyets that cover the drainage, multiply the 1st 6-hr incremental depth by the 1st 6-hr percentages obtained from table 15 or the nomogram (fig- 16) for the area size determined in step C13. Then multiply the 2nd 6- hr incremental depth by the 2nd 6—hr percentages from table l6 or the nomogram (fig. 18) for the same area size, and similarly for the 3rd 6—hr increment (table 17 or fig. 19). Finally, multiply each remaining 6-hr incremental depth by the 4th through 12th percentages in table 18 or the nomogram (fig. 20). As a result of this step, a matrix of the following form can be completed (to the extent of whichever isohyets cover the drainage).*

The next step involved distributing the incremental depth values over the five isohyets (A-E) that were selected for the Whitethorn Creek Study Watershed and the ten isohyets (A-J) that were used for the Banister River Study Watershed. To obtain the isohyetal depths, the nomogram percentages from Tables 15-18 in HMR52 are used. These percentages are presented in Table 62 and Table 63 for the Whitethorn Creek and Banister River analyses, respectively.

Table 62: Incremental PMP Percentage Multipliers (Tables 15-18 from HMR52) Corresponding to a 50 mi^2 Area – Whitethorn Creek Analysis

Isohyet	Nomogram Percentages for Each 6-hr Period (%)			
	1	2	3	4-12
A	106	105.5	101.6	100
B	99	100.5	99.8	100
C	92	96.5	98.5	100
D	66	76	78.5	78.5
E	54	62.5	63	63

Table 63: Incremental PMP Percentage Multipliers (Tables 15-18 from HMR52) Corresponding to a 560 mi^2 Area – Banister River Analysis

Isohyet	Nomogram Percentages for Each 6-hr Period (%)			
	1	2	3	4-12
A	136	114	104	100
B	128	109.5	102.7	100
C	120	106	101.5	100
D	111	102.5	100.6	100
E	104	100.5	100	100
F	95	98	99.7	100
G	89	96	99.4	100
-	85	95	97	100
H	72	85	91	91
I	56	71.5	77.5	77.5
J	43	60	64.5	64.5

Once the relevant nomogram values were obtained, the isohyetal depths were assigned by multiplying the 6-hr incremental depths values from Table 59 and Table 61 by their corresponding percentages from Table 62 and Table 63. These new values are shown in Table 64 and Table 65 for the Whitethorn Creek and Banister River analyses, respectively. Note that for the fourth through the twelfth 6-hr increments, the depths are the same in each increment with the exception of the D and E isohyets for the Whitethorn Creek study and the H, I, and J isohyets for the Banister River study. Because these isohyets are larger than the pattern areas of maximum volume (50 mi^2 and 560 mi^2), "residual precipitation" is considered to occur. This residual precipitation has a reduction factor applied to it, whereas there is no scaling done to the other isohyets in the last nine 6-hr periods. For these periods, HMR52 recommends modeling the precipitation depths as constant values over the entire area of maximum volume (50 mi^2 and 560 mi^2), rather than assigning different values to each isohyet, as is done for the first three 6-hr increments. The authors of HMR52 recognized that intense rainfall cannot be sustained for long periods of time and therefore suggest only having three periods of high intensity precipitation.

Table 64: Isohyetal PMP Depths for Each 6-hr Period in the 72-hr Storm – Whitethorn Creek Analysis

Isohyet	Area (mi^2)	Incremental PMP Depths (in.) - 6-hr Periods - Whitethorn Creek Analysis											
		1	2	3	4	5	6	7	8	9	10	11	12
A	10	25.91	4.91	2.55	1.62	1.19	1.00	1.00	0.81	0.56	0.45	0.37	0.39
B	25	24.20	4.68	2.50	1.62	1.19	1.00	1.00	0.81	0.56	0.45	0.37	0.39
C	50	22.49	4.50	2.47	1.62	1.19	1.00	1.00	0.81	0.56	0.45	0.37	0.39
D	100	16.13	3.54	1.97	1.27	0.94	0.79	0.79	0.63	0.44	0.35	0.29	0.31
E	175	13.20	2.91	1.58	1.02	0.75	0.63	0.63	0.51	0.35	0.28	0.23	0.24

Table 65: Isohyetal PMP Depths for Each 6-hr Period in the 72-hr Storm – Banister River Analysis

Isohyet	Area (mi^2)	Incremental PMP Depths (in.) - 6-hr Periods - Banister River Analysis											
		1	2	3	4	5	6	7	8	9	10	11	12
A	10	22.71	4.64	2.70	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
B	25	21.38	4.46	2.66	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
C	50	20.04	4.32	2.63	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
D	100	18.54	4.17	2.61	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
E	175	17.37	4.09	2.59	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
F	300	15.87	3.99	2.58	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
G	450	14.86	3.91	2.58	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
-	560	14.20	3.87	2.51	1.74	1.02	0.79	0.69	0.64	0.64	0.49	0.46	0.44
H	700	12.02	3.46	2.36	1.59	0.92	0.72	0.63	0.58	0.58	0.45	0.42	0.40
I	1000	9.35	2.91	2.01	1.35	0.79	0.61	0.53	0.50	0.50	0.38	0.36	0.34
J	1500	7.18	2.44	1.67	1.13	0.65	0.51	0.45	0.41	0.41	0.32	0.30	0.29

4. *To obtain incremental average depths for the drainage, compute the incremental volumes for the area size of the PMP pattern determined in step C10. Divide each incremental volume by the drainage area (that portion covered by precipitation).*

The values in Table 64 and Table 65 represent the incremental isohyetal depths for the Whitethorn Creek and Banister River Study Watersheds with the 175 mi^2 and 1500 mi^2 PMP patterns placed as shown in Figure 57 and Figure 58. To analyze the watershed on a basin-wide scale (modeling the entire basin as having a single representative precipitation gauge), it is necessary to obtain incremental basin-averaged PMP depths for the entire watershed. The isohyetal pattern over the entire watershed is distributed and averaged based on how much of each isohyet falls inside of the watershed boundary. By summing up the products of each depth and the area to which it applies, and then by dividing the sum by the total area of the watershed, a basin-average PMP depth was obtained for each 6-hr period. In this way, one rainfall depth is applied to the entire watershed for any one six hour period. The final basin-averaged incremental PMP depths for the Whitethorn Creek Study Watershed are displayed in Table 66. The intermediate calculation results involved in this process are shown on the computation sheets in Table 68. In the same fashion, Table 67 shows the basin-averaged incremental PMP depths for the Banister River Study Watershed and Table 69 displays the computation sheets used to determine these values.

Table 66: Basin-Averaged Incremental PMP Depths for the Whitethorn Creek Study Watershed

6-hr Periods	1	2	3	4	5	6	7	8	9	10	11	12
Average PMP (in.)	24.23	4.7	2.49	1.6	1.18	0.99	0.99	0.8	0.55	0.45	0.39	0.37

Table 67: Basin-Averaged Incremental PMP Depths for the Banister River Study Watershed

6-hr Periods	1	2	3	4	5	6	7	8	9	10	11	12
Average PMP (in.)	16.04	3.94	2.53	1.70	0.99	0.77	0.67	0.62	0.62	0.48	0.45	0.43

5. *Should it be of interest to determine the isohyetal values for durations less than 6 hr within the greatest 6-hr increment, the procedure discussed in section 6.3 gives the following steps.*

For these analyses, durations of less than six hours were not considered so the steps outlined in HMR52 for this procedure were not carried out.

Table 68: Computation Sheets for Determining the Incremental Basin-Averaged PMP Depths for the Whitethorn Creek Study Watershed

Increment: 1 to 6

Drainage: Whitethorn Creek Study Watershed *Area:* 41.2 square miles *Date:* 11/21/2011

Area Size	I Iso.	II Nomo.	III Amt.	IV Avg. Depth	V Δ A	VI Δ V
			24.44			
50/1	A	106	25.91	25.91	10.00	259.07
	B	99	24.20	25.05	14.78	370.30
	C	92	22.48	23.34	13.15	306.99
	D	66	16.13	19.31	3.08	59.56
	E	54	13.20	15.84	0.22	3.45
				Total =	41.24	
					Sum =	999.36
					Avg. Depth =	24.23

Area Size	I Iso.	II Nomo.	III Amt.	IV Avg. Depth	V Δ A	VI Δ V
			1.62			
50/4	A	100	1.62	1.62	10.00	16.20
	B	100	1.62	1.62	14.78	23.95
	C	100	1.62	1.62	13.15	21.31
	D	78.5	1.27	1.45	3.08	4.46
	E	63	1.02	1.25	0.22	0.27
					Sum =	66.19
					Avg. Depth =	1.61

Area Size			Amt.			
			4.66			
50/2	A	105.5	4.92	4.92	10.00	49.16
	B	100.5	4.68	4.80	14.78	70.95
	C	96.5	4.50	4.59	13.15	60.37
	D	76	3.54	4.02	3.08	12.40
	E	62.5	2.91	3.48	0.22	0.76
					Sum =	193.64
					Avg. Depth =	4.70

Area Size			Amt.			
			1.19			
50/5	A	100	1.19	1.19	10.00	11.90
	B	100	1.19	1.19	14.78	17.59
	C	100	1.19	1.19	13.15	15.65
	D	78.5	0.93	1.06	3.08	3.28
	E	63	0.75	0.92	0.22	0.20
					Sum =	48.62
					Avg. Depth =	1.18

Area Size			Amt.			
			2.51			
50/3	A	101.6	2.55	2.55	10.00	25.50
	B	99.8	2.50	2.53	14.78	37.36
	C	98.5	2.47	2.49	13.15	32.73
	D	78.5	1.97	2.22	3.08	6.85
	E	63	1.58	1.93	0.22	0.42
					Sum =	102.87
					Avg. Depth =	2.49

Area Size			Amt.			
			1.00			
50/6	A	100	1.00	1.00	10.00	10.00
	B	100	1.00	1.00	14.78	14.78
	C	100	1.00	1.00	13.15	13.15
	D	78.5	0.79	0.89	3.08	2.75
	E	63	0.63	0.77	0.22	0.17
					Sum =	40.86
					Avg. Depth =	0.99

(continued)

Drainage: Whitethorn Creek Study Watershed | *Area:* 41.2 square miles | *Increment:* 7 to 12 | *Date:* 11/21/2011

Area Size	I Iso.	II Nomo.	III Amt. 1.00	IV Avg. Depth	V Δ A	VI Δ V
	A	100	1.00	1.00	10.00	10.00
	B	100	1.00	1.00	14.78	14.78
50/7	C	100	1.00	1.00	13.15	13.15
	D	78.5	0.79	0.89	3.08	2.75
	E	63	0.63	0.77	0.22	0.17
					Sum =	40.86
					Avg. Depth =	0.99

Area Size	I Iso.	II Nomo.	III Amt. 0.45	IV Avg. Depth	V Δ A	VI Δ V
	A	100	0.45	0.45	10.00	4.50
	B	100	0.45	0.45	14.78	6.65
50/10	C	100	0.45	0.45	13.15	5.92
	D	78.5	0.35	0.40	3.08	1.24
	E	63	0.28	0.35	0.22	0.08
					Sum =	18.38
					Avg. Depth =	0.45

Area Size			Amt. 0.81			
	A	100	0.81	0.81	10.00	8.10
	B	100	0.81	0.81	14.78	11.97
50/8	C	100	0.81	0.81	13.15	10.65
	D	78.5	0.64	0.72	3.08	2.23
	E	63	0.51	0.62	0.22	0.14
					Sum =	33.09
					Avg. Depth =	0.80

Area Size			Amt. 0.37			
	A	100	0.37	0.37	10.00	3.70
	B	100	0.37	0.37	14.78	5.47
50/11	C	100	0.37	0.37	13.15	4.87
	D	78.5	0.29	0.33	3.08	1.02
	E	63	0.23	0.28	0.22	0.06
					Sum =	15.12
					Avg. Depth =	0.37

Area Size			Amt. 0.56			
	A	100	0.56	0.56	10.00	5.60
	B	100	0.56	0.56	14.78	8.28
50/9	C	100	0.56	0.56	13.15	7.37
	D	78.5	0.44	0.50	3.08	1.54
	E	63	0.35	0.43	0.22	0.09
					Sum =	22.88
					Avg. Depth =	0.55

Area Size			Amt. 0.39			
	A	100	0.39	0.39	10.00	3.90
	B	100	0.39	0.39	14.78	5.76
50/12	C	100	0.39	0.39	13.15	5.13
	D	78.5	0.31	0.35	3.08	1.07
	E	63	0.25	0.30	0.22	0.07
					Sum =	15.93
					Avg. Depth =	0.39

Table 69: Computation Sheets for Determining the Incremental Basin-Averaged PMP Depths for the Banister River Study Watershed

Drainage: Banister River Study Watershed *Area:* 546.7 square miles *Increment:* 1 to 6 *Date:* 3/13/2012

Area Size	I Iso.	II Nomo.	III Amt. 16.70	IV Avg. Depth	V Δ A	VI Δ V
	A	136	22.71	22.71	10	227.13
	B	128	21.38	22.05	15	330.68
560/1	C	120	20.04	20.71	25	517.73
	D	111	18.54	19.29	50	964.47
	E	104	17.37	17.95	75	1346.50
	F	95	15.87	16.62	107.08	1779.38
	G	89	14.86	15.36	110.17	1692.74
	-	85	14.20	14.53	53.74	780.83
	H	72	12.02	13.11	39.47	517.46
	I	56	9.35	10.69	39.08	417.71
	J	43	7.18	8.70	22.14	192.64
				Total =	546.68	
					Sum =	8767.27
					Avg. Depth =	16.04

Area Size	I Iso.	II Nomo.	III Amt. 1.74	IV Avg. Depth	V Δ A	VI Δ V
	A	100	1.74	1.74	10	17.45
	B	100	1.74	1.74	15	26.17
560/4	C	100	1.74	1.74	25	43.62
	D	100	1.74	1.74	50	87.24
	E	100	1.74	1.74	75	130.86
	F	100	1.74	1.74	107.08	186.84
	G	100	1.74	1.74	110.17	192.23
	-	100	1.74	1.74	53.74	93.77
	H	91	1.59	1.67	39.47	65.77
	I	77.5	1.35	1.47	39.08	57.45
	J	64.5	1.13	1.28	22.14	28.43
					Sum =	929.85
					Avg. Depth =	1.70

Area Size			Amt. 4.07			
	A	114	4.64	4.64	10	46.41
	B	109.5	4.46	4.55	15	68.25
560/2	C	106	4.32	4.39	25	109.67
	D	102.5	4.17	4.24	50	212.22
	E	100.5	4.09	4.13	75	309.93
	F	98	3.99	4.04	107.08	432.69
	G	96	3.91	3.95	110.17	435.08
	-	95	3.87	3.89	53.74	208.95
	H	85	3.46	3.66	39.47	144.63
	I	71.5	2.91	3.19	39.08	124.50
	J	60	2.44	2.77	22.14	61.34
					Sum =	2153.68
					Avg. Depth =	3.94

Area Size			Amt. 1.02			
	A	100	1.02	1.02	10	10.15
	B	100	1.02	1.02	15	15.23
560/5	C	100	1.02	1.02	25	25.38
	D	100	1.02	1.02	50	50.77
	E	100	1.02	1.02	75	76.15
	F	100	1.02	1.02	107.08	108.73
	G	100	1.02	1.02	110.17	111.86
	-	100	1.02	1.02	53.74	54.57
	H	91	0.92	0.97	39.47	38.27
	I	77.5	0.79	0.86	39.08	33.43
	J	64.5	0.65	0.75	22.14	16.55
					Sum =	541.10
					Avg. Depth =	0.99

Area Size			Amt. 2.59			
	A	104	2.70	2.70	10	26.96
	B	102.7	2.66	2.68	15	40.19
560/3	C	101.5	2.63	2.65	25	66.18
	D	100.6	2.61	2.62	50	130.99
	E	100	2.59	2.60	75	195.03
	F	99.7	2.58	2.59	107.08	277.20
	G	99.4	2.58	2.58	110.17	284.35
	-	97	2.51	2.55	53.74	136.82
	H	91	2.36	2.44	39.47	96.19
	I	77.5	2.01	2.18	39.08	85.36
	J	64.5	1.67	1.91	22.14	42.25
					Sum =	1381.54
					Avg. Depth =	2.53

Area Size			Amt. 0.79			
	A	100	0.79	0.79	10	7.89
	B	100	0.79	0.79	15	11.83
560/6	C	100	0.79	0.79	25	19.72
	D	100	0.79	0.79	50	39.43
	E	100	0.79	0.79	75	59.15
	F	100	0.79	0.79	107.08	84.45
	G	100	0.79	0.79	110.17	86.88
	-	100	0.79	0.79	53.74	42.38
	H	91	0.72	0.75	39.47	29.73
	I	77.5	0.61	0.66	39.08	25.97
	J	64.5	0.51	0.58	22.14	12.85
					Sum =	420.27
					Avg. Depth =	0.77

(continued)

Drainage: Banister River Study Watershed *Area:* 546.7 square miles *Increment:* 7 to 12 *Date:* 3/13/2012

	I	II	III	IV	V	VI
Area Size	Iso.	Nomo.	Amt. 0.69	Avg. Depth	Δ A	Δ V
	A	100	0.69	0.69	10	6.90
	B	100	0.69	0.69	15	10.35
560/7	C	100	0.69	0.69	25	17.25
	D	100	0.69	0.69	50	34.50
	E	100	0.69	0.69	75	51.75
	F	100	0.69	0.69	107.08	73.89
	G	100	0.69	0.69	110.17	76.02
	-	100	0.69	0.69	53.74	37.08
	H	91	0.63	0.66	39.47	26.01
	I	77.5	0.53	0.58	39.08	22.72
	J	64.5	0.45	0.51	22.14	11.24
					Sum =	367.74
					Avg. Depth =	0.67

	I	II	III	IV	V	VI
Area Size	Iso.	Nomo.	Amt. 0.49	Avg. Depth	Δ A	Δ V
	A	100	0.49	0.49	10	4.93
	B	100	0.49	0.49	15	7.39
560/10	C	100	0.49	0.49	25	12.32
	D	100	0.49	0.49	50	24.65
	E	100	0.49	0.49	75	36.97
	F	100	0.49	0.49	107.08	52.78
	G	100	0.49	0.49	110.17	54.30
	-	100	0.49	0.49	53.74	26.49
	H	91	0.45	0.47	39.47	18.58
	I	77.5	0.38	0.42	39.08	16.23
	J	64.5	0.32	0.36	22.14	8.03
					Sum =	262.67
					Avg. Depth =	0.48

Area Size			Amt. 0.64			
	A	100	0.64	0.64	10	6.41
	B	100	0.64	0.64	15	9.61
560/8	C	100	0.64	0.64	25	16.02
	D	100	0.64	0.64	50	32.04
	E	100	0.64	0.64	75	48.06
	F	100	0.64	0.64	107.08	68.61
	G	100	0.64	0.64	110.17	70.59
	-	100	0.64	0.64	53.74	34.43
	H	91	0.58	0.61	39.47	24.15
	I	77.5	0.50	0.54	39.08	21.10
	J	64.5	0.41	0.47	22.14	10.44
					Sum =	341.47
					Avg. Depth =	0.62

Area Size			Amt. 0.46			
	A	100	0.46	0.46	10	4.63
	B	100	0.46	0.46	15	6.95
560/11	C	100	0.46	0.46	25	11.58
	D	100	0.46	0.46	50	23.17
	E	100	0.46	0.46	75	34.75
	F	100	0.46	0.46	107.08	49.61
	G	100	0.46	0.46	110.17	51.04
	-	100	0.46	0.46	53.74	24.90
	H	91	0.42	0.44	39.47	17.46
	I	77.5	0.36	0.39	39.08	15.25
	J	64.5	0.30	0.34	22.14	7.55
					Sum =	246.91
					Avg. Depth =	0.45

Area Size			Amt. 0.64			
	A	100	0.64	0.64	10	6.41
	B	100	0.64	0.64	15	9.61
560/9	C	100	0.64	0.64	25	16.02
	D	100	0.64	0.64	50	32.04
	E	100	0.64	0.64	75	48.06
	F	100	0.64	0.64	107.08	68.61
	G	100	0.64	0.64	110.17	70.59
	-	100	0.64	0.64	53.74	34.43
	H	91	0.58	0.61	39.47	24.15
	I	77.5	0.50	0.54	39.08	21.10
	J	64.5	0.41	0.47	22.14	10.44
					Sum =	341.47
					Avg. Depth =	0.62

Area Size			Amt. 0.44			
	A	100	0.44	0.44	10	4.44
	B	100	0.44	0.44	15	6.65
560/12	C	100	0.44	0.44	25	11.09
	D	100	0.44	0.44	50	22.18
	E	100	0.44	0.44	75	33.27
	F	100	0.44	0.44	107.08	47.50
	G	100	0.44	0.44	110.17	48.87
	-	100	0.44	0.44	53.74	23.84
	H	91	0.40	0.42	39.47	16.72
	I	77.5	0.34	0.37	39.08	14.61
	J	64.5	0.29	0.33	22.14	7.23
					Sum =	236.40
					Avg. Depth =	0.43

E. Temporal Distribution

<u>Step:</u>

1. *In the matrix in step D3, storm-area averaged PMP has been distributed according to increasing 6-hr period. The discussion in chapter 2 provides guidance on distributing these incremental periods with time. A number of distributions are possible, with the choice being left to the user, depending on which is most appropriate for the drainage under study. Whatever distribution is selected must be applied to all isohyets. An example of one possible distribution is reordering the 6-hr incremental periods in step D3 as follows*:

6—hr Periods	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Temporal Order	*11*	*10*	*8*	*5*	*1*	*2*	*3*	*4*	*6*	*7*	*9*	*12*

The previous sections involved calculating storm-area averaged PMP depths for the twelve 6-hr periods in a 72-hr storm in decreasing order in terms of intensity. In this way, the three periods with the greatest intensity comprised the first 18 hours of the storm. After analyzing historic storm data, the creators of HMR52 recognized that a temporal sequence in which the most intense rainfall occurs in the first six hours and then decreases in intensity for each subsequent period is somewhat unrealistic. HMR52 suggests arranging the individual 6-hr increments so that the depths progressively decrease to either side of the greatest 6-hr increment. This would cause the smallest 6-hr increments to exist at either the beginning or the end of the sequence. In addition, the authors urge that the four greatest 6-hr increments should not be placed within the first 24 hours of the storm sequence. There are a number of possible distributions for practitioners to choose from but as a preliminary guide, HMR52 suggests some temporal patterns. Ideally, the selected sequence would result in the most critical flow (highest peaks) for the study watershed and therefore, multiple sequences could be evaluated.

For both the Whitethorn Creek and Banister River analyses, the same HMR52 sample distribution was chosen for evaluation. The selected temporal sequence placed the most intense rainfall at the beginning of the third day of the 72-hr storm, starting two thirds of the way into the storm. In this way, the first two days of the PMP event acted to saturate or nearly saturate the watershed, theoretically resulting in greater runoff/flow rates during the most intense period of the storm. The values from Table 64 and Table 65 have been reorganized in Table 70 and Table 71 to fit this sequence. The numbers in red beneath the tables correspond to the column numbers of the 6-hr periods from Table 64 and Table 65 and show how the columns have been reordered to match the selected temporal distribution. This shows how the storms begin with the four least intense periods, gradually building up to the third day of the storm. Figure 64 and Figure 65 show these distributions graphically as PMP depth histograms. Each colored bar on the plots corresponds to a different isohyet. The histograms show the evolution of the PMP storm over the 72-hr period and depict the precipitation depths for each isohyet for each of the 6-hr periods.

Table 70: Isohyetal PMP Depths for Whitethorn Creek Study Watershed

			Incremental PMP Depths (in.) for each 6-hr Period of the 72-hr Storm											
Isohyet	Area (km^2)	Area (mi^2)	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
			0 - 6	6 - 12	12 - 18	18 - 24	24 - 30	30 - 36	36 - 42	42 - 48	48 - 54	54 - 60	60 - 66	66 - 72
A	26	10	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.55	25.91	4.91	1.62	0.81
B	65	25	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.50	24.20	4.68	1.62	0.81
C	129	50	0.37	0.39	0.45	0.56	1.00	1.00	1.19	2.47	22.49	4.50	1.62	0.81
D	259	100	0.29	0.31	0.35	0.44	0.79	0.79	0.94	1.97	16.13	3.54	1.27	0.63
E	453	175	0.23	0.24	0.28	0.35	0.63	0.63	0.75	1.58	13.20	2.91	1.02	0.51
Order of Intensity			12	11	10	9	7	6	5	3	1	2	4	8

Table 71: Isohyetal PMP Depths for Banister River Study Watershed

			Incremental PMP Depths (in.) for each 6-hr Period of the 72-hr Storm											
Isohyet	Area (km^2)	Area (mi^2)	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
			0 - 6	6 - 12	12 - 18	18 - 24	24 - 30	30 - 36	36 - 42	42 - 48	48 - 54	54 - 60	60 - 66	66 - 72
A	26	10	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.70	22.71	4.64	1.74	0.64
B	65	25	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.66	21.38	4.46	1.74	0.64
C	129	50	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.63	20.04	4.32	1.74	0.64
D	259	100	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.61	18.54	4.17	1.74	0.64
E	453	175	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.59	17.37	4.09	1.74	0.64
F	777	300	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	15.87	3.99	1.74	0.64
G	1165	450	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.58	14.86	3.91	1.74	0.64
-	1450	560	0.44	0.46	0.49	0.64	0.69	0.79	1.02	2.51	14.20	3.87	1.74	0.64
H	1813	700	0.40	0.42	0.45	0.58	0.63	0.72	0.92	2.36	12.02	3.46	1.59	0.58
I	2590	1000	0.34	0.36	0.38	0.50	0.53	0.61	0.79	2.01	9.35	2.91	1.35	0.50
J	3885	1500	0.29	0.30	0.32	0.41	0.45	0.51	0.65	1.67	7.18	2.44	1.13	0.41
Order of Intensity			12	11	10	9	7	6	5	3	1	2	4	8

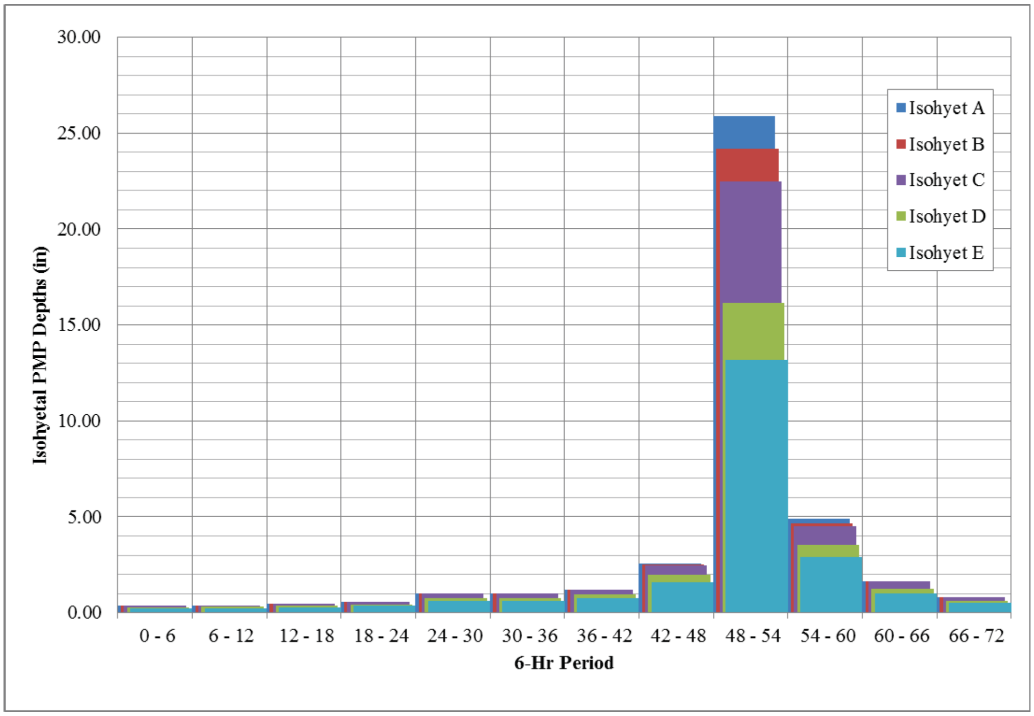

Figure 64: Temporal and Spatial (Depth) Distribution of the PMS - 72 Hour Storm – Whitethorn Creek Analysis

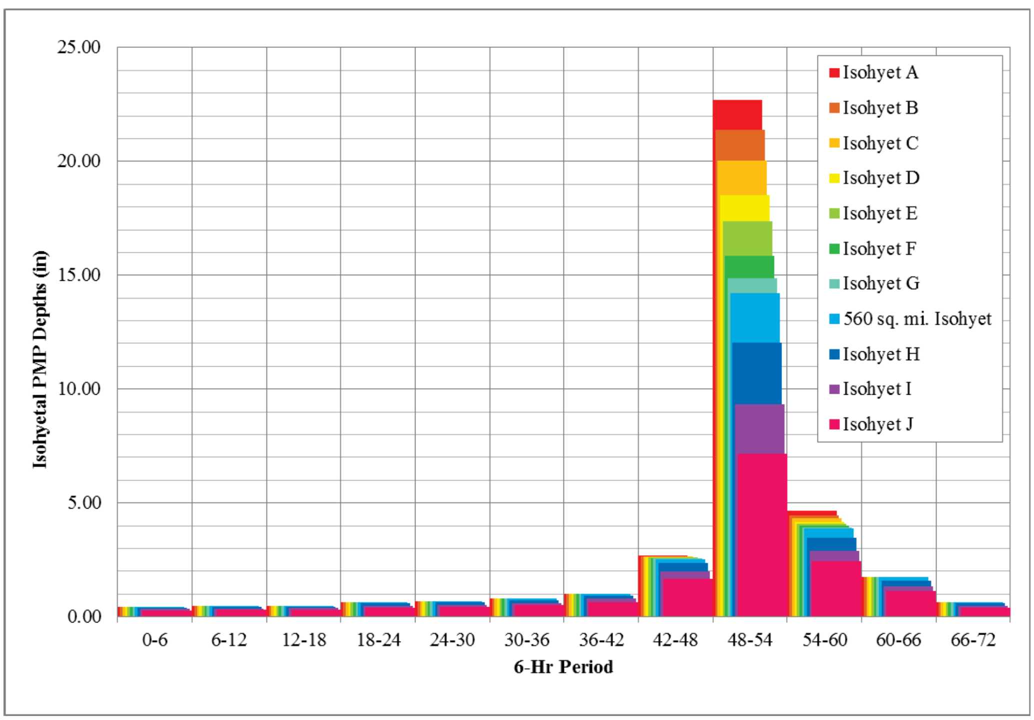

Figure 65: Temporal and Spatial (Depth) Distribution of PMS – 72-hr Storm – Banister River Analysis

CONCLUSION:

As the Probable Maximum Precipitation represents the theoretical worst-case rainstorm that can occur over a particular area, it must be considered as a driving control in the design and development of the Coles Hill site. By modeling the PMP and routing it through a hydrologic rainfall-runoff model, resulting stream flow hydrographs can be developed and used in conjunction with a hydraulic model to determine the extent of inundation from the ensuing Probable Maximum Flood. In this way, the PMF floodplain extent can be determined and mapped to ensure that the tailings cells and other important facilities are located at a high enough elevation so that they remain unaffected by the PMF. The PMP analyses for the Whitethorn Creek and Banister River Study Watershed outlined in this Appendix were conducted following the guidance and methodologies outlined in HMR51 and HMR52 as is the current best and standard engineering practice.

REFERENCES:

Hansen, E. M., Schreiner, L. C., and Miller, J. F. (1982). *NOAA Hydrometeorological Report No. 52: Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian*. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, and U.S. Department of the Army - Corps of Engineers.

Schreiner, L. C., and Riedel, J. T. (1978). *Hydrometeorological Report No. 51: Probable Maximum Precipitation Estimates, United States East of the 105th Meridian*. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, and U.S. Department of the Army - Corps of Engineers.

Appendix D:

Background Data Used to Compute T_c the Banister River Analysis

- **Banister River Study Watershed**

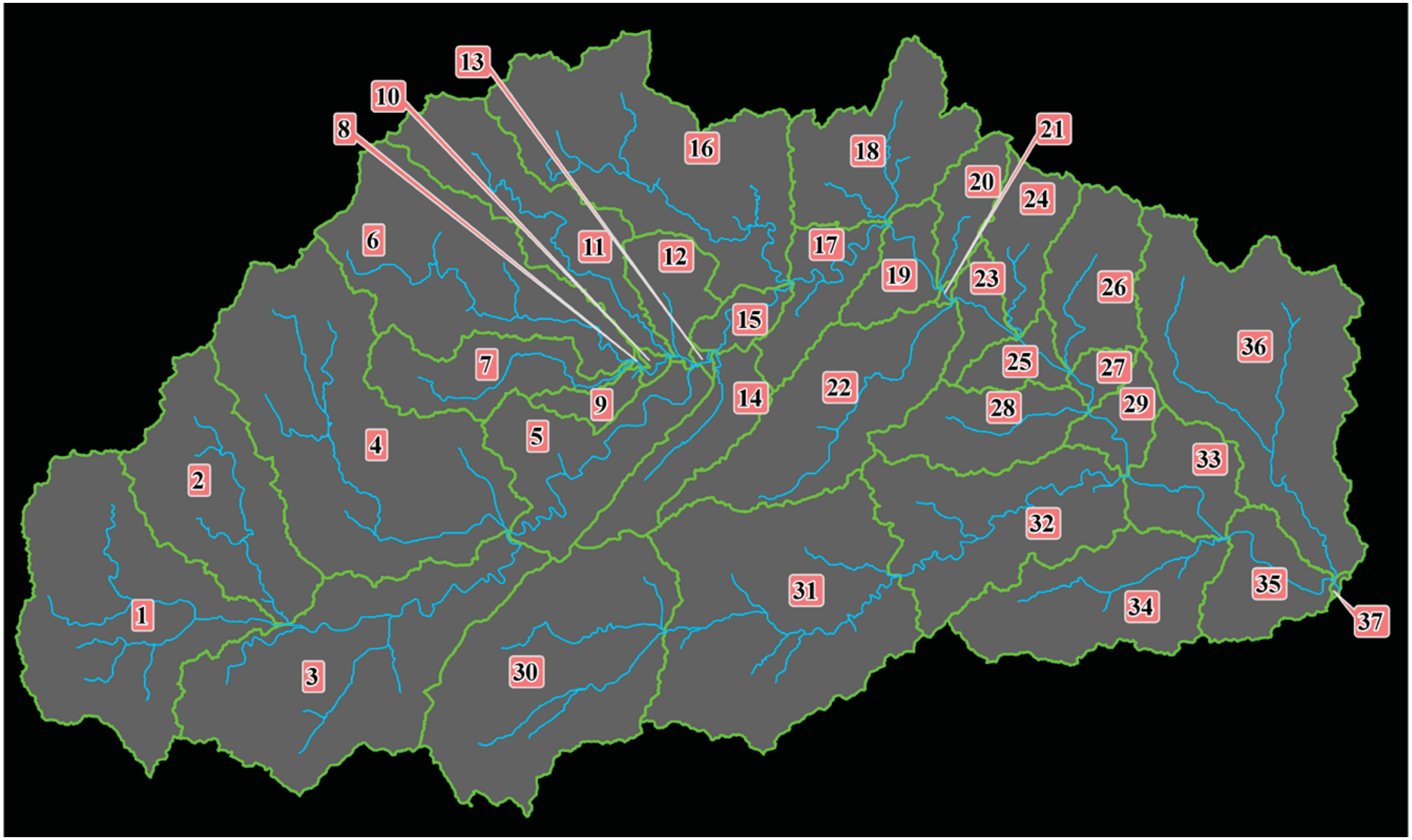

Figure 66: Subbasin Identification Map – Reference Table 72 for HEC-HMS Subbasin ID Numbers, Subbasin Names/Descriptions, and Subbasin Areas

Table 72: Selected Channel Roughness Coefficients (Manning's *n*) for Subbasins in the Banister River Study Watershed – Reference Figure 66 for Subbasin Map

HEC-HMS Subbasin ID Number	Subbasin Map Number	Subbasin Drainage Area (mi^2)	Subbasin Name/Description	Channel Roughness Coefficient (Manning's *n*)
W2420	1	35.0	Banister River Headwaters	0.040
W1990	2	21.9	Bearskin Creek	0.032
W2430	3	36.1	Banister River Upstream of Lake 12	0.042
W1980	4	45.5	Cherrystone Creek	0.040
W1880	5	15.9	Banister River Upstream of Lake 11	0.042
W1540	6	27.6	Whitethorn Creek (Upstream)	0.035
W1860	7	11.0	Mill Creek	0.040
W4710	8	0.1	Whitethorn Creek - From Mill Creek to Dry Branch	0.035
W4700	9	2.5	Dry Branch	0.025
W4720	10	0.6	Whitethorn Creek - From Dry Branch to Georges Creek	0.040
W2800	11	17.3	Georges Creek	0.032
W2830	12	6.3	Whitethorn Creek Downstream of Georges Creek	0.040
W4740	13	0.3	Banister River Upstream of Lake 10	0.045
W4730	14	9.8	Unnamed in NHD	0.032
W4750	15	3.3	Banister River Upstream of Lake 9	0.045
W1430	16	34.4	Stinking River	0.032
W4510	17	8.3	Banister River Upstream of Lake 8	0.045
W4500	18	17.0	Allen Creek	0.032
W4490	19	5.9	Banister River Upstream of Lake 7	0.041
W4540	20	5.4	Brush Creek	0.032
W4600	21	0.2	Banister River Upstream of Lake 6	0.041
W1970	22	22.2	Elkhorn Creek	0.032
W4630	23	4.0	Banister River Upstream of Lake 5	0.041
W4620	24	7.7	Runaway Creek	0.032
W4670	25	4.0	Banister River Upstream of Lake 4	0.040
W4650	26	11.1	Bradley Creek	0.032
W4680	27	2.1	Banister River Upstream of Lake 3	0.040
W4640	28	10.8	Bye Creek	0.032
W4690	29	4.7	Banister River Upstream of Lake 2	0.040
W2320	30	35.0	Sandy Creek (Upper)	0.040
W2520	31	41.0	Sandy Creek (Middle)	0.035
W2090	32	23.2	Sand Creek (Lower)	0.032
W2100	33	8.9	Banister River Upstream of Lake 1	0.040
W2300	34	19.3	Polecat Creek	0.032
W2190	35	9.0	Banister Lake	0.040
W1770	36	38.9	Terrible Creek	0.032
W2310	37	0.2	Banister River Downstream of Banister Dam	0.040

*HEC-HMS Reaches and Watersheds *HEC-HMS Watersheds Only

Table 73: Sheet Flow Travel Time Computation Sheet Used to Find the NRCS Segmental Velocity T_c Lag Time for Each Subbasin in the Banister River Study Watershed

			Sheet Flow Characteristics					
Watershed Name	Watershed Name	Watershed ID	Manning's Roughness Coefficient[1]	Flow Length (ft)	Two-Year 24-hour Rainfall[2] (in)	Land Slope (ft/ft)	Average Velocity - computed (ft/s)	Sheet Flow Tt (hr)
Stinking River	W1430	143	0.0404	100	3.4	1.97%	0.498	0.056
Whitethorn Creek (Upstream)	W1540	154	0.2535	100	3.4	5.43%	0.172	0.162
Terrible Creek	W1770	177	0.3250	100	3.4	2.68%	0.106	0.262
Mill Creek	W1860	186	0.0404	100	3.4	1.31%	0.423	0.066
Banister River Upstream of Lake 11	W1880	188	0.3600	100	3.4	6.05%	0.136	0.205
Elkhorn Creek	W1970	197	0.3600	100	3.4	1.65%	0.081	0.345
Cherrystone Creek	W1980	198	0.0678	100	3.4	1.68%	0.309	0.090
Bearskin Creek	W1990	199	0.3250	100	3.4	1.17%	0.076	0.364
Sand Creek (Lower)	W2090	209	0.3250	100	3.4	0.61%	0.059	0.473
Banister River Upstream of Lake 1	W2100	210	0.0678	100	3.4	0.35%	0.165	0.169
Georges Creek	W2800	280	0.3600	100	3.4	5.12%	0.127	0.219
Whitethorn Creek Downstream of Georges Creek	W2830	283	0.3250	100	3.4	1.04%	0.073	0.382
Banister River Upstream of Lake 7	W4490	449	0.0878	100	3.4	2.73%	0.305	0.091
Allen Creek	W4500	450	0.3200	100	3.4	1.74%	0.090	0.307
Dry Branch	W4700	470	0.0404	100	3.4	1.49%	0.445	0.062
Unnamed in NHD	W4730	473	0.3600	100	3.4	9.60%	0.163	0.170
Banister Lake	W2190	219	0.0678	100	3.4	1.20%	0.270	0.103
Polecat Creek	W2300	230	0.3250	100	3.4	2.42%	0.102	0.272
Banister River Downstream of Banister Dam	W2310	231	0.3600	100	3.4	1.72%	0.082	0.339
Sandy Creek (Upper)	W2320	232	0.3600	100	3.4	13.35%	0.186	0.149
Banister River Headwaters	W2420	242	0.3640	100	3.4	9.97%	0.164	0.169
Banister River Upstream of Lake 12	W2430	243	0.1535	100	3.4	1.81%	0.165	0.168
Sandy Creek (Middle)	W2520	252	0.2202	100	3.4	1.29%	0.108	0.257
Banister River Upstream of Lake 8	W4510	451	0.3250	100	3.4	0.69%	0.062	0.450
Brush Creek	W4540	454	0.2178	100	3.4	1.58%	0.118	0.235
Banister River Upstream of Lake 6	W4600	460	0.3250	100	3.4	0.72%	0.063	0.443
Runaway Creek	W4620	462	0.3250	100	3.4	3.17%	0.114	0.245
Banister River Upstream of Lake 5	W4630	463	0.4000	100	3.4	0.69%	0.052	0.531
Bye Creek	W4640	464	0.1827	100	3.4	1.68%	0.140	0.199
Bradley Creek	W4650	465	0.3600	100	3.4	1.90%	0.085	0.326
Banister River Upstream of Lake 10	W4740	474	0.3680	100	3.4	6.38%	0.136	0.204
Banister River Upstream of Lake 9	W4750	475	0.2301	100	3.4	2.47%	0.135	0.205
Banister River Upstream of Lake 4	W4670	467	0.3250	100	3.4	1.11%	0.075	0.372
Banister River Upstream of Lake 3	W4680	468	0.1827	100	3.4	3.28%	0.183	0.152
Banister River Upstream of Lake 2	W4690	469	0.0678	100	3.4	2.94%	0.386	0.072
Whitethorn Creek - From Mill Creek to Dry Branch	W4710	471	0.3787	100	3.4	0.70%	0.055	0.506
Whitethorn Creek - From Dry Branch to Georges Creek	W4720	472	0.3600	100	3.4	1.17%	0.070	0.395

[1] Estimates based on NLCD2006 Land Cover and Kalyanapu et al. Methodology (2009)

[2] 2-yr 24-hr precipitation estimates from NOAA Atlas 14 PF Data Server ranged from 3.25" to 3.40" within the watershed - 3.40" Selected as a Conservative Number

Table 74: Shallow Concentrated Flow Travel Time Computation Sheet Used to Find the NRCS Segmental Velocity Tc Lag Time for Each Subbasin in the Banister River Study Watershed

			Shallow Concentrated Flow Characteristics				
Watershed Name	Watershed Name	Watershed ID	Surface Description (1 - unpaved, 2 - paved)	Flow Length (ft)	Watercourse Slope (ft/ft)	Average Velocity - computed (ft/s)	Shallow Concentrated Flow Tt (hr)
Stinking River	**W1430**	**143**	1	20127	1.44%	1.94	2.888
Whitethorn Creek (Upstream)	**W1540**	**154**	1	18307	1.42%	1.92	2.645
Terrible Creek	**W1770**	**177**	1	14298	1.31%	1.85	2.151
Mill Creek	**W1860**	**186**	1	13006	0.98%	1.60	2.262
Banister River Upstream of Lake 11	**W1880**	**188**	1	6981	5.08%	3.64	0.533
Elkhorn Creek	**W1970**	**197**	1	19573	0.99%	1.61	3.387
Cherrystone Creek	**W1980**	**198**	1	15978	1.55%	2.01	2.209
Bearskin Creek	**W1990**	**199**	1	12438	1.53%	2.00	1.731
Sand Creek (Lower)	**W2090**	**209**	1	13450	1.43%	1.93	1.936
Banister River Upstream of Lake 1	**W2100**	**210**	1	16922	1.43%	1.93	2.436
Georges Creek	**W2800**	**280**	1	16120	2.12%	2.35	1.906
Whitethorn Creek Downstream of Georges Creek	**W2830**	**283**	1	12286	1.52%	1.99	1.716
Banister River Upstream of Lake 7	**W4490**	**449**	1	13892	1.74%	2.13	1.813
Allen Creek	**W4500**	**450**	1	11491	1.63%	2.06	1.550
Dry Branch	**W4700**	**470**	1	14516	1.28%	1.83	2.209
Unnamed in NHD	**W4730**	**473**	1	16679	2.54%	2.57	1.802
Banister Lake	**W2190**	**219**	1	18574	1.08%	1.68	3.077
Polecat Creek	**W2300**	**230**	1	16780	1.38%	1.90	2.459
Banister River Downstream of Banister Dam	**W2310**	**231**	1	3268	4.11%	3.27	0.278
Sandy Creek (Upper)	**W2320**	**232**	1	13626	3.29%	2.93	1.293
Banister River Headwaters	**W2420**	**242**	1	21010	1.97%	2.26	2.577
Banister River Upstream of Lake 12	**W2430**	**243**	1	13551	1.23%	1.79	2.104
Sandy Creek (Middle)	**W2520**	**252**	1	16447	1.34%	1.87	2.446
Banister River Upstream of Lake 8	**W4510**	**451**	1	15071	1.41%	1.92	2.185
Brush Creek	**W4540**	**454**	1	16297	1.35%	1.87	2.415
Banister River Upstream of Lake 6	**W4600**	**460**	1	2437	4.27%	3.33	0.203
Runaway Creek	**W4620**	**462**	1	17384	1.29%	1.83	2.635
Banister River Upstream of Lake 5	**W4630**	**463**	1	11099	1.93%	2.24	1.375
Bye Creek	**W4640**	**464**	1	15828	1.24%	1.80	2.447
Bradley Creek	**W4650**	**465**	1	12903	1.77%	2.15	1.670
Banister River Upstream of Lake 10	**W4740**	**474**	1	3336	3.12%	2.85	0.325
Banister River Upstream of Lake 9	**W4750**	**475**	1	7395	2.76%	2.68	0.766
Banister River Upstream of Lake 4	**W4670**	**467**	1	15180	1.53%	2.00	2.113
Banister River Upstream of Lake 3	**W4680**	**468**	1	10212	2.15%	2.37	1.199
Banister River Upstream of Lake 2	**W4690**	**469**	1	15781	1.41%	1.92	2.288
Whitethorn Creek - From Mill Creek to Dry Branch	**W4710**	**471**	1	2777	0.94%	1.56	0.493
Whitethorn Creek - From Dry Branch to Georges Creek	**W4720**	**472**	1	3145	3.35%	2.95	0.296

Table 75: Channel Flow Travel Time Computation Sheet Used to Find the NRCS Segmental Velocity T_c Lag Time for Each Subbasin in the Banister River Study Watershed

			Channel Flow Characteristics							
Watershed Name	**Watershed Name**	**Watershed ID**	**Cross-sectional Flow Area[3] (ft^2)**	**Wetted Perimeter[3] (ft)**	**Hydraulic Radius - computed (ft)**	**Channel Slope[4] (ft/ft)**	**Manning's Roughness Coefficient**	**Average Velocity - computed (ft/s)**	**Flow Length (ft)**	**Channel Flow Tt (hr)**
Stinking River	W1430	143	195.94	65.88	2.97	0.0042	0.032	6.22	69822	3.116
Whitethorn Creek (Upstream)	W1540	154	164.29	60	2.74	0.0038	0.035	5.12	67344	3.652
Terrible Creek	W1770	177	216.12	69.4	3.11	0.0021	0.032	4.54	66432	4.066
Mill Creek	W1860	186	79	40.68	1.94	0.0037	0.04	3.52	46637	3.683
Banister River Upstream of Lake 11	W1880	188	30.45	25.85	1.18	0.001	0.042	1.25	60800	13.534
Elkhorn Creek	W1970	197	138.02	54.7	2.52	0.0032	0.032	4.87	52327	2.985
Cherrystone Creek	W1980	198	244.74	74.13	3.30	0.0023	0.04	3.95	69085	4.858
Bearskin Creek	W1990	199	136.64	54.41	2.51	0.0035	0.032	5.08	44598	2.441
Sand Creek (Lower)	W2090	209	456.25	103.2	4.42	0.0021	0.032	5.73	52093	2.524
Banister River Upstream of Lake 1	W2100	210	82.46	34.6	2.38	0.0006	0.04	1.62	13444	2.300
Georges Creek	W2800	280	113.4	49.28	2.30	0.0042	0.032	5.25	63195	3.346
Whitethorn Creek Downstream of Georges Creek	W2830	283	327.43	86.53	3.78	0.0025	0.04	4.51	14760	0.909
Banister River Upstream of Lake 7	W4490	449	58.88	30.36	1.94	0.0017	0.041	2.32	10327	1.234
Allen Creek	W4500	450	111.71	48.89	2.28	0.0035	0.032	4.77	23341	1.360
Dry Branch	W4700	470	24.03	21.65	1.11	0.0035	0.025	3.77	6686	0.493
Unnamed in NHD	W4730	473	71.96	38.72	1.86	0.0024	0.032	3.44	27621	2.231
Banister Lake	W2190	219	384.255	145.894	2.63	0.0012	0.04	2.45	16509	1.868
Polecat Creek	W2300	230	123.76	51.62	2.40	0.0025	0.032	4.16	40933	2.734
Banister River Downstream of Banister Dam	W2310	231	127.38	45.7	2.79	0.0002	0.04	1.04	1370	0.366
Sandy Creek (Upper)	W2320	232	198.59	66.35	2.99	0.0023	0.04	3.70	37965	2.850
Banister River Headwaters	W2420	242	198.56	66.34	2.99	0.0031	0.04	4.30	47021	3.040
Banister River Upstream of Lake 12	W2430	243	433.24	100.4	4.32	0.0019	0.042	4.09	76267	5.183
Sandy Creek (Middle)	W2520	252	368.82	92.18	4.00	0.0018	0.035	4.54	49836	3.049
Banister River Upstream of Lake 8	W4510	451	64.85	38.05	1.70	0.0019	0.045	2.05	32133	4.346
Brush Creek	W4540	454	44.43	29.98	1.48	0.007	0.032	5.05	14508	0.798
Banister River Upstream of Lake 6	W4600	460	58.88	30.36	1.94	0.0002	0.041	0.80	2223	0.775
Runaway Creek	W4620	462	59.2	34.91	1.70	0.0045	0.032	4.43	19167	1.202
Banister River Upstream of Lake 5	W4630	463	74.33	31.98	2.32	0.0002	0.041	0.90	9725	3.004
Bye Creek	W4640	464	77.55	40.29	1.92	0.0038	0.032	4.43	26057	1.634
Bradley Creek	W4650	465	79.63	40.86	1.95	0.0028	0.032	3.83	25197	1.826
Banister River Upstream of Lake 10	W4740	474	55.36	24.81	2.23	0.0002	0.045	0.80	4530	1.578
Banister River Upstream of Lake 9	W4750	475	55.36	24.81	2.23	0.0016	0.045	2.26	20711	2.551
Banister River Upstream of Lake 4	W4670	467	74.33	31.98	2.32	0.0002	0.04	0.92	9218	2.778
Banister River Upstream of Lake 3	W4680	468	68.52	37.74	1.82	0.0019	0.04	2.41	4116	0.474
Banister River Upstream of Lake 2	W4690	469	68.52	37.74	1.82	0.0002	0.04	0.78	5856	2.080
Whitethorn Creek - From Mill Creek to Dry Branch	W4710	471	215.49	69.3	3.11	0.0042	0.035	5.86	1484	0.070
Whitethorn Creek - From Dry Branch to Georges Creek	W4720	472	228.94	71.56	3.20	0.0006	0.04	1.98	5544	0.779

[3] Green - Estimated Using Southern Piedmont Regression Equations From USGS

[3] Red - Estimated Using Data from VDOT and field surveys by VT students

[3] Blue - Estimated Using Southern Piedmont Regression Equations From USGS - Cumulative Areas

[4] Orange - Manually altered Due to Raster Cell Error at Either DS or US Point

Table 76: Summary of T_c Segmental Travel Times and NRCS Segmental Velocity Tc Lag Times for Each Subbasin in the Banister River Study Watershed

Watershed Name	Watershed Name	Watershed ID	Sheet Flow Tt (hr)	Shallow Concentrated Flow Tt (hr)	Channel Flow Tt (hr)	Watershed Time of travel (Tc) (hr)	Longest Flow Path (ft)	NRCS Segmental Velocity Lag Time (0.6 * Tc) (hr)
Stinking River	**W1430**	**143**	0.056	2.888	3.116	6.060	90049	3.636
Whitethorn Creek (Upstream)	**W1540**	**154**	0.162	2.645	3.652	6.458	85751	3.875
Terrible Creek	**W1770**	**177**	0.262	2.151	4.066	6.479	80830	3.887
Mill Creek	**W1860**	**186**	0.066	2.262	3.683	6.011	59743	3.606
Banister River Upstream of Lake 11	**W1880**	**188**	0.205	0.533	13.534	14.272	67881	8.563
Elkhorn Creek	**W1970**	**197**	0.345	3.387	2.985	6.717	72000	4.030
Cherrystone Creek	**W1980**	**198**	0.090	2.209	4.858	7.157	85162	4.294
Bearskin Creek	**W1990**	**199**	0.364	1.731	2.441	4.536	57136	2.722
Sand Creek (Lower)	**W2090**	**209**	0.473	1.936	2.524	4.934	65643	2.960
Banister River Upstream of Lake 1	**W2100**	**210**	0.169	2.436	2.300	4.905	30466	2.943
Georges Creek	**W2800**	**280**	0.219	1.906	3.346	5.472	79414	3.283
Whitethorn Creek Downstream of Georges Creek	**W2830**	**283**	0.382	1.716	0.909	3.007	27146	1.804
Banister River Upstream of Lake 7	**W4490**	**449**	0.091	1.813	1.234	3.139	24319	1.883
Allen Creek	**W4500**	**450**	0.307	1.550	1.360	3.217	34932	1.930
Dry Branch	**W4700**	**470**	0.062	2.209	0.493	2.764	21302	1.658
Unnamed in NHD	**W4730**	**473**	0.170	1.802	2.231	4.203	44400	2.522
Banister Lake	**W2190**	**219**	0.103	3.077	1.868	5.049	35184	3.029
Polecat Creek	**W2300**	**230**	0.272	2.459	2.734	5.465	57812	3.279
Banister River Downstream of Banister Dam	**W2310**	**231**	0.339	0.278	0.366	0.982	4739	0.589
Sandy Creek (Upper)	**W2320**	**232**	0.149	1.293	2.850	4.293	51691	2.576
Banister River Headwaters	**W2420**	**242**	0.169	2.577	3.040	5.787	68131	3.472
Banister River Upstream of Lake 12	**W2430**	**243**	0.168	2.104	5.183	7.454	89918	4.473
Sandy Creek (Middle)	**W2520**	**252**	0.257	2.446	3.049	5.752	66383	3.451
Banister River Upstream of Lake 8	**W4510**	**451**	0.450	2.185	4.346	6.981	47304	4.189
Brush Creek	**W4540**	**454**	0.235	2.415	0.798	3.447	30905	2.068
Banister River Upstream of Lake 6	**W4600**	**460**	0.443	0.203	0.775	1.420	4760	0.852
Runaway Creek	**W4620**	**462**	0.245	2.635	1.202	4.082	36651	2.449
Banister River Upstream of Lake 5	**W4630**	**463**	0.531	1.375	3.004	4.911	20924	2.946
Bye Creek	**W4640**	**464**	0.199	2.447	1.634	4.280	41985	2.568
Bradley Creek	**W4650**	**465**	0.326	1.670	1.826	3.821	38200	2.293
Banister River Upstream of Lake 10	**W4740**	**474**	0.204	0.325	1.578	2.107	7966	1.264
Banister River Upstream of Lake 9	**W4750**	**475**	0.205	0.766	2.551	3.522	28206	2.113
Banister River Upstream of Lake 4	**W4670**	**467**	0.372	2.113	2.778	5.263	24498	3.158
Banister River Upstream of Lake 3	**W4680**	**468**	0.152	1.199	0.474	1.826	14428	1.095
Banister River Upstream of Lake 2	**W4690**	**469**	0.072	2.288	2.080	4.440	21737	2.664
Whitethorn Creek - From Mill Creek to Dry Branch	**W4710**	**471**	0.506	0.493	0.070	1.069	4361	0.642
Whitethorn Creek - From Dry Branch to Georges Creek	**W4720**	**472**	0.395	0.296	0.779	1.471	8789	0.882

Appendix E:

HEC-HMS Basin Model Input Parameter Tables

- **Whitethorn Creek Study Watershed**
- **Banister River Study Watershed**

Table 77: Whitethorn Creek Study Watershed Selected Basin Model Parameters – Basin Model #1 (ARC II & NRCS Watershed Lag Equation)

HEC-HMS Watershed ID	Watershed Description	Watershed Area (mi^2)	Loss Method - SCS Curve Number			Transform Method - SCS Unit Hydrograph with NRCS Basin Lag Eq.		
			Initial Abstraction (in)	Curve Number - ARC II	Imperviousness (%)	Graph Type	ARC II Lag Time (hr)	ARC II Lag Time (min)
W570	Dry Branch Up	0.98	0.886	69.292	0	Standard	1.630	97.81
W580	Whitethorn Creek Up	12.02	1.367	59.397	0	Standard	3.692	221.52
W690	Whitethorn Creek Middle	12.89	1.358	59.565	0	Standard	3.227	193.60
W780	Whitethorn Creek Down	2.69	1.056	65.445	0	Standard	2.209	132.55
W800	Mill Creek Up	7.91	1.414	58.574	0	Standard	3.417	205.02
W810	Mill Creek Middle	1.54	1.336	59.951	0	Standard	1.673	100.39
W840	Mill Creek Down	0.61	0.873	69.615	0	Standard	2.076	124.57
W850	Whitethorn Creek - Mill Creek to Dry Branch	0.14	0.620	76.327	0	Standard	0.987	59.21
W890	Dry Branch Down	1.50	0.584	77.406	0	Standard	1.673	100.38
W930	Unnamed Tributary to Mill Creek	0.95	1.237	61.779	0	Standard	1.324	79.43

HEC-HMS Reach ID	Reach Description	Muskingum Routing Method		
		Muskingum K (hr)	Muskingum X	# of Subreaches
R100	Dry Branch Down	1.073	0.2	9
R120	Whitethorn Creek Middle	1.719	0.2	14
R330	Whitethorn Creek Down	1.406	0.2	12
R370	Whitethorn Creek - Mill Creek to Dry Branch	0.128	0.2	2
R410	Mill Creek Middle	0.814	0.2	6
R440	Mill Creek Down	0.928	0.2	8

Table 78: Whitethorn Creek Study Watershed Selected Basin Model Parameters – Basin Model #3 (ARC III & NRCS Watershed Lag Equation)

HEC-HMS Watershed ID	Watershed Description	Watershed Area (mi^2)	Loss Method - SCS Curve Number			Transform Method - SCS Unit Hydrograph with NRCS Basin Lag Eq.		
			Initial Abstraction (in)	Curve Number - ARC III	Imperviousness (%)	Graph Type	ARC III Lag Time (hr)	ARC III Lag Time (min)
W570	Dry Branch Up	0.98	0.376	84.158	0	Standard	1.046	62.77
W580	Whitethorn Creek Up	12.02	0.599	76.950	0	Standard	2.304	138.25
W690	Whitethorn Creek Middle	12.89	0.619	76.362	0	Standard	2.058	123.45
W780	Whitethorn Creek Down	2.69	0.463	81.189	0	Standard	1.413	84.79
W800	Mill Creek Up	7.91	0.618	76.401	0	Standard	2.123	127.35
W810	Mill Creek Middle	1.54	0.582	77.466	0	Standard	1.043	62.57
W840	Mill Creek Down	0.61	0.382	83.976	0	Standard	1.352	81.14
W850	Whitethorn Creek - Mill Creek to Dry Branch	0.14	0.255	88.709	0	Standard	0.653	39.17
W890	Dry Branch Down	1.50	0.237	89.404	0	Standard	1.112	66.69
W930	Unnamed Tributary to Mill Creek	0.95	0.544	78.621	0	Standard	0.835	50.09

HEC-HMS Reach ID	Reach Description	Muskingum Routing Method		
		Muskingum K (hr)	Muskingum X	# of Subreaches
R100	Dry Branch Down	1.073	0.2	9
R120	Whitethorn Creek Middle	1.719	0.2	14
R330	Whitethorn Creek Down	1.406	0.2	12
R370	Whitethorn Creek - Mill Creek to Dry Branch	0.128	0.2	2
R410	Mill Creek Middle	0.814	0.2	6
R440	Mill Creek Down	0.928	0.2	8

Table 79: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #1 (ARC II & NRCS Watershed Lag Equation)

HEC-HMS Watershed ID	Watershed Description	Watershed Area (mi^2)	Loss Method - SCS Curve Number			Transform Method - SCS Unit Hydrograph with NRCS Basin Lag Eq.		
			Initial Abstraction (in)	Curve Number - ARC II	Imperviousness (%)	Graph Type	ARC II Lag Time (hr)	ARC II Lag Time (min)
W1430	Stinking River	34.40	1.319	60.267	0	Standard	7.237	434.22
W1540	Whitethorn Creek (Upstream)	27.59	1.356	59.597	0	Standard	6.768	406.10
W1770	Terrible Creek	38.90	1.268	61.198	0	Standard	6.213	372.80
W1860	Mill Creek	11.02	1.352	59.658	0	Standard	5.291	317.49
W1880	Banister River Upstream of Lake 11	15.88	1.061	65.334	0	Standard	5.226	313.54
W1970	Elkhorn Creek	22.18	1.387	59.050	0	Standard	5.722	343.31
W1980	Cherrystone Creek	45.45	1.316	60.307	0	Standard	6.206	372.37
W1990	Bearskin Creek	21.90	1.393	58.946	0	Standard	4.719	283.12
W2090	Sand Creek (Lower)	23.21	1.293	60.731	0	Standard	4.671	280.27
W2100	Banister River Upstream of Lake 1	8.95	1.234	61.848	0	Standard	2.657	159.41
W2190	Banister Lake	9.02	1.326	60.131	0	Standard	3.019	181.14
W2300	Polecat Creek	19.34	1.251	61.515	0	Standard	4.372	262.30
W2310	Banister River Downstream of Banister Dam	0.18	1.053	65.501	0	Standard	0.543	32.59
W2320	Sandy Creek (Upper)	34.98	1.294	60.721	0	Standard	4.119	247.15
W2420	Banister River Headwaters	34.98	1.389	59.011	0	Standard	5.056	303.39
W2430	Banister River Upstream of Lake 12	36.09	1.278	61.019	0	Standard	6.761	405.67
W2520	Sandy Creek (Middle)	41.00	1.399	58.846	0	Standard	5.225	313.52
W2800	Georges Creek	17.34	1.329	60.083	0	Standard	6.286	377.16
W2830	Whitethorn Creek Downstream of Georges Creek	6.31	0.892	69.148	0	Standard	3.071	184.24
W4490	Banister River Upstream of Lake 7	5.90	1.343	59.827	0	Standard	2.037	122.24
W4500	Allen Creek	17.01	1.433	58.260	0	Standard	3.228	193.65
W4510	Banister River Upstream of Lake 8	8.27	1.280	60.983	0	Standard	3.985	239.12
W4540	Brush Creek	5.36	1.506	57.048	0	Standard	2.983	179.00
W4600	Banister River Upstream of Lake 6	0.24	0.758	72.507	0	Standard	0.523	31.36
W4620	Runaway Creek	7.68	1.263	61.285	0	Standard	3.172	190.31
W4630	Banister River Upstream of Lake 5	3.99	1.247	61.594	0	Standard	1.769	106.13
W4640	Bye Creek	10.77	1.299	60.624	0	Standard	3.415	204.89
W4650	Bradley Creek	11.13	1.387	59.048	0	Standard	3.119	187.12
W4670	Banister River Upstream of Lake 4	4.01	1.302	60.575	0	Standard	2.017	121.01
W4680	Banister River Upstream of Lake 3	2.14	1.190	62.697	0	Standard	1.343	80.58
W4690	Banister River Upstream of Lake 2	4.73	1.177	62.954	0	Standard	1.846	110.75
W4700	Dry Branch	2.48	0.695	74.206	0	Standard	2.506	150.34
W4710	Whitethorn Creek - From Mill Creek to Dry Branch	0.15	0.618	76.387	0	Standard	1.007	60.40
W4720	Whitethorn Creek - From Dry Branch to Georges Creek	0.57	0.909	68.750	0	Standard	0.866	51.98
W4730	Unnamed in NHD	9.80	1.266	61.239	0	Standard	4.069	244.14
W4740	Banister River Upstream of Lake 10	0.35	1.005	66.559	0	Standard	1.218	73.09
W4750	Banister River Upstream of Lake 9	3.33	1.098	64.550	0	Standard	2.421	145.28

HEC-HMS Reach ID	Reach Description	Muskingum Routing Method		
		Muskingum K (hr)	Muskingum X	# of Subreaches
R240	Banister River Down - US of Banister Lake 8	2.125	0.2	11
R270	Banister River Down - US of Banister Lake 7	1.343	0.2	7
R280	Banister River Down - US of Banister Lake 6	1.550	0.2	8
R360	Banister River Down - US of Banister Lake 5	1.281	0.2	7
R380	Banister River Down - US of Banister Lake 9	1.169	0.2	6
R430	Banister River Down - US of Banister Lake 10	1.841	0.2	9
R440	Whitethorn Creek - DS from Georges Cr	0.293	0.2	2
R450	Whitethorn Creek - Mill Cr to Dry Branch	0.118	0.2	1
R460	Banister River Down - US of Banister Lake 4	0.901	0.2	5
R480	Whitethorn Creek - Dry Branch to Georges Cr	0.482	0.2	3
R530	Banister River Down - US of Banister Lake 3	0.592	0.2	3
R640	Banister River Down - US of Banister Lake 2	3.628	0.2	18
R650	Banister River Up - US of Banister Lake 11	5.780	0.2	28
R680	Sandy Creek - DS	4.493	0.2	22
R790	Banister River Down - US of Banister Lake 1	2.240	0.2	11
R900	Banister River Down - DS of Banister Lake	0.555	0.2	3
R920	Banister Lake	8.175	0.2	40
R1010	Banister River Up - US of Banister Lake 12	5.409	0.2	26
R1030	Sandy Creek - MID	3.466	0.2	17

Table 80: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #2 (ARC II & NRCS Segmental Velocity Lag Equation (0.6 * Tc))

HEC-HMS Watershed ID	Watershed Description	Watershed Area (mi^2)	Loss Method - SCS Curve Number			Transform Method - SCS Unit Hydrograph with NRCS Segmental Velocity Lag Equation (0.6 * Tc)		
			Initial Abstraction (in)	Curve Number - ARC II	Imperviousness (%)	Graph Type	Lag Time (hr)	ARC II
W1430	Stinking River	34.40	1.319	60.267	0	Standard	3.636	218.15
W1540	Whitethorn Creek (Upstream)	27.59	1.356	59.597	0	Standard	3.875	232.50
W1770	Terrible Creek	38.90	1.268	61.198	0	Standard	3.887	233.23
W1860	Mill Creek	11.02	1.352	59.658	0	Standard	3.606	216.38
W1880	Banister River Upstream of Lake 11	15.88	1.061	65.334	0	Standard	8.563	513.79
W1970	Elkhorn Creek	22.18	1.387	59.050	0	Standard	4.030	241.81
W1980	Cherrystone Creek	45.45	1.316	60.307	0	Standard	4.294	257.66
W1990	Bearskin Creek	21.90	1.393	58.946	0	Standard	2.722	163.31
W2090	Sand Creek (Lower)	23.21	1.293	60.731	0	Standard	2.960	177.61
W2100	Banister River Upstream of Lake 1	8.95	1.234	61.848	0	Standard	2.943	176.58
W2190	Banister Lake	9.02	1.326	60.131	0	Standard	3.029	181.75
W2300	Polecat Creek	19.34	1.251	61.515	0	Standard	3.279	196.75
W2310	Banister River Downstream of Banister Dam	0.18	1.053	65.501	0	Standard	0.589	35.37
W2320	Sandy Creek (Upper)	34.98	1.294	60.721	0	Standard	2.576	154.54
W2420	Banister River Headwaters	34.98	1.389	59.011	0	Standard	3.472	208.33
W2430	Banister River Upstream of Lake 12	36.09	1.278	61.019	0	Standard	4.473	268.36
W2520	Sandy Creek (Middle)	41.00	1.399	58.846	0	Standard	3.451	207.07
W2800	Georges Creek	17.34	1.329	60.083	0	Standard	3.283	196.98
W2830	Whitethorn Creek Downstream of Georges Creek	6.31	0.892	69.148	0	Standard	1.804	108.24
W4490	Banister River Upstream of Lake 7	5.90	1.343	59.827	0	Standard	1.883	112.99
W4500	Allen Creek	17.01	1.433	58.260	0	Standard	1.930	115.81
W4510	Banister River Upstream of Lake 8	8.27	1.280	60.983	0	Standard	4.189	251.33
W4540	Brush Creek	5.36	1.506	57.048	0	Standard	2.068	124.11
W4600	Banister River Upstream of Lake 6	0.24	0.758	72.507	0	Standard	0.852	51.13
W4620	Runaway Creek	7.68	1.263	61.285	0	Standard	2.449	146.94
W4630	Banister River Upstream of Lake 5	3.99	1.247	61.594	0	Standard	2.946	176.78
W4640	Bye Creek	10.77	1.299	60.624	0	Standard	2.568	154.08
W4650	Bradley Creek	11.13	1.387	59.048	0	Standard	2.293	137.56
W4670	Banister River Upstream of Lake 4	4.01	1.302	60.575	0	Standard	3.158	189.45
W4680	Banister River Upstream of Lake 3	2.14	1.190	62.697	0	Standard	1.095	65.72
W4690	Banister River Upstream of Lake 2	4.73	1.177	62.954	0	Standard	2.664	159.85
W4700	Dry Branch	2.48	0.695	74.206	0	Standard	1.658	99.51
W4710	Whitethorn Creek - From Mill Creek to Dry Branch	0.15	0.618	76.387	0	Standard	0.642	38.49
W4720	Whitethorn Creek - From Dry Branch to Georges Creek	0.57	0.909	68.750	0	Standard	0.882	52.95
W4730	Unnamed in NHD	9.80	1.266	61.239	0	Standard	2.522	151.32
W4740	Banister River Upstream of Lake 10	0.35	1.005	66.559	0	Standard	1.264	75.86
W4750	Banister River Upstream of Lake 9	3.33	1.098	64.550	0	Standard	2.113	126.80

HEC-HMS Reach ID	Reach Description	Muskingum Routing Method		
		Muskingum K (hr)	Muskingum X	# of Subreaches
R240	Banister River Down - US of Banister Lake 8	2.125	0.2	11
R270	Banister River Down - US of Banister Lake 7	1.343	0.2	7
R280	Banister River Down - US of Banister Lake 6	1.550	0.2	8
R360	Banister River Down - US of Banister Lake 5	1.281	0.2	7
R380	Banister River Down - US of Banister Lake 9	1.169	0.2	6
R430	Banister River Down - US of Banister Lake 10	1.841	0.2	9
R440	Whitethorn Creek - DS from Georges Cr	0.293	0.2	2
R450	Whitethorn Creek - Mill Cr to Dry Branch	0.118	0.2	1
R460	Banister River Down - US of Banister Lake 4	0.901	0.2	5
R480	Whitethorn Creek - Dry Branch to Georges Cr	0.482	0.2	3
R530	Banister River Down - US of Banister Lake 3	0.592	0.2	3
R640	Banister River Down - US of Banister Lake 2	3.628	0.2	18
R650	Banister River Up - US of Banister Lake 11	5.780	0.2	28
R680	Sandy Creek - DS	4.493	0.2	22
R790	Banister River Down - US of Banister Lake 1	2.240	0.2	11
R900	Banister River Down - DS of Banister Lake	0.555	0.2	3
R920	Banister Lake	8.175	0.2	40
R1010	Banister River Up - US of Banister Lake 12	5.409	0.2	26
R1030	Sandy Creek - MID	3.466	0.2	17

Table 81: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #3 (ARC III & NRCS Watershed Lag Equation)

HEC-HMS Watershed ID	Watershed Description	Watershed Area (mi^2)	Loss Method - SCS Curve Number			Transform Method - SCS Unit Hydrograph with NRCS Lag Eq.		
			Initial Abstraction (in)	Curve Number - ARC III	Imperviousness (%)	Graph Type	ARC III Lag Time (hr)	ARC III Lag Time (min)
W1430	Stinking River	34.40	0.577	77.604	0	Standard	4.528	271.69
W1540	Whitethorn Creek (Upstream)	27.59	0.594	77.088	0	Standard	4.228	253.69
W1770	Terrible Creek	38.90	0.565	77.986	0	Standard	3.935	236.13
W1860	Mill Creek	11.02	0.592	77.164	0	Standard	3.303	198.19
W1880	Banister River Upstream of Lake 11	15.88	0.462	81.229	0	Standard	3.329	199.72
W1970	Elkhorn Creek	22.18	0.606	76.737	0	Standard	3.562	213.71
W1980	Cherrystone Creek	45.45	0.577	77.603	0	Standard	3.887	233.23
W1990	Bearskin Creek	21.90	0.609	76.670	0	Standard	2.936	176.13
W2090	Sand Creek (Lower)	23.21	0.569	77.839	0	Standard	2.937	176.20
W2100	Banister River Upstream of Lake 1	8.95	0.553	78.344	0	Standard	1.692	101.55
W2190	Banister Lake	9.02	0.591	77.178	0	Standard	1.907	114.39
W2300	Polecat Creek	19.34	0.552	78.356	0	Standard	2.760	165.62
W2310	Banister River Downstream of Banister Dam	0.18	0.476	80.778	0	Standard	0.352	21.15
W2320	Sandy Creek (Upper)	34.98	0.569	77.847	0	Standard	2.588	155.30
W2420	Banister River Headwaters	34.98	0.608	76.679	0	Standard	3.150	189.00
W2430	Banister River Upstream of Lake 12	36.09	0.560	78.113	0	Standard	4.247	254.80
W2520	Sandy Creek (Middle)	41.00	0.611	76.596	0	Standard	3.250	194.97
W2800	Georges Creek	17.34	0.582	77.455	0	Standard	3.932	235.93
W2830	Whitethorn Creek Downstream of Georges Creek	6.31	0.385	83.873	0	Standard	1.982	118.93
W4490	Banister River Upstream of Lake 7	5.90	0.588	77.270	0	Standard	1.273	76.40
W4500	Allen Creek	17.01	0.625	76.191	0	Standard	2.001	120.08
W4510	Banister River Upstream of Lake 8	8.27	0.560	78.133	0	Standard	2.499	149.96
W4540	Brush Creek	5.36	0.657	75.268	0	Standard	1.843	110.57
W4600	Banister River Upstream of Lake 6	0.24	0.353	85.000	0	Standard	0.356	21.34
W4620	Runaway Creek	7.68	0.556	78.253	0	Standard	1.997	119.84
W4630	Banister River Upstream of Lake 5	3.99	0.554	78.318	0	Standard	1.120	67.23
W4640	Bye Creek	10.77	0.573	77.741	0	Standard	2.147	128.84
W4650	Bradley Creek	11.13	0.608	76.693	0	Standard	1.944	116.63
W4670	Banister River Upstream of Lake 4	4.01	0.573	77.719	0	Standard	1.267	76.05
W4680	Banister River Upstream of Lake 3	2.14	0.530	79.049	0	Standard	0.856	51.34
W4690	Banister River Upstream of Lake 2	4.73	0.523	79.264	0	Standard	1.176	70.56
W4700	Dry Branch	2.48	0.290	87.336	0	Standard	1.643	98.60
W4710	Whitethorn Creek - From Mill Creek to Dry Branch	0.15	0.253	88.755	0	Standard	0.666	39.96
W4720	Whitethorn Creek - From Dry Branch to Georges Creek	0.57	0.400	83.327	0	Standard	0.564	33.82
W4730	Unnamed in NHD	9.80	0.552	78.382	0	Standard	2.549	152.95
W4740	Banister River Upstream of Lake 10	0.35	0.438	82.040	0	Standard	0.780	46.83
W4750	Banister River Upstream of Lake 9	3.33	0.476	80.764	0	Standard	1.534	92.03

HEC-HMS Reach ID	Reach Description	Muskingum Routing Method		
		Muskingum K (hr)	Muskingum X	# of Subreaches
R240	Banister River Down - US of Banister Lake 8	2.125	0.2	11
R270	Banister River Down - US of Banister Lake 7	1.343	0.2	7
R280	Banister River Down - US of Banister Lake 6	1.550	0.2	8
R360	Banister River Down - US of Banister Lake 5	1.281	0.2	7
R380	Banister River Down - US of Banister Lake 9	1.169	0.2	6
R430	Banister River Down - US of Banister Lake 10	1.841	0.2	9
R440	Whitethorn Creek - DS from Georges Cr	0.293	0.2	2
R450	Whitethorn Creek - Mill Cr to Dry Branch	0.118	0.2	1
R460	Banister River Down - US of Banister Lake 4	0.901	0.2	5
R480	Whitethorn Creek - Dry Branch to Georges Cr	0.482	0.2	3
R530	Banister River Down - US of Banister Lake 3	0.592	0.2	3
R640	Banister River Down - US of Banister Lake 2	3.628	0.2	18
R650	Banister River Up - US of Banister Lake 11	5.780	0.2	28
R680	Sandy Creek - DS	4.493	0.2	22
R790	Banister River Down - US of Banister Lake 1	2.240	0.2	11
R900	Banister River Down - DS of Banister Lake	0.555	0.2	3
R920	Banister Lake	8.175	0.2	40
R1010	Banister River Up - US of Banister Lake 12	5.409	0.2	26
R1030	Sandy Creek - MID	3.466	0.2	17

Table 82: Banister River Study Watershed Selected Basin Model Parameters – Basin Model #4 (ARC III & NRCS Segmental Velocity Lag Equation (0.6 * Tc))

HEC-HMS Watershed ID	Watershed Description	Watershed Area (mi^2)	Loss Method - SCS Curve Number			Transform Method - SCS Unit Hydrograph with NRCS Segmental Velocity Lag Equation (0.6 * Tc)		
			Initial Abstraction (in)	Curve Number - ARC III	Imperviousness (%)	Graph Type	Lag Time (hr)	Lag Time (min)
W1430	Stinking River	34.40	0.577	77.604	0	Standard	3.636	218.15
W1540	Whitethorn Creek (Upstream)	27.59	0.594	77.088	0	Standard	3.875	232.50
W1770	Terrible Creek	38.90	0.565	77.986	0	Standard	3.887	233.23
W1860	Mill Creek	11.02	0.592	77.164	0	Standard	3.606	216.38
W1880	Banister River Upstream of Lake 11	15.88	0.462	81.229	0	Standard	8.563	513.79
W1970	Elkhorn Creek	22.18	0.606	76.737	0	Standard	4.030	241.81
W1980	Cherrystone Creek	45.45	0.577	77.603	0	Standard	4.294	257.66
W1990	Bearskin Creek	21.90	0.609	76.670	0	Standard	2.722	163.31
W2090	Sand Creek (Lower)	23.21	0.569	77.839	0	Standard	2.960	177.61
W2100	Banister River Upstream of Lake 1	8.95	0.553	78.344	0	Standard	2.943	176.58
W2190	Banister Lake	9.02	0.591	77.178	0	Standard	3.029	181.75
W2300	Polecat Creek	19.34	0.552	78.356	0	Standard	3.279	196.75
W2310	Banister River Downstream of Banister Dam	0.18	0.476	80.778	0	Standard	0.589	35.37
W2320	Sandy Creek (Upper)	34.98	0.569	77.847	0	Standard	2.576	154.54
W2420	Banister River Headwaters	34.98	0.608	76.679	0	Standard	3.472	208.33
W2430	Banister River Upstream of Lake 12	36.09	0.560	78.113	0	Standard	4.473	268.36
W2520	Sandy Creek (Middle)	41.00	0.611	76.596	0	Standard	3.451	207.07
W2800	Georges Creek	17.34	0.582	77.455	0	Standard	3.283	196.98
W2830	Whitethorn Creek Downstream of Georges Creek	6.31	0.385	83.873	0	Standard	1.804	108.24
W4490	Banister River Upstream of Lake 7	5.90	0.588	77.270	0	Standard	1.883	112.99
W4500	Allen Creek	17.01	0.625	76.191	0	Standard	1.930	115.81
W4510	Banister River Upstream of Lake 8	8.27	0.560	78.133	0	Standard	4.189	251.33
W4540	Brush Creek	5.36	0.657	75.268	0	Standard	2.068	124.11
W4600	Banister River Upstream of Lake 6	0.24	0.353	85.000	0	Standard	0.852	51.13
W4620	Runaway Creek	7.68	0.556	78.253	0	Standard	2.449	146.94
W4630	Banister River Upstream of Lake 5	3.99	0.554	78.318	0	Standard	2.946	176.78
W4640	Bye Creek	10.77	0.573	77.741	0	Standard	2.568	154.08
W4650	Bradley Creek	11.13	0.608	76.693	0	Standard	2.293	137.56
W4670	Banister River Upstream of Lake 4	4.01	0.573	77.719	0	Standard	3.158	189.45
W4680	Banister River Upstream of Lake 3	2.14	0.530	79.049	0	Standard	1.095	65.72
W4690	Banister River Upstream of Lake 2	4.73	0.523	79.264	0	Standard	2.664	159.85
W4700	Dry Branch	2.48	0.290	87.336	0	Standard	1.658	99.51
W4710	Whitethorn Creek - From Mill Creek to Dry Branch	0.15	0.253	88.755	0	Standard	0.642	38.49
W4720	Whitethorn Creek - From Dry Branch to Georges Creek	0.57	0.400	83.327	0	Standard	0.882	52.95
W4730	Unnamed in NHD	9.80	0.552	78.382	0	Standard	2.522	151.32
W4740	Banister River Upstream of Lake 10	0.35	0.438	82.040	0	Standard	1.264	75.86
W4750	Banister River Upstream of Lake 9	3.33	0.476	80.764	0	Standard	2.113	126.80

HEC-HMS Reach ID	Reach Description	Muskingum Routing Method		
		Muskingum K (hr)	Muskingum X	# of Subreaches
R240	Banister River Down - US of Banister Lake 8	2.125	0.2	11
R270	Banister River Down - US of Banister Lake 7	1.343	0.2	7
R280	Banister River Down - US of Banister Lake 6	1.550	0.2	8
R360	Banister River Down - US of Banister Lake 5	1.281	0.2	7
R380	Banister River Down - US of Banister Lake 9	1.169	0.2	6
R430	Banister River Down - US of Banister Lake 10	1.841	0.2	9
R440	Whitethorn Creek - DS from Georges Cr	0.293	0.2	2
R450	Whitethorn Creek - Mill Cr to Dry Branch	0.118	0.2	1
R460	Banister River Down - US of Banister Lake 4	0.901	0.2	5
R480	Whitethorn Creek - Dry Branch to Georges Cr	0.482	0.2	3
R530	Banister River Down - US of Banister Lake 3	0.592	0.2	3
R640	Banister River Down - US of Banister Lake 2	3.628	0.2	18
R650	Banister River Up - US of Banister Lake 11	5.780	0.2	28
R680	Sandy Creek - DS	4.493	0.2	22
R790	Banister River Down - US of Banister Lake 1	2.240	0.2	11
R900	Banister River Down - DS of Banister Lake	0.555	0.2	3
R920	Banister Lake	8.175	0.2	40
R1010	Banister River Up - US of Banister Lake 12	5.409	0.2	26
R1030	Sandy Creek - MID	3.466	0.2	17

Appendix F:

HEC-HMS Outflow Hydrographs for Comparison Point Locations

Frequency Storms & PMS

- **Whitethorn Creek Study Watershed**
- **Banister River Study Watershed**

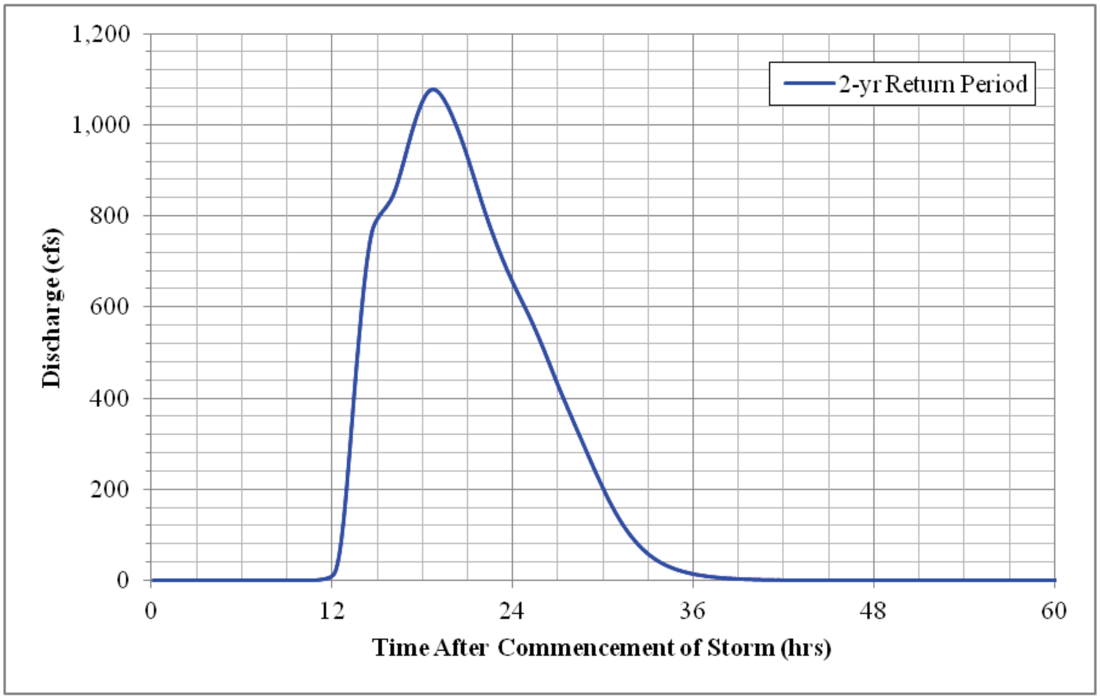

Figure 67: 2-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

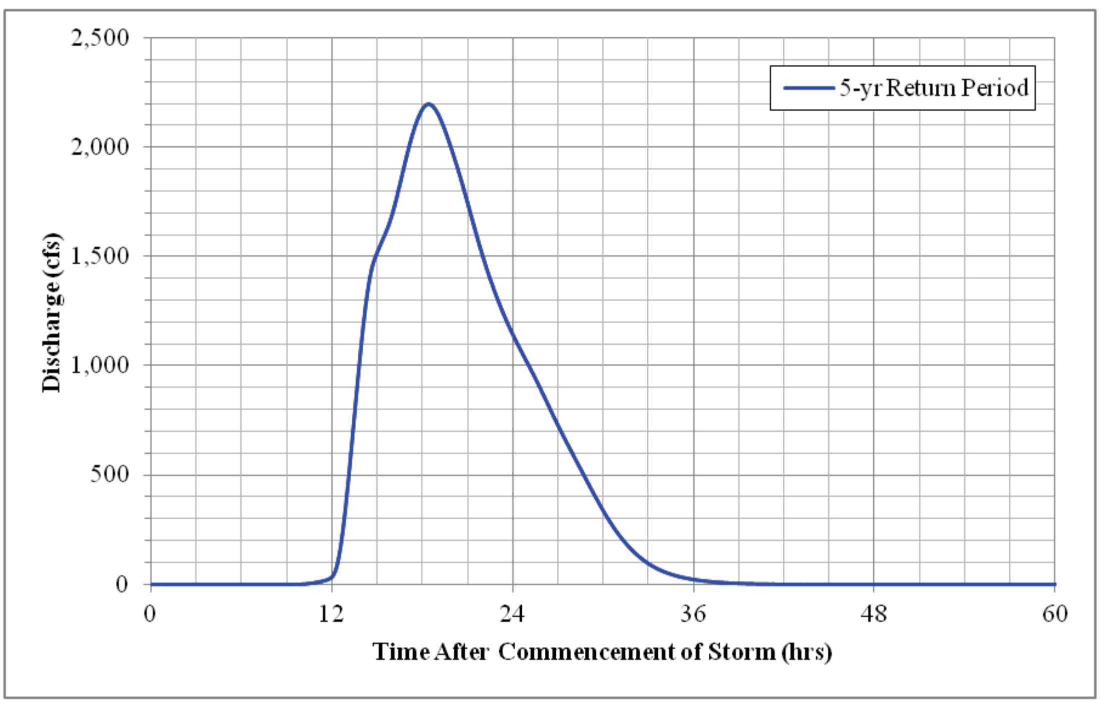

Figure 68: 5-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

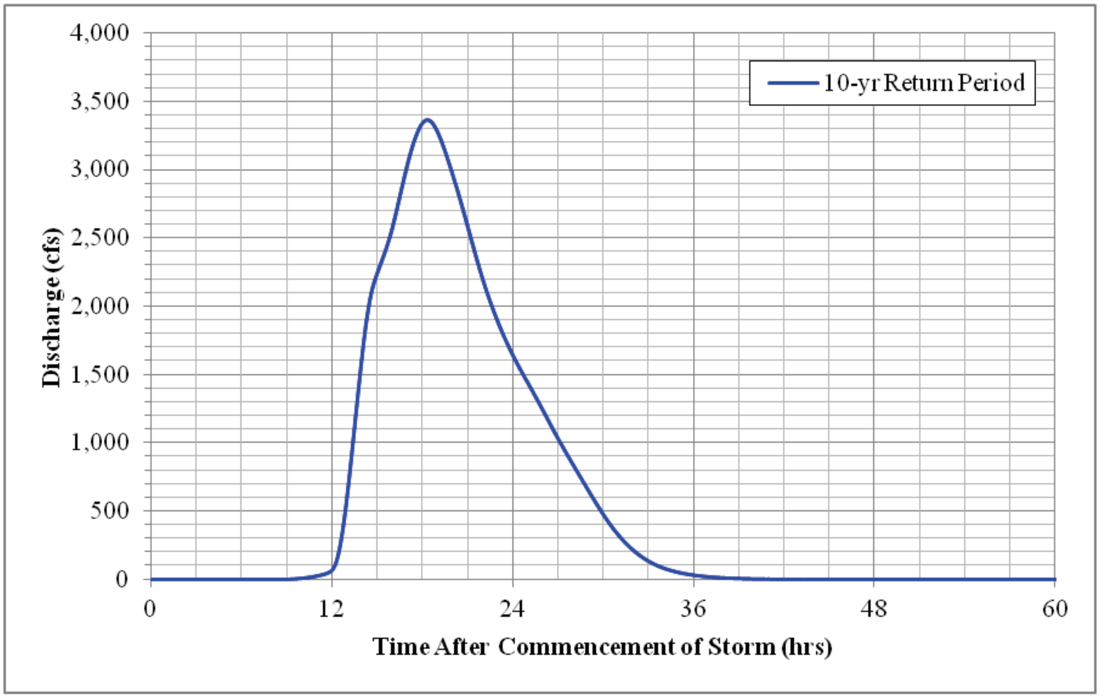

Figure 69: 10-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

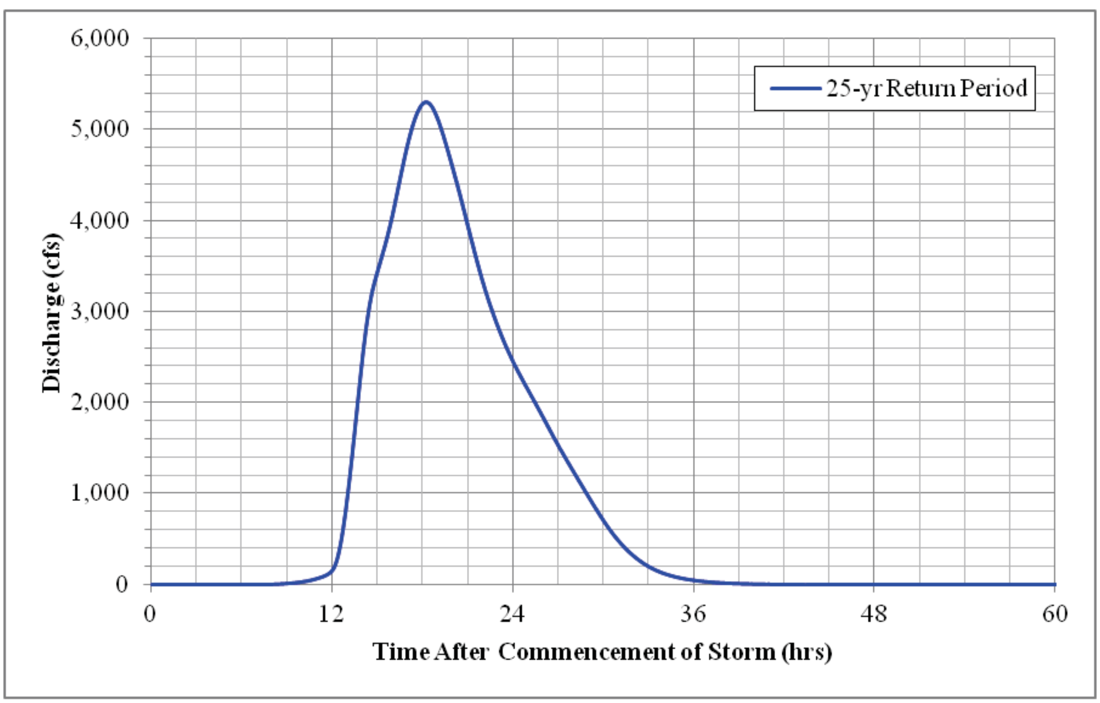

Figure 70: 25-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

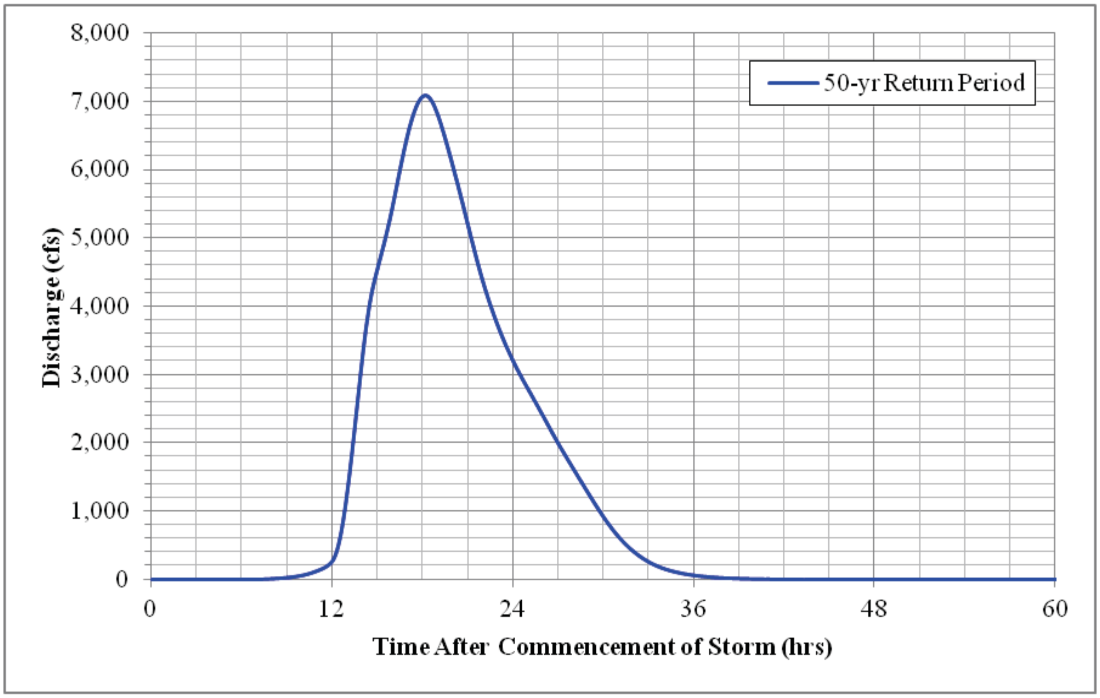

Figure 71: 50-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

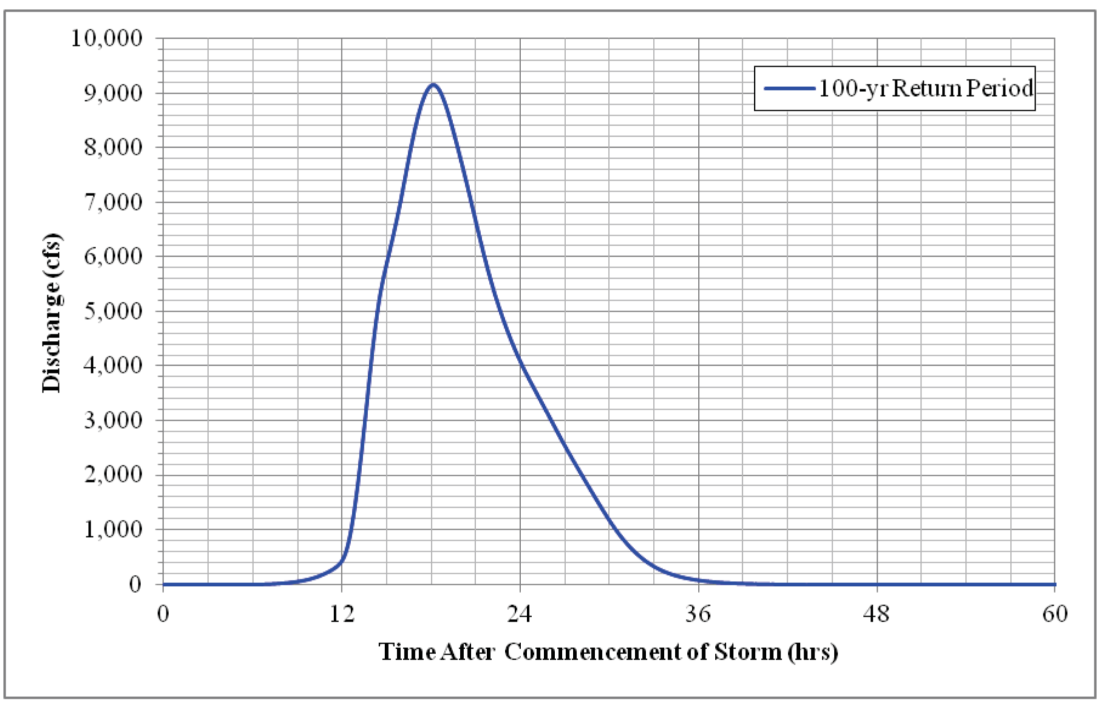

Figure 72: 100-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

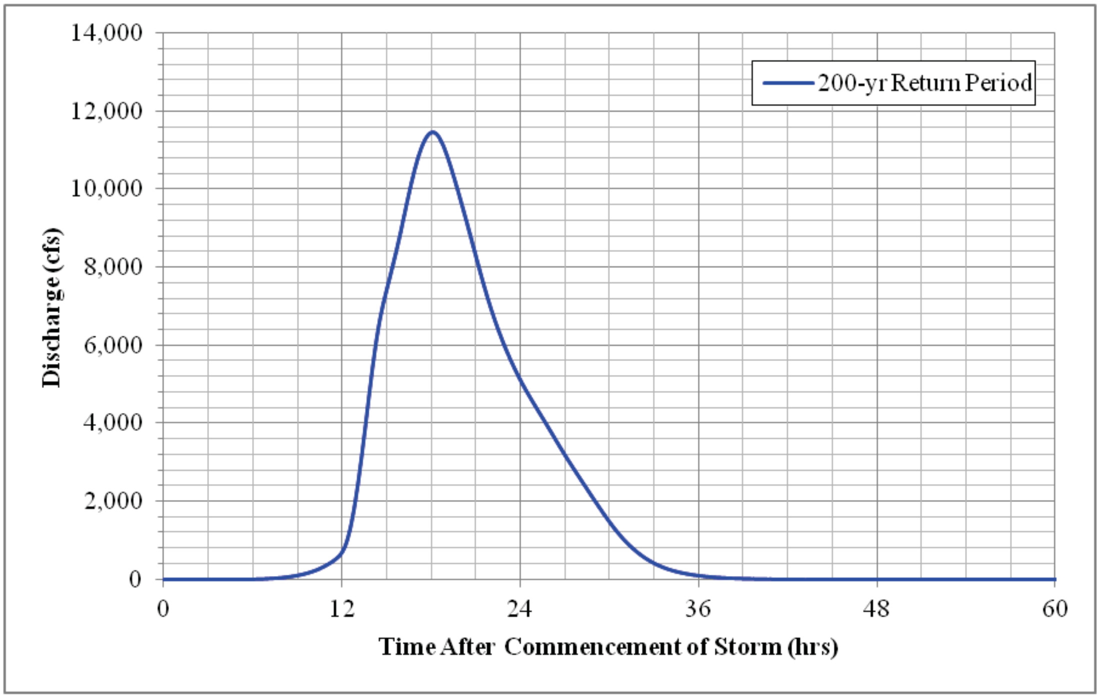

Figure 73: 200-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

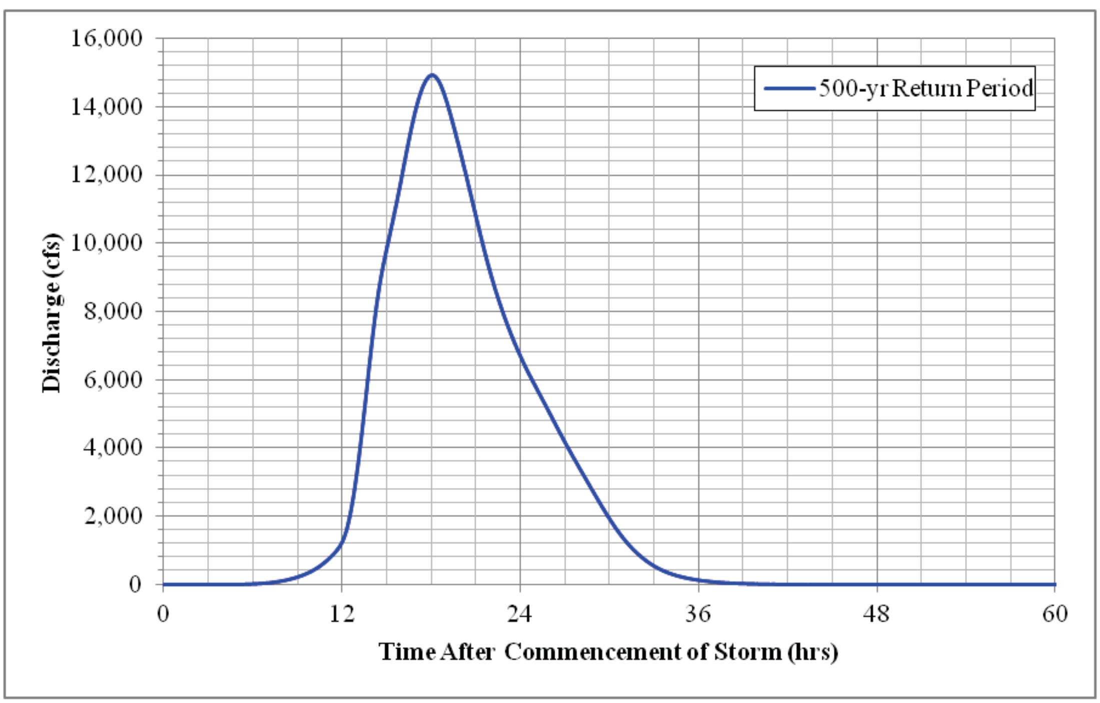

Figure 74: 500-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

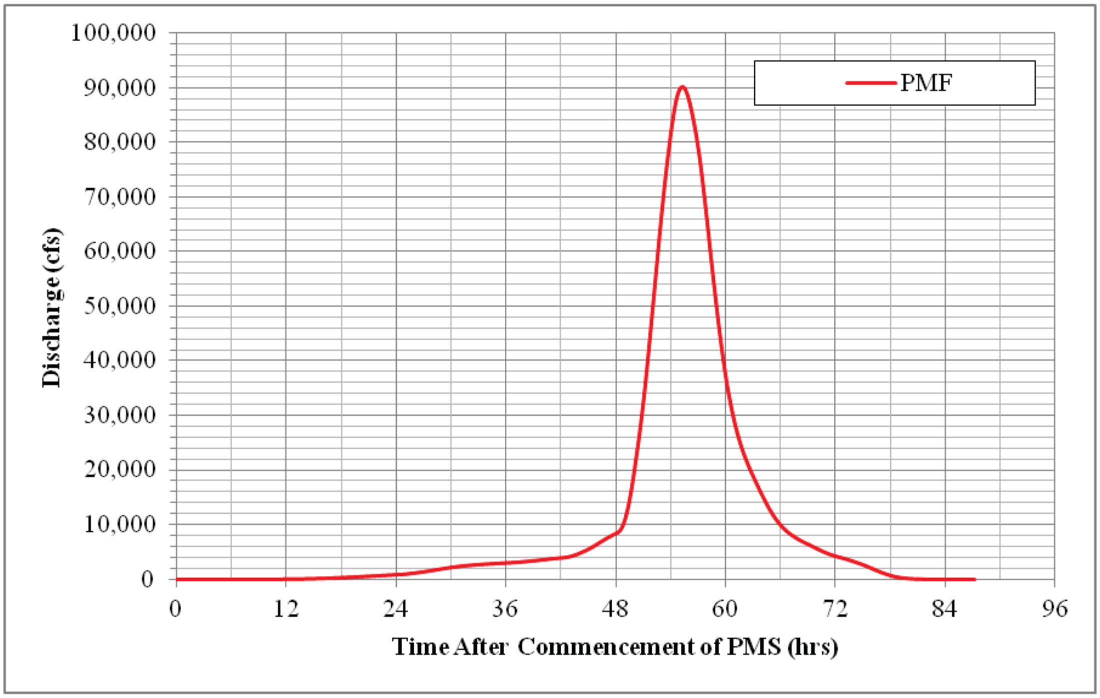

Figure 75: PMF Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 1

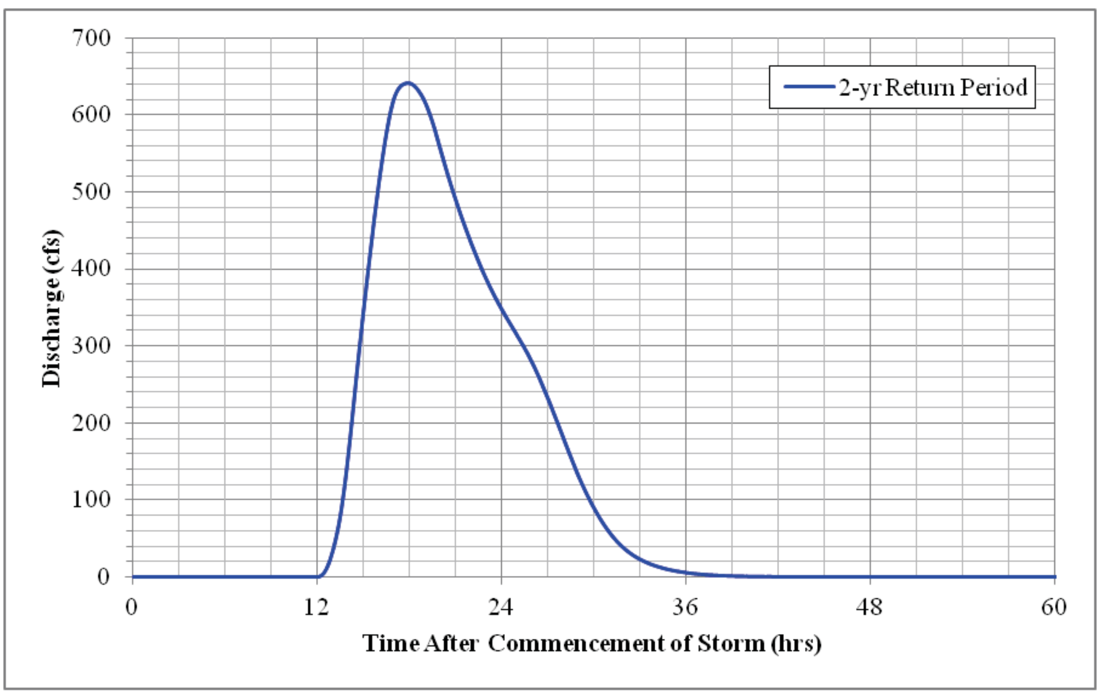

Figure 76: 2-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

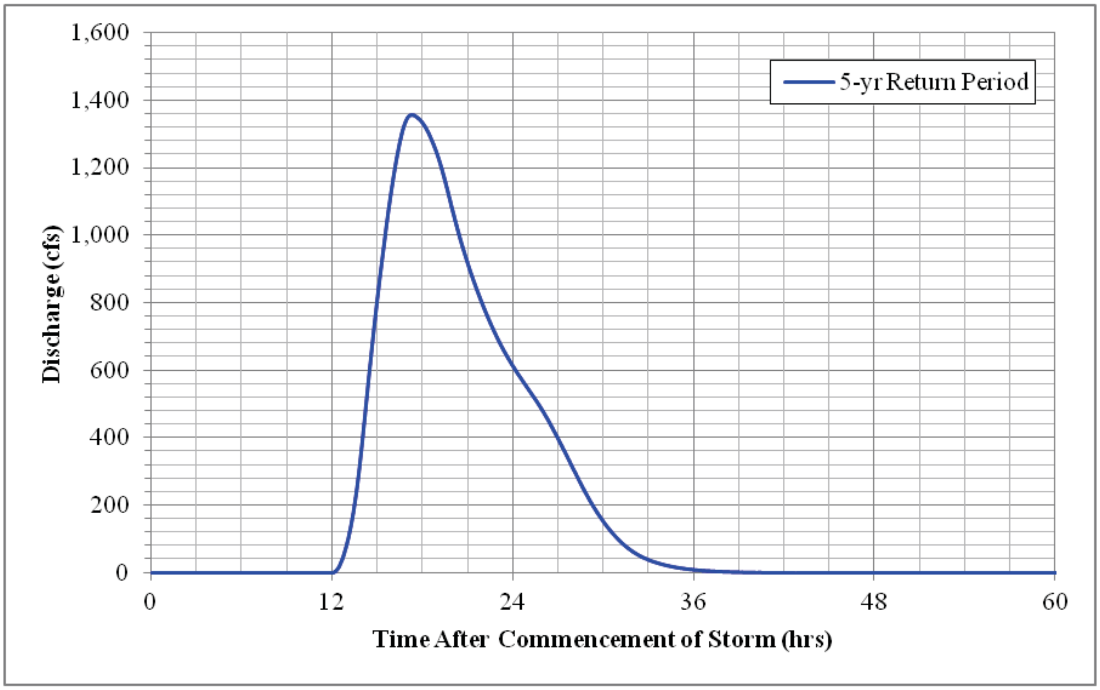

Figure 77: 5-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

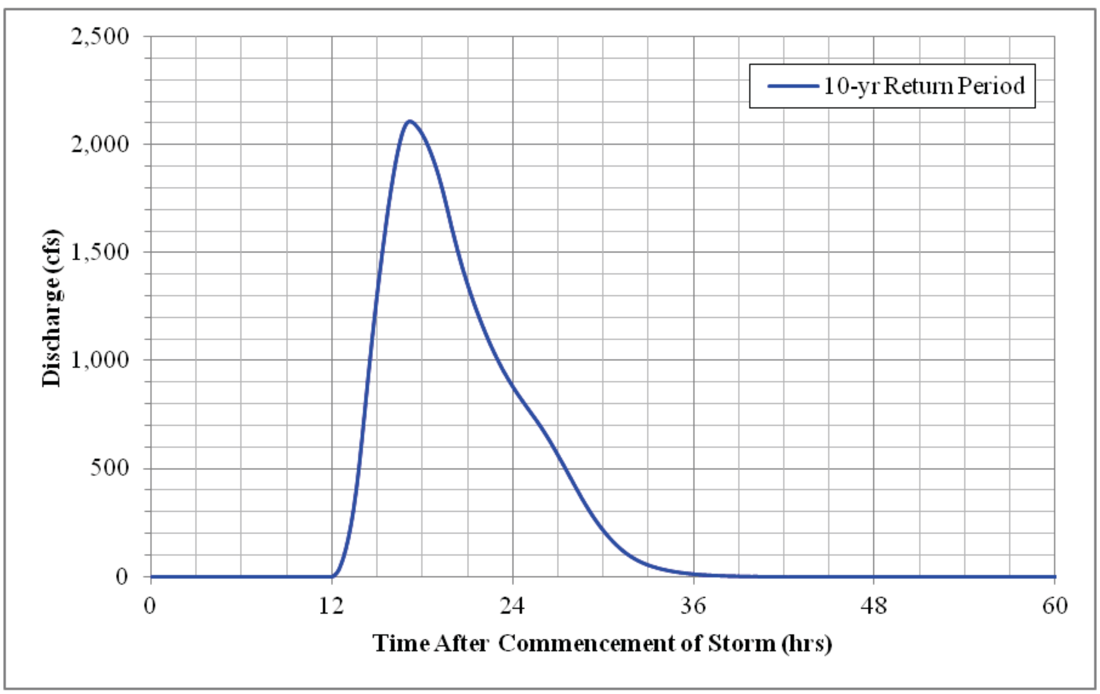

Figure 78: 10-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

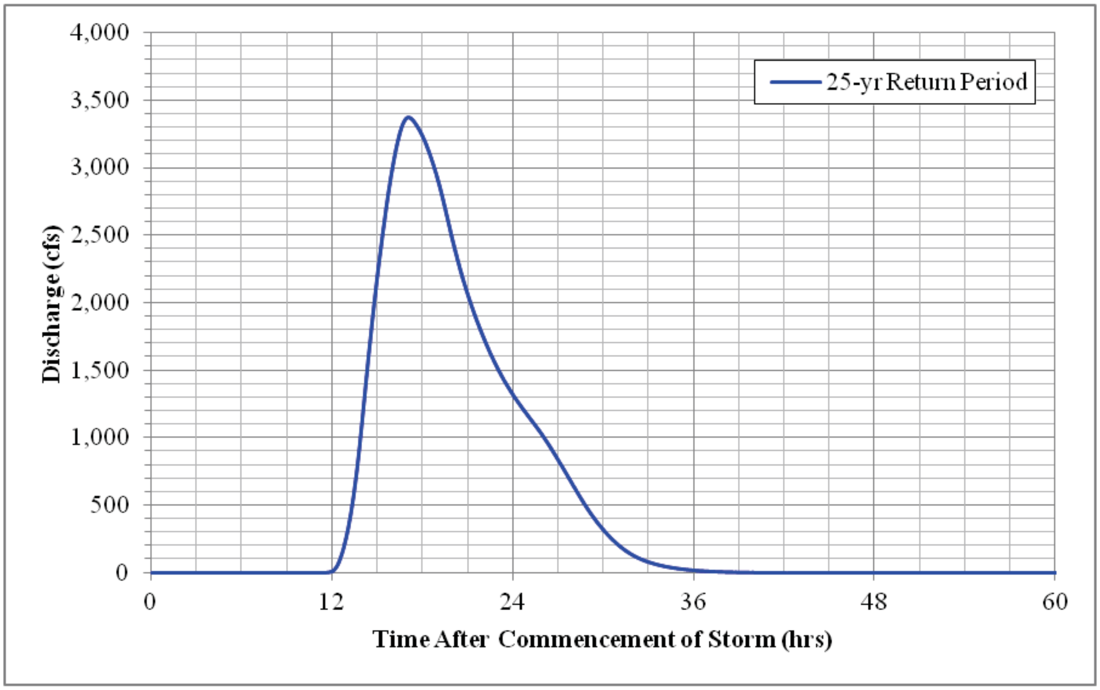

Figure 79: 25-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

Figure 80: 50-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

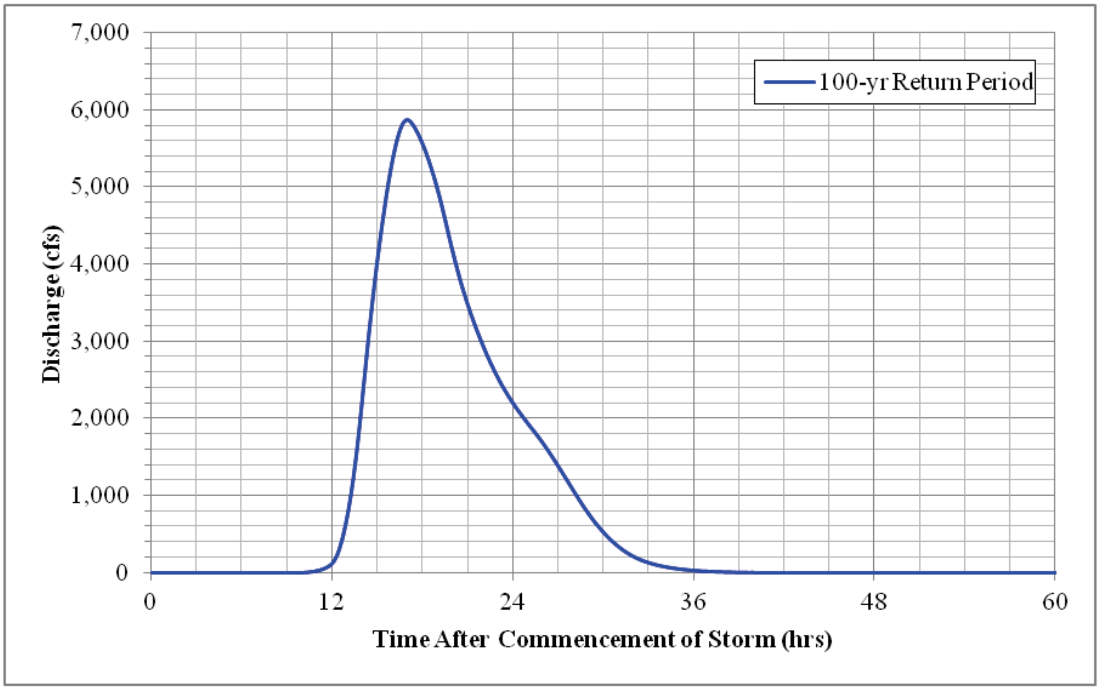

Figure 81: 100-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

Figure 82: 200-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

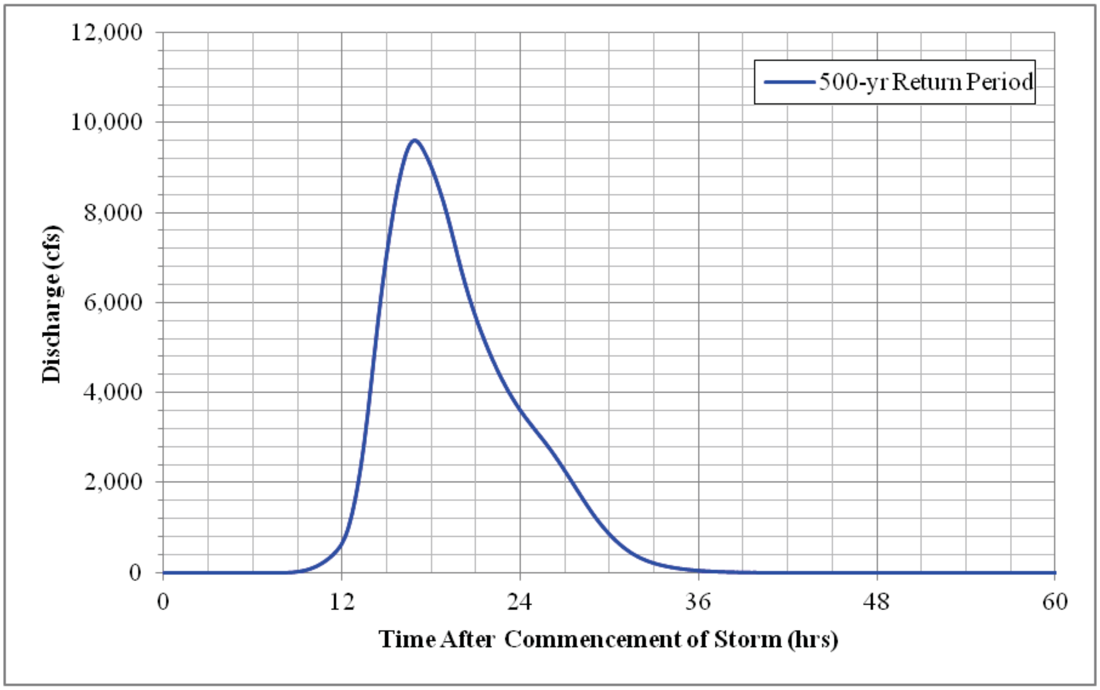

Figure 83: 500-yr Frequency Storm Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

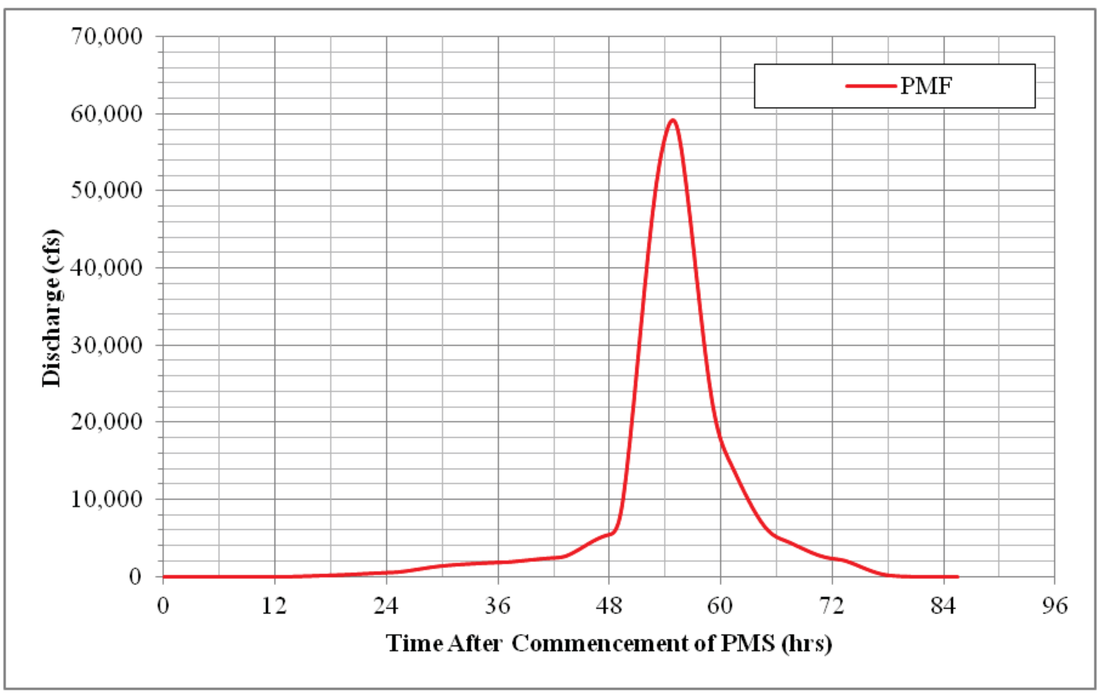

Figure 84: PMF Outflow Hydrograph - Whitethorn Creek Analysis – Location Corresponding to Bisese Comparison Point 2

Figure 85: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

Figure 86: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

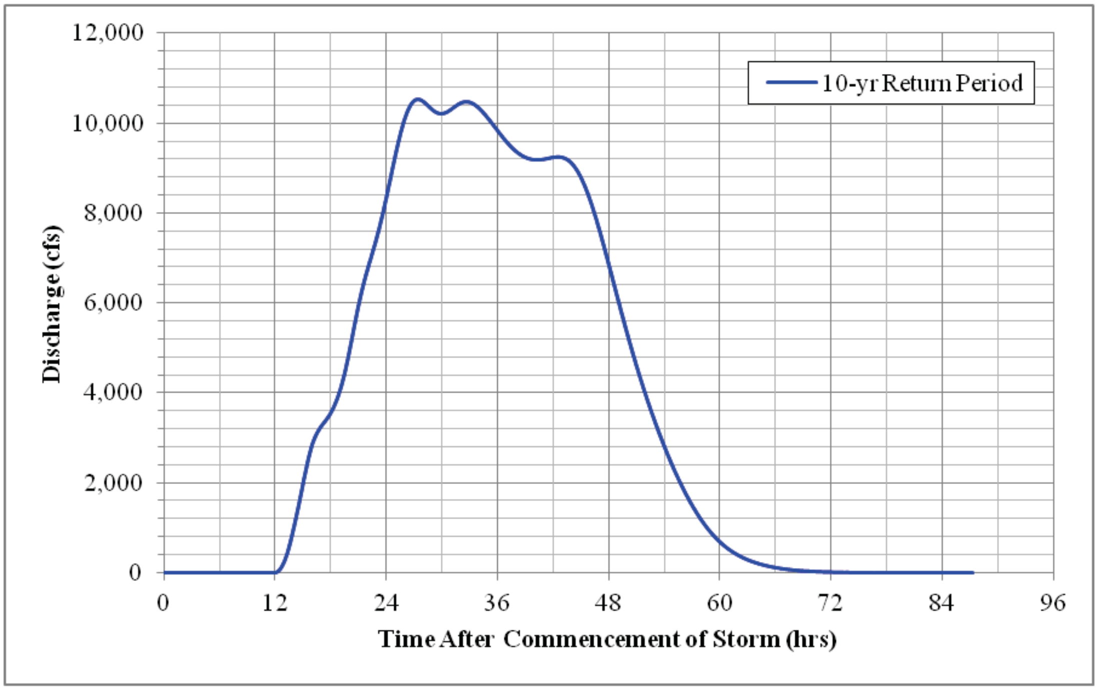

Figure 87: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

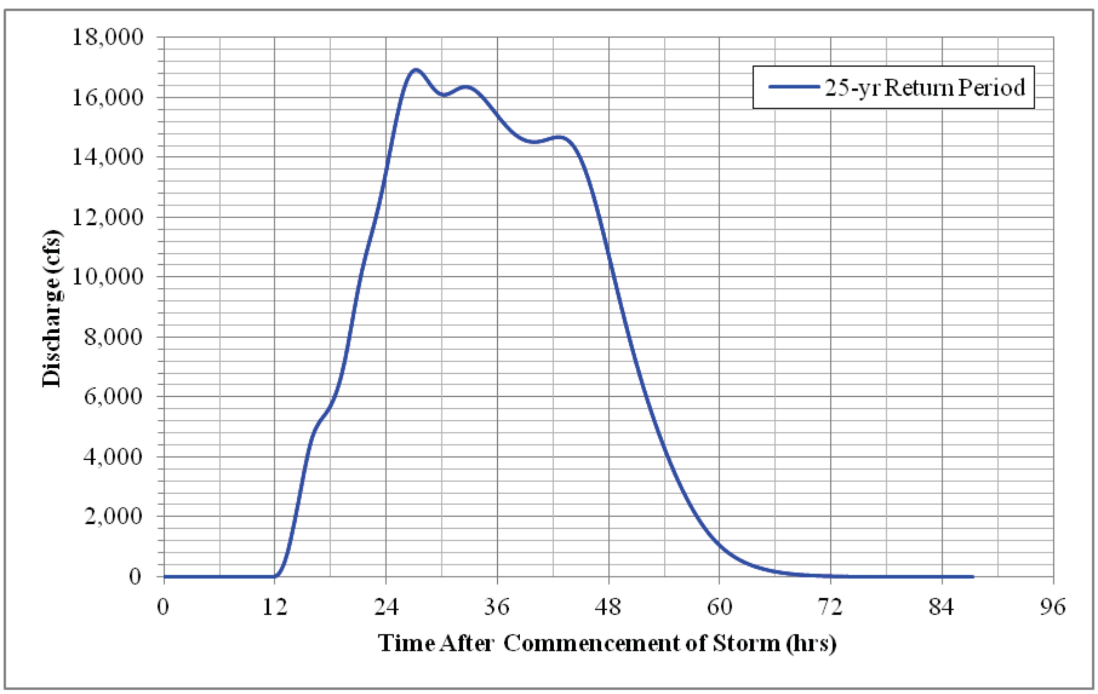

Figure 88: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

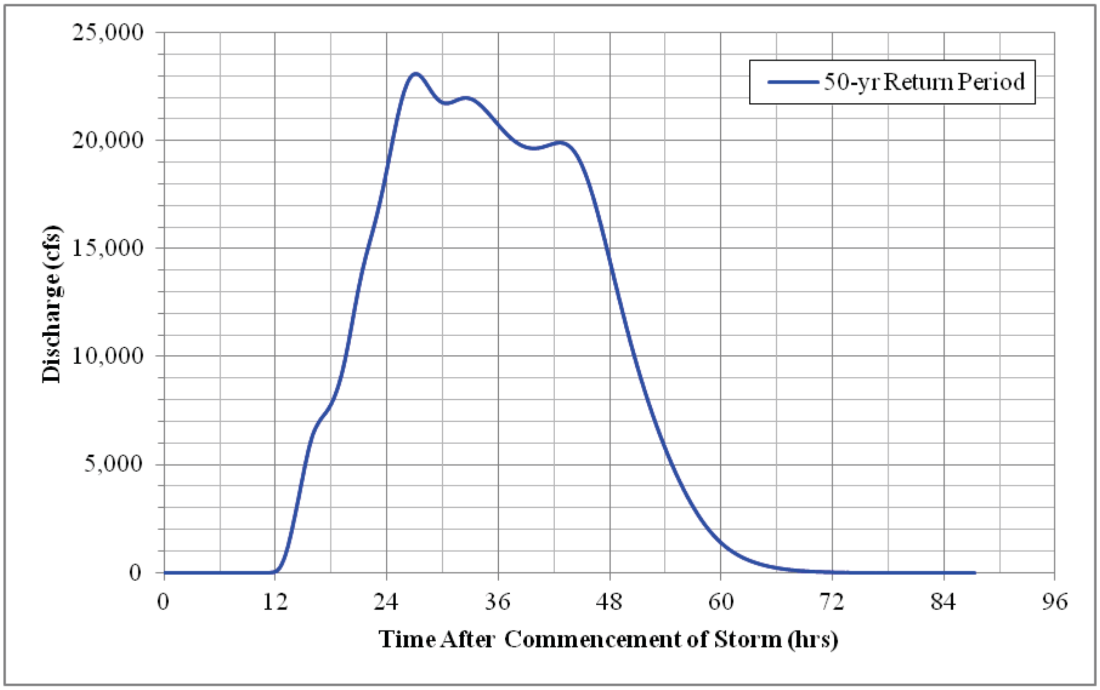

Figure 89: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

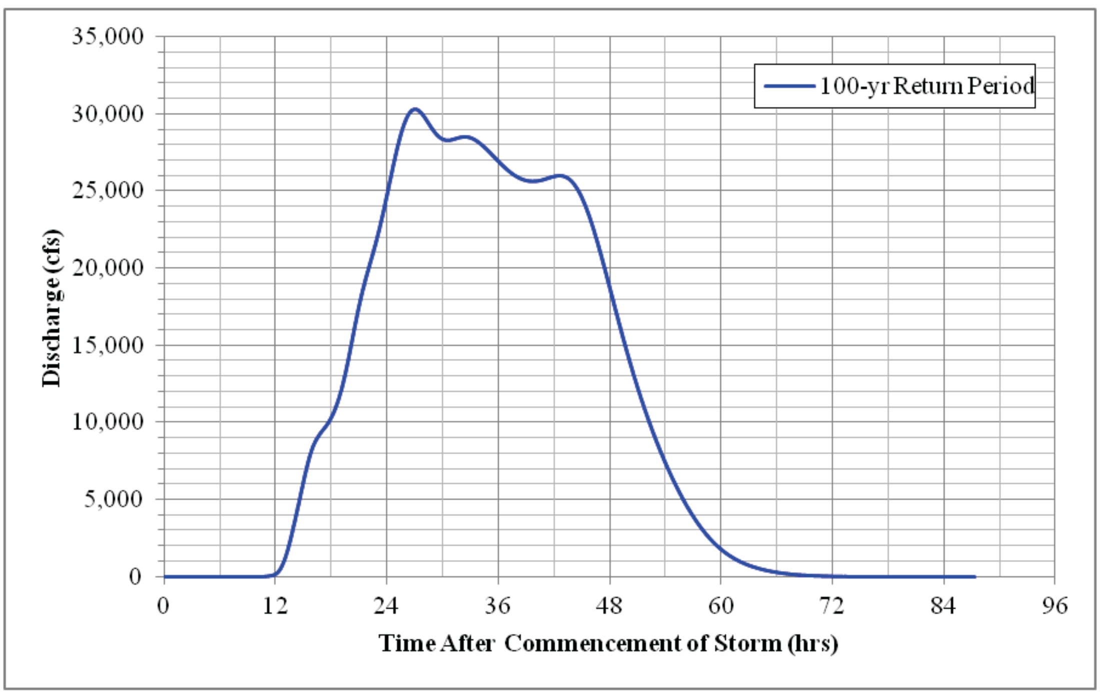

Figure 90: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

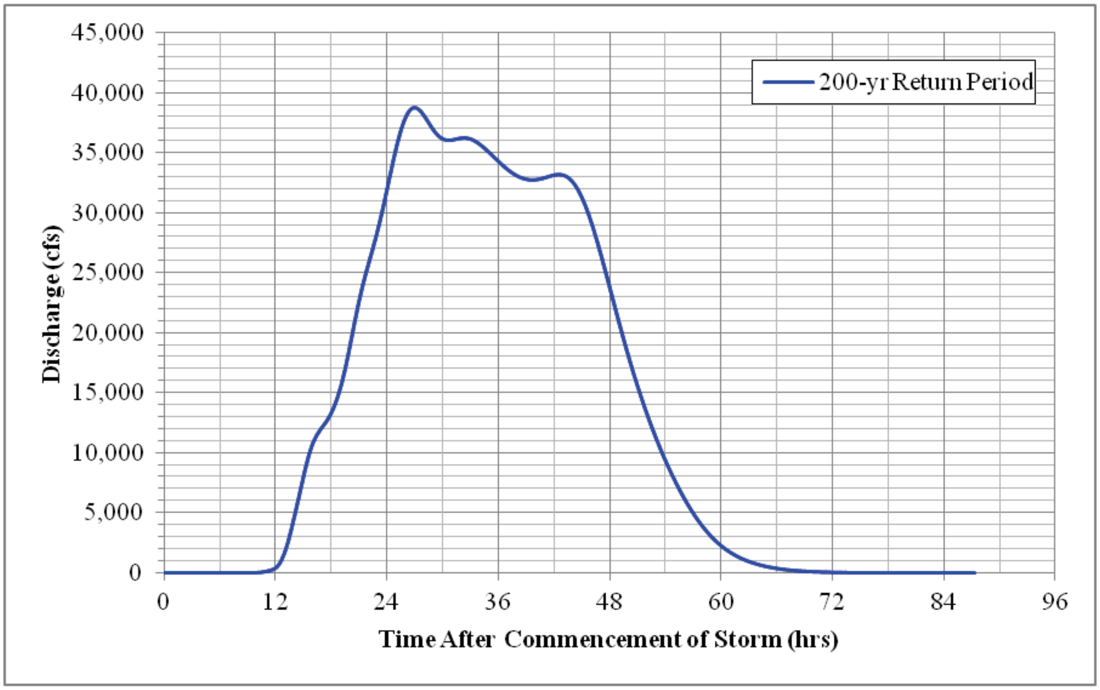

Figure 91: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

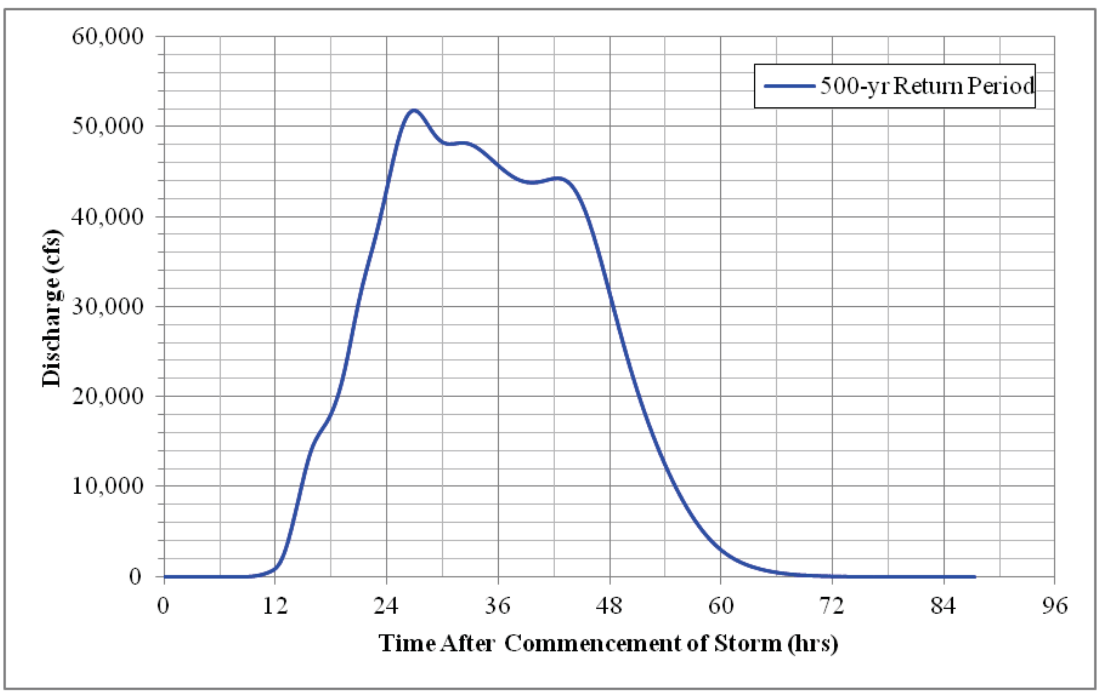

Figure 92: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

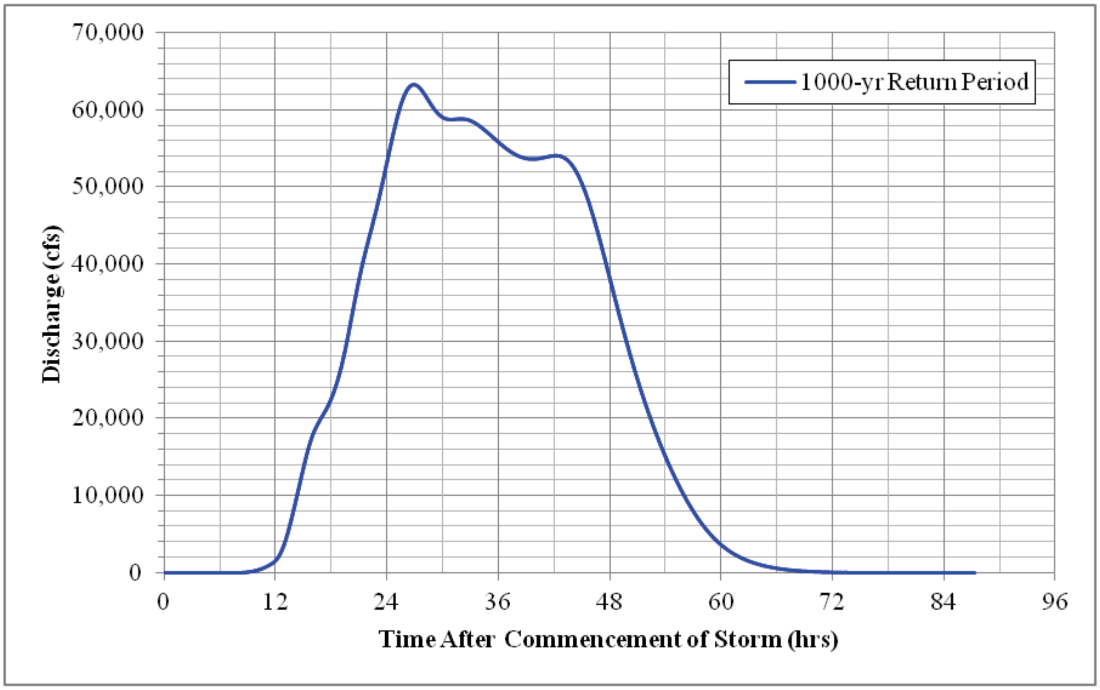

Figure 93: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

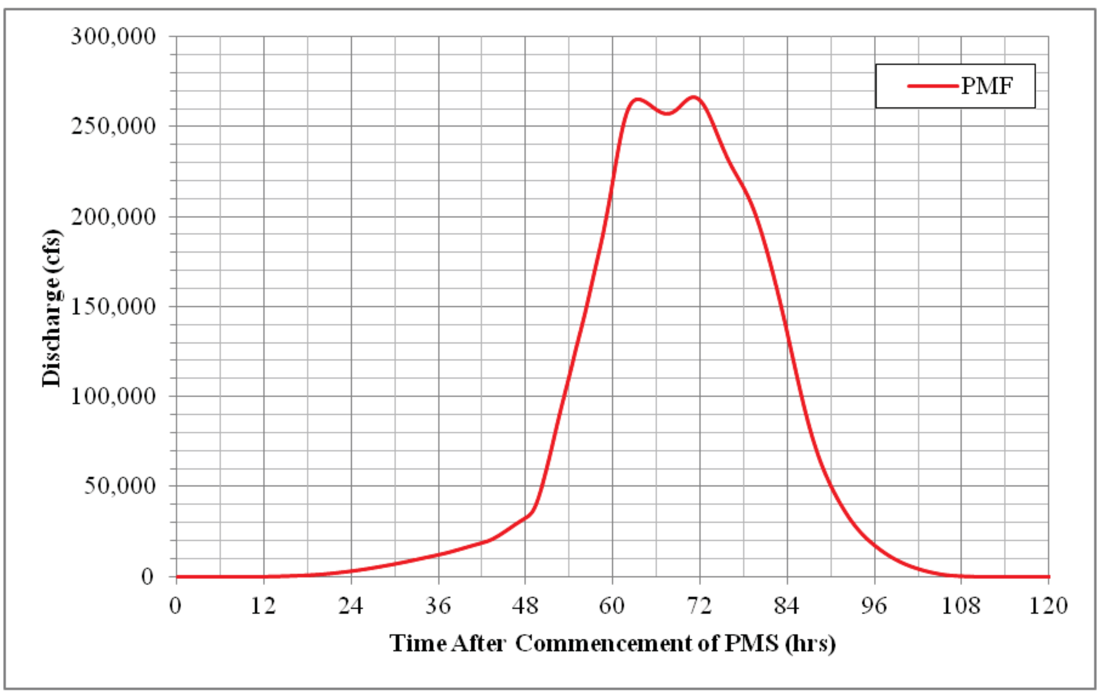

Figure 94: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 1

Figure 95: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

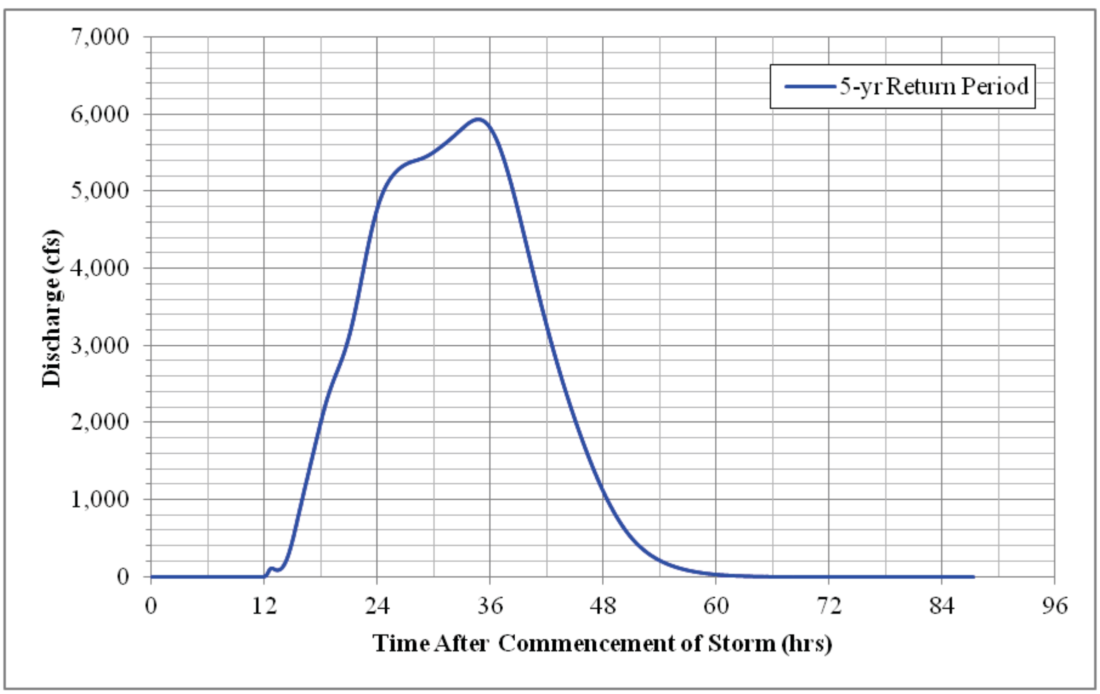

Figure 96: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

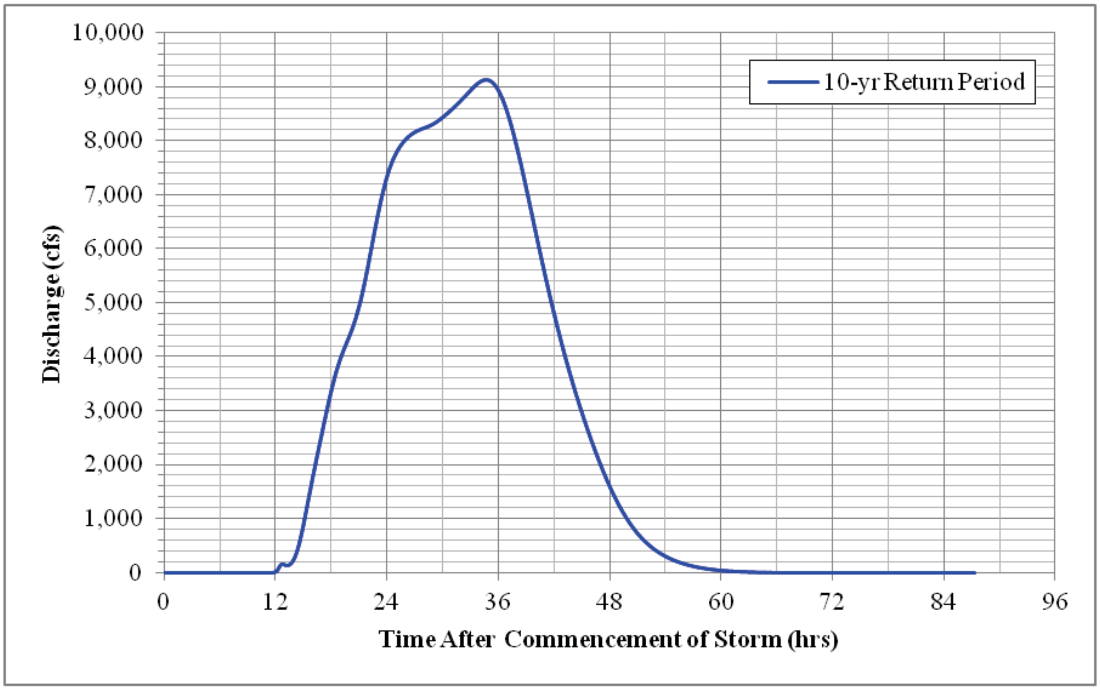

Figure 97: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

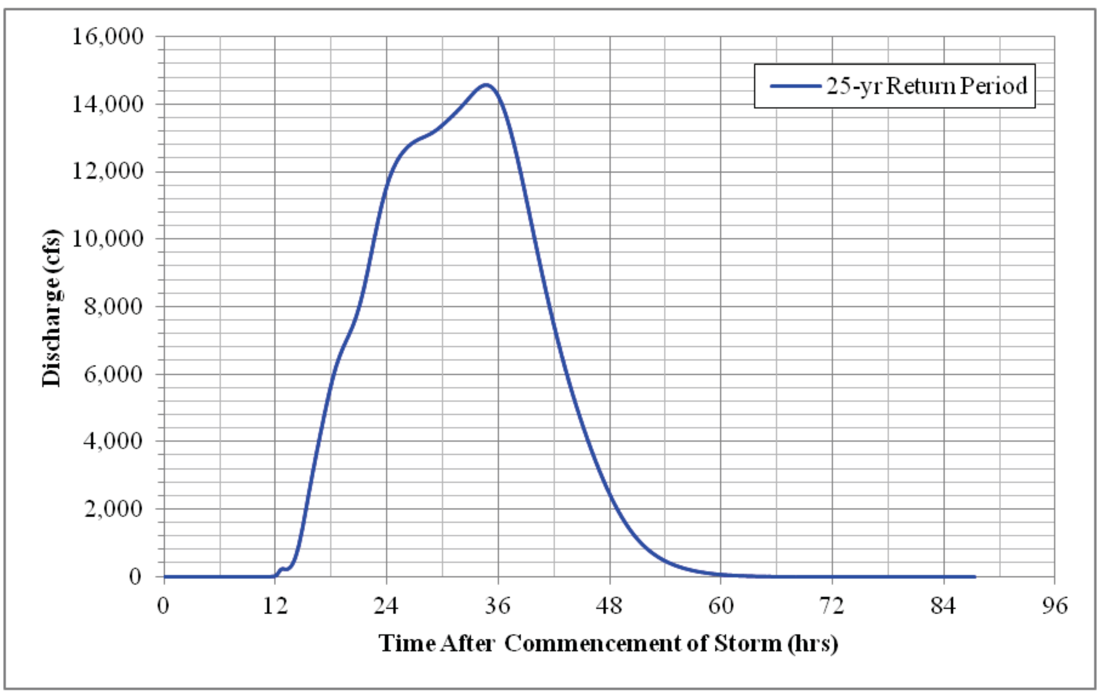

Figure 98: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

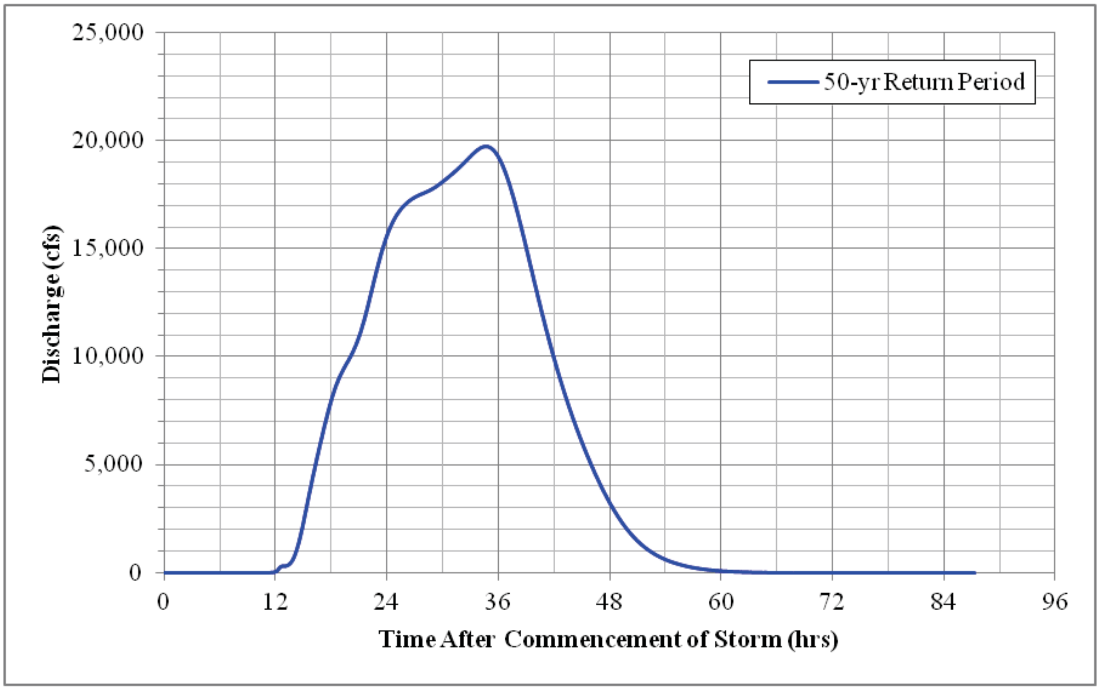

Figure 99: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

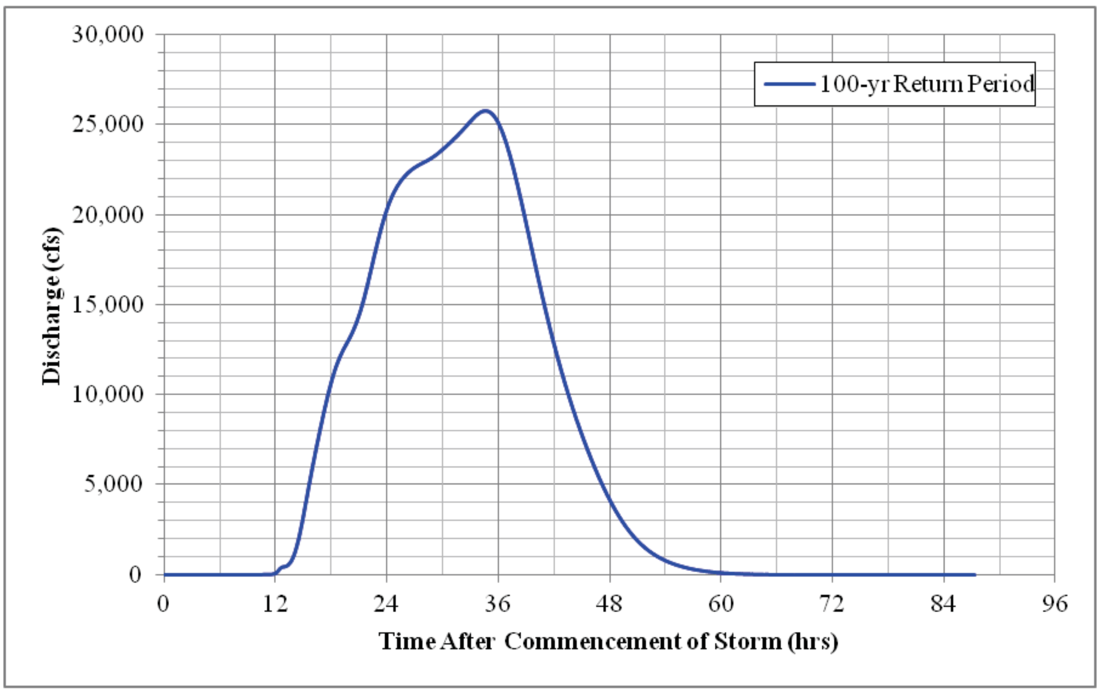

Figure 100: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

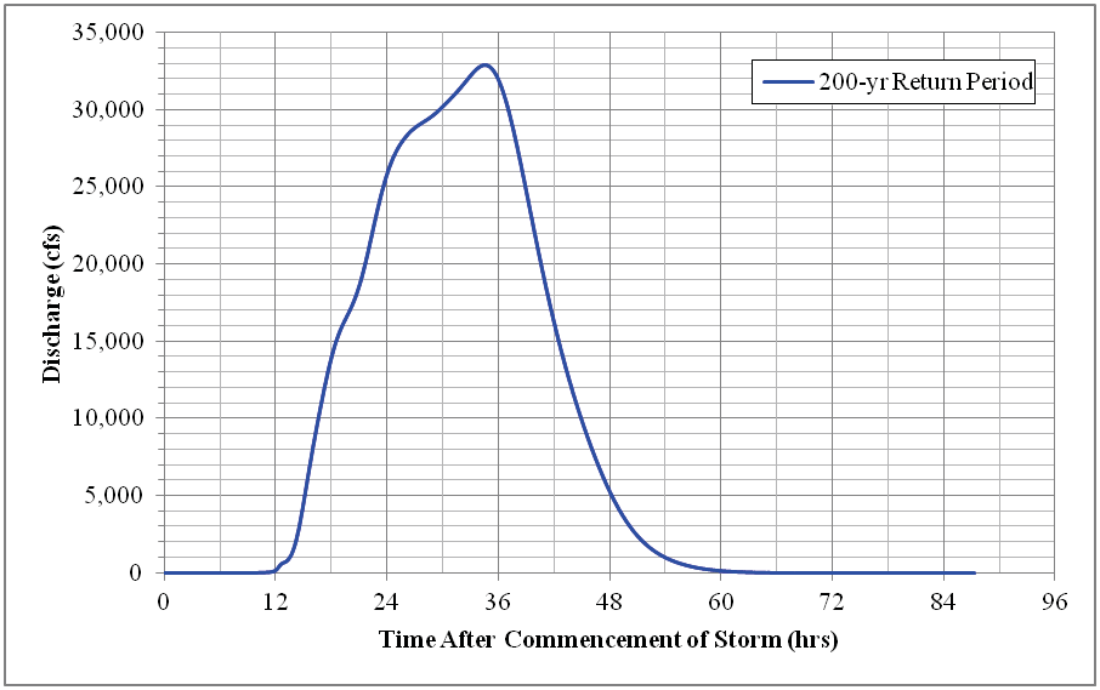

Figure 101: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

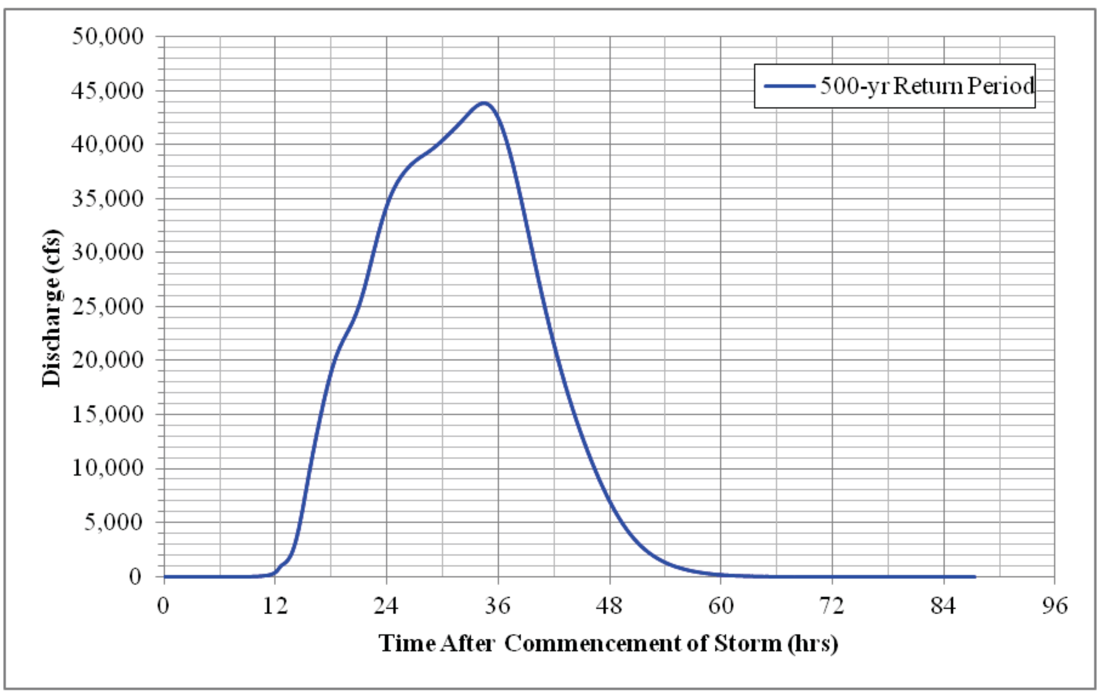

Figure 102: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

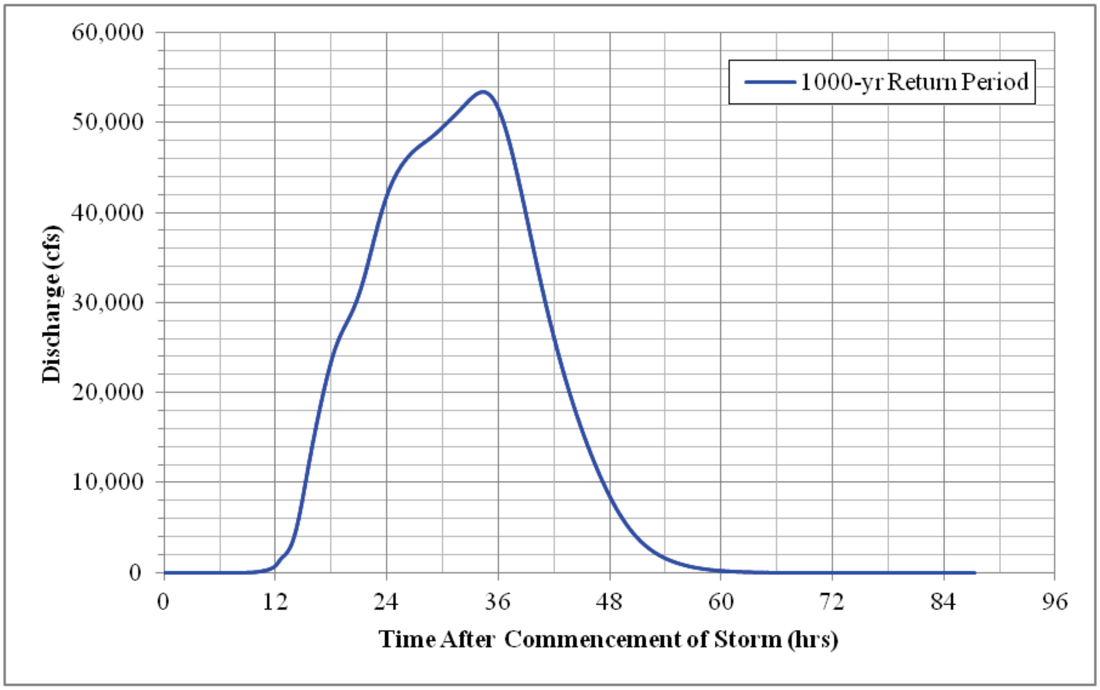

Figure 103: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

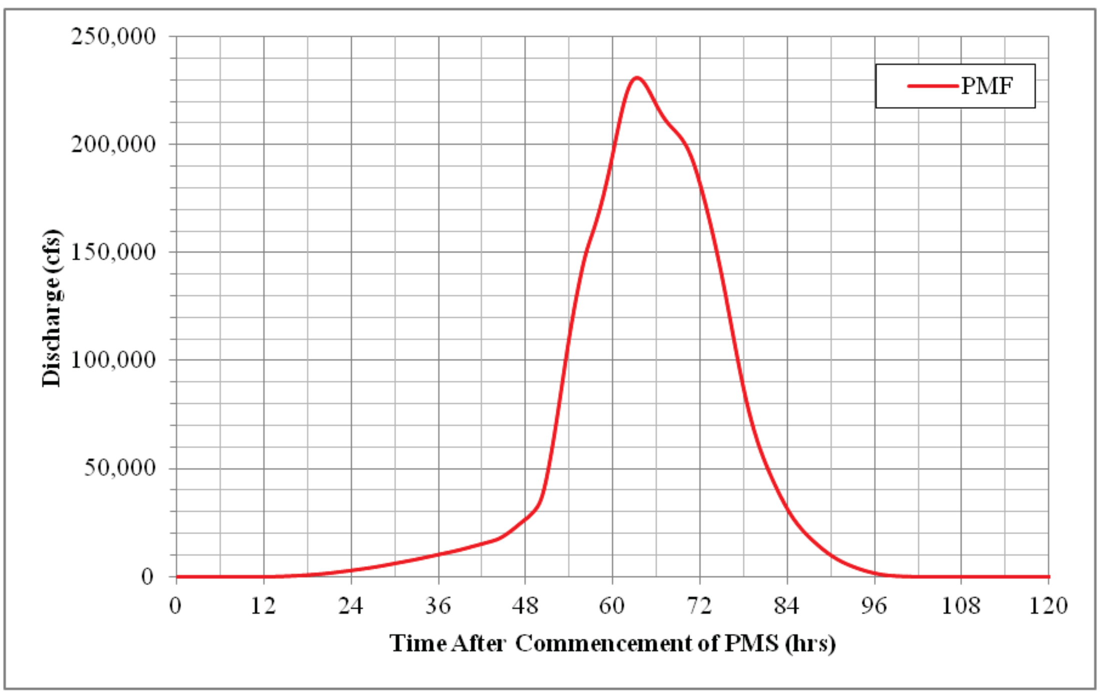

Figure 104: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 2

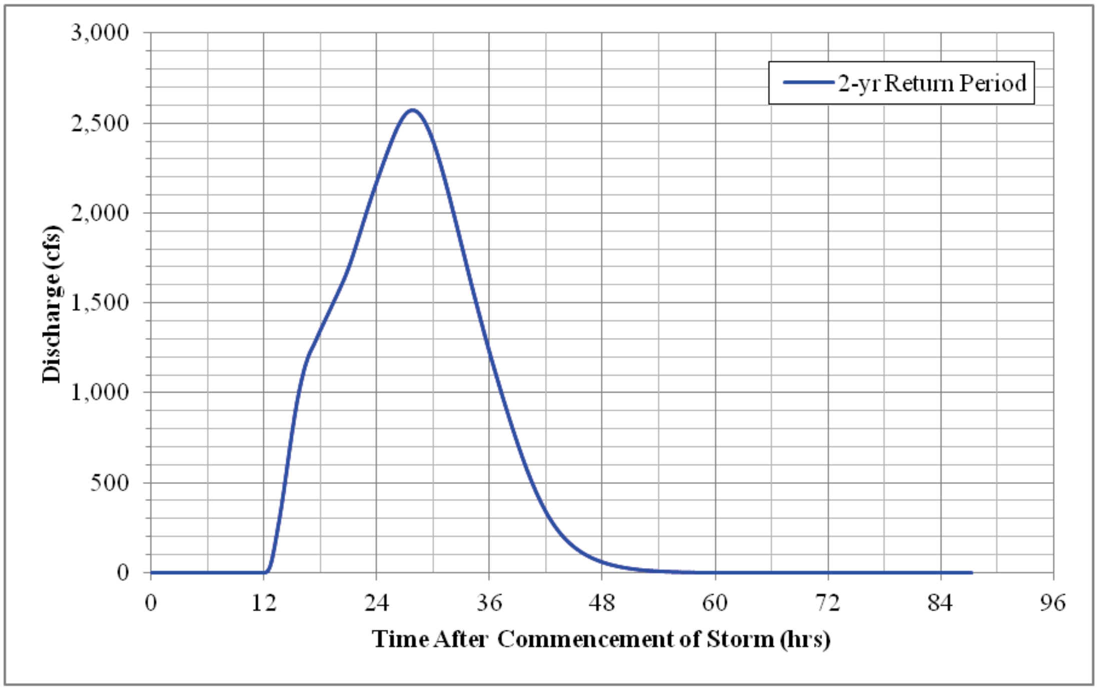

Figure 105: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

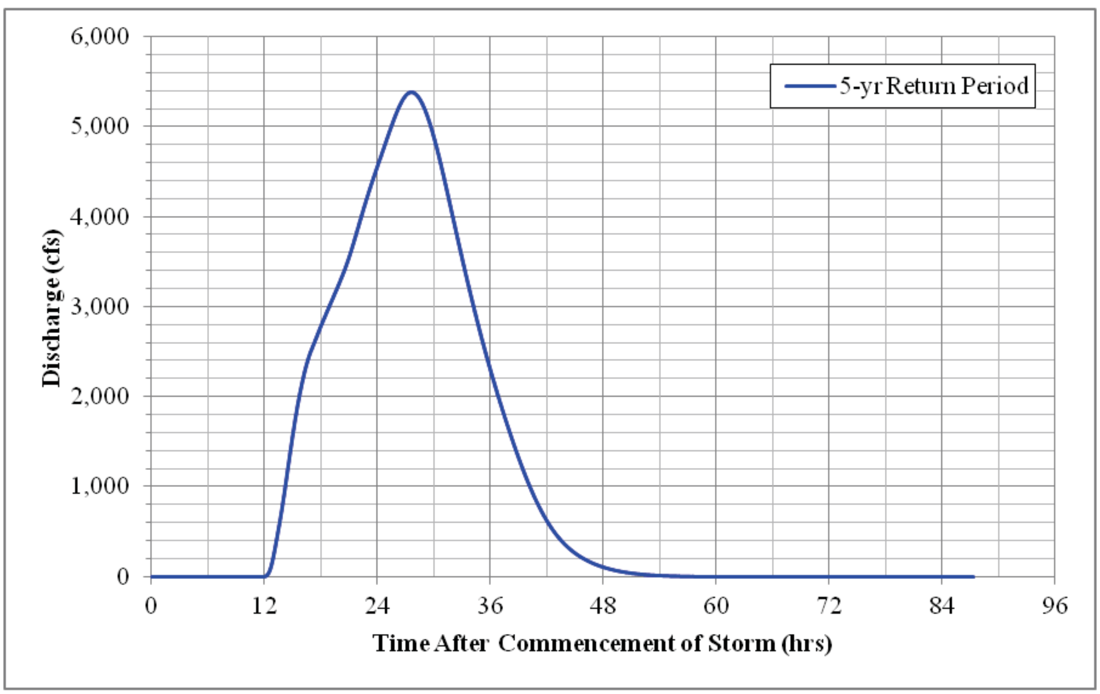

Figure 106: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

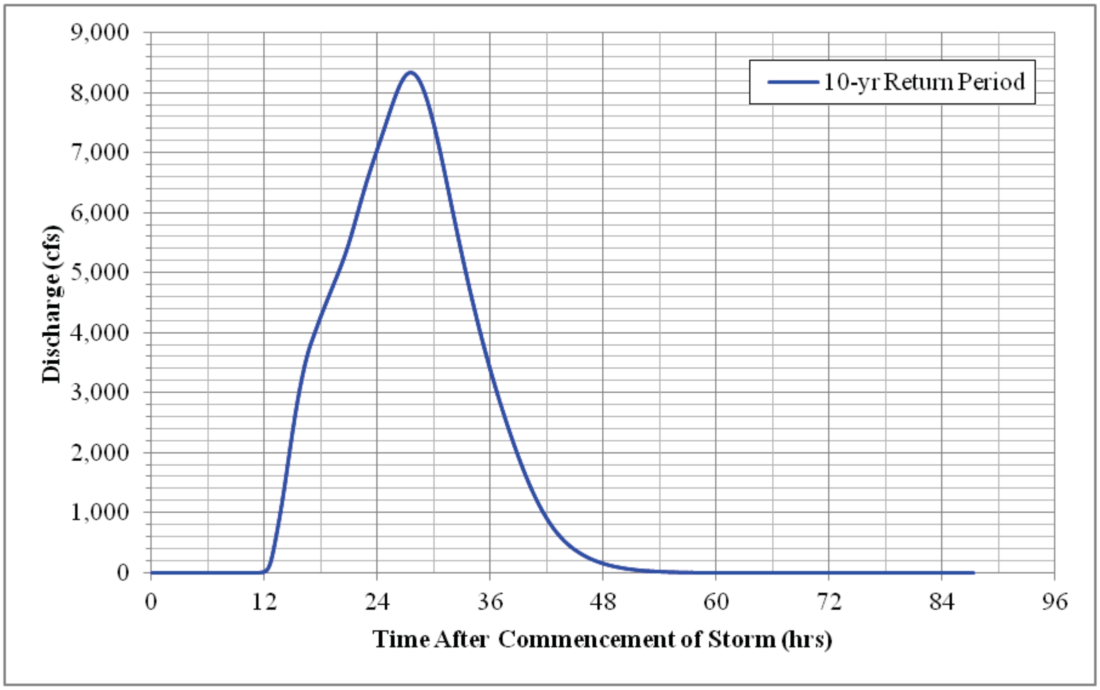

Figure 107: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

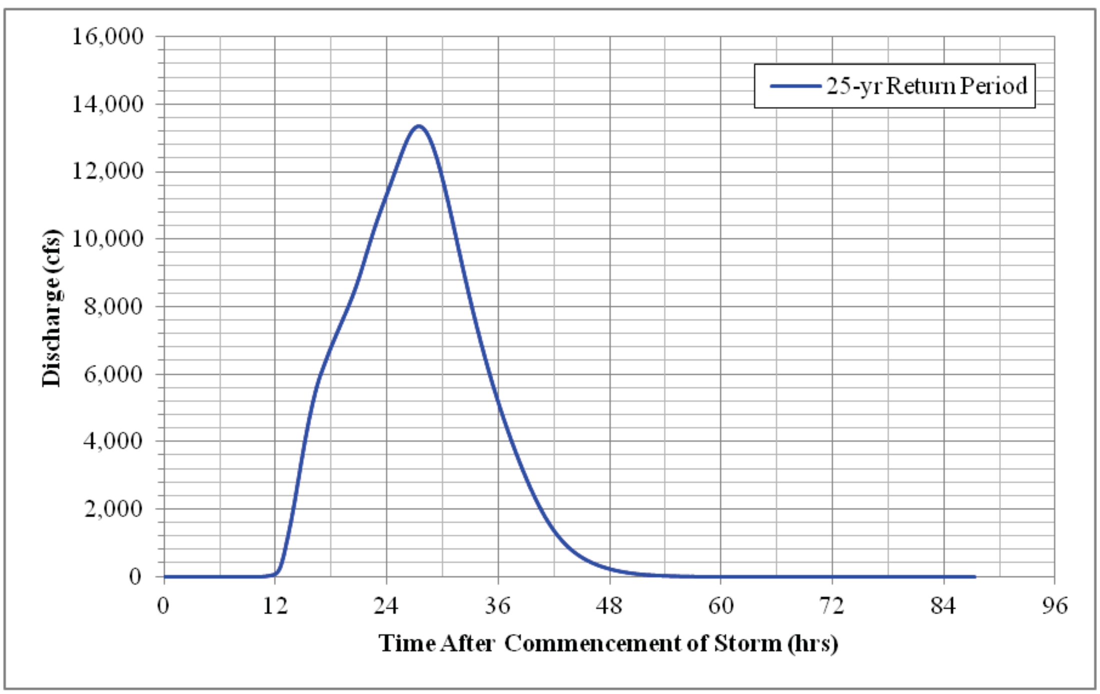

Figure 108: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

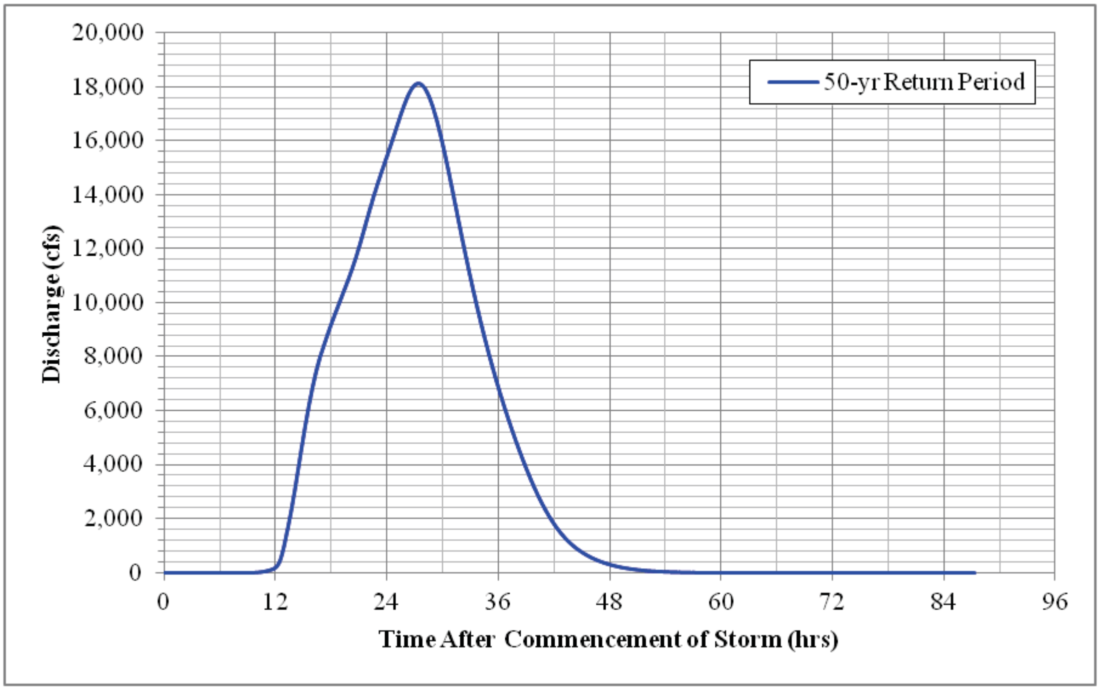

Figure 109: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

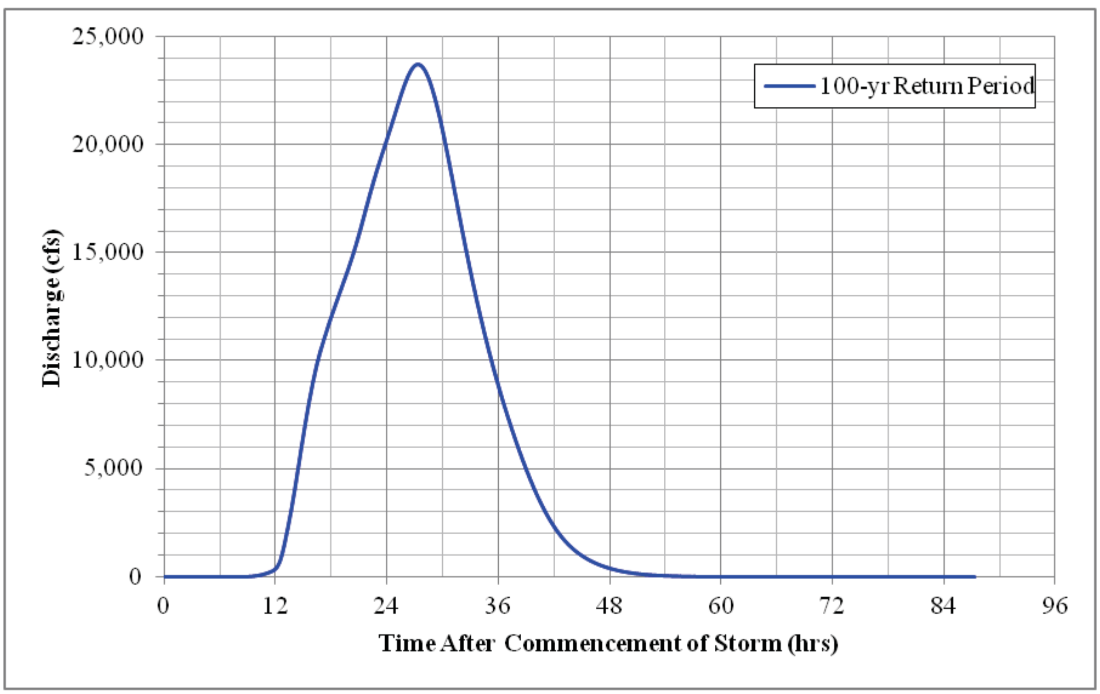

Figure 110: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

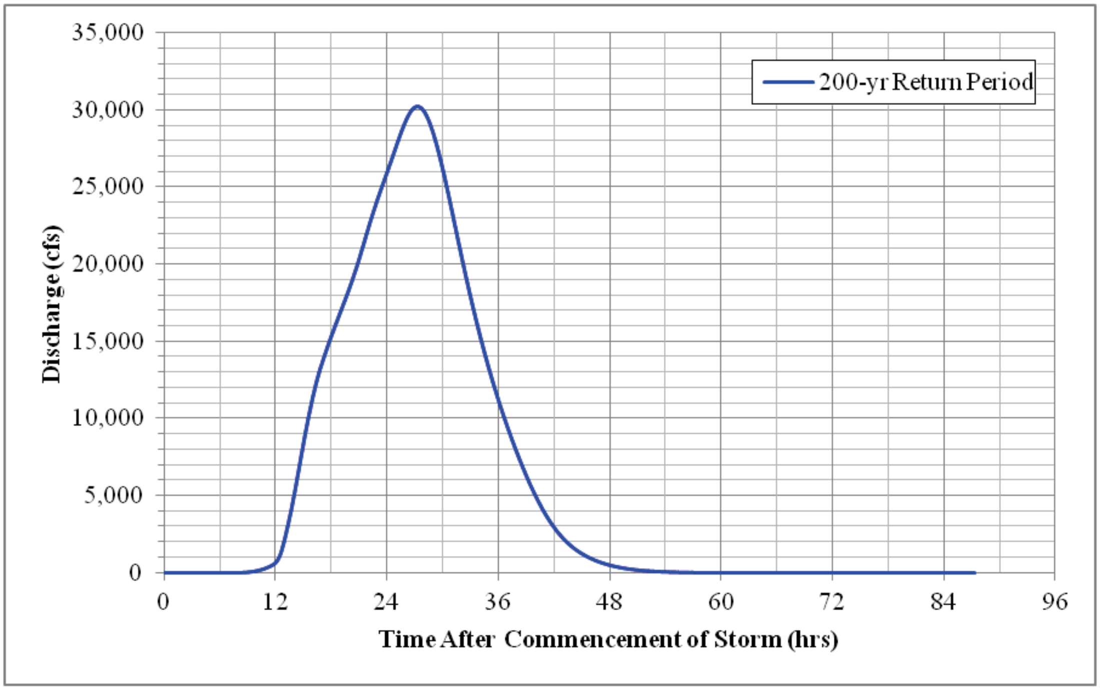

Figure 111: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

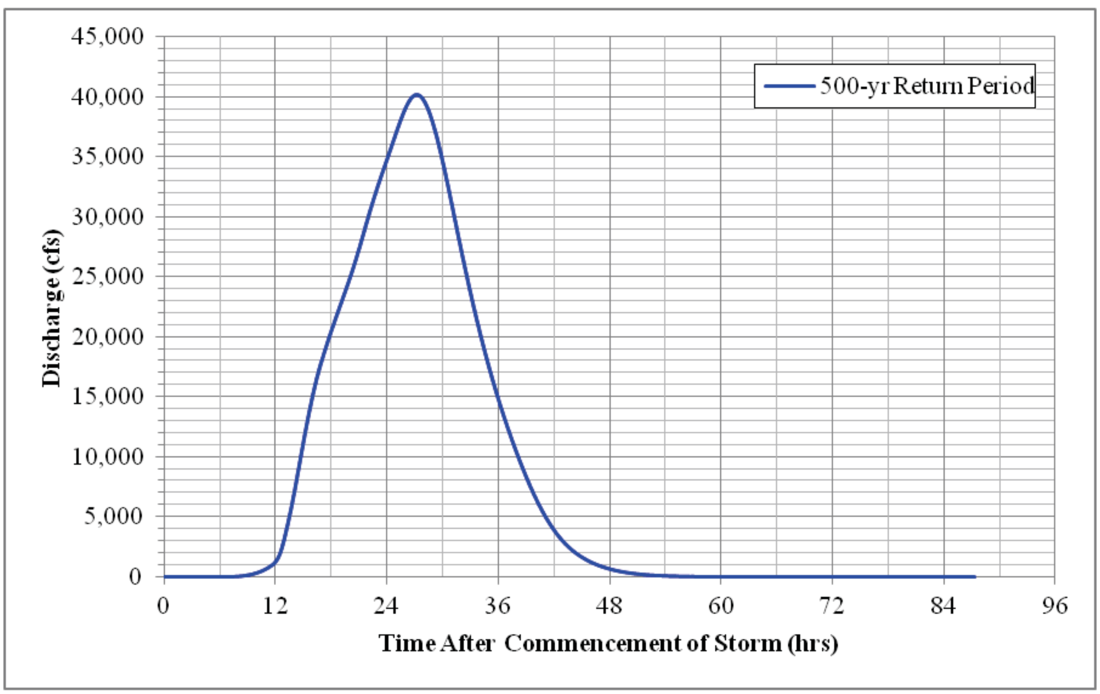

Figure 112: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

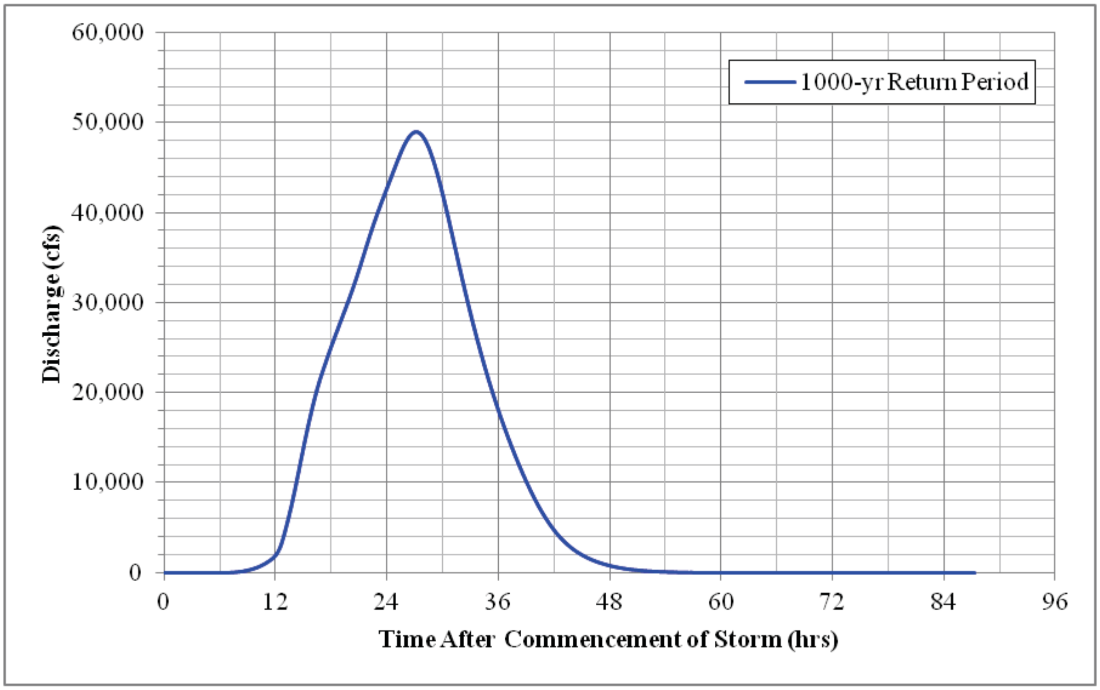

Figure 113: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

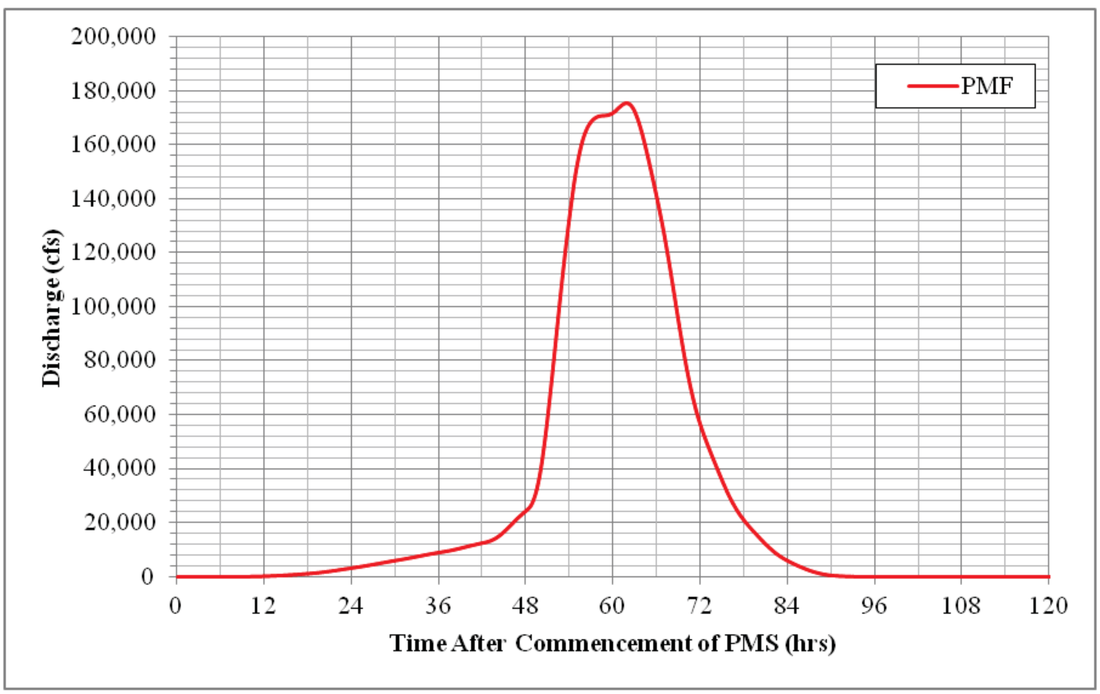

Figure 114: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to Bisese Comparison Point 3

Figure 115: 2-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

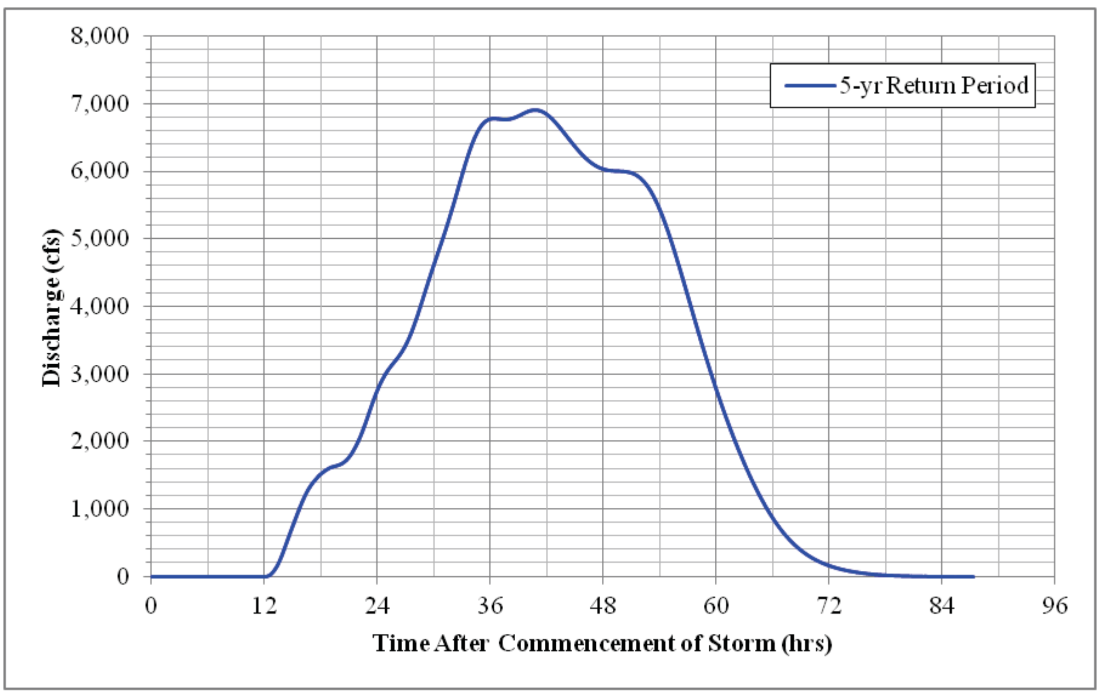

Figure 116: 5-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

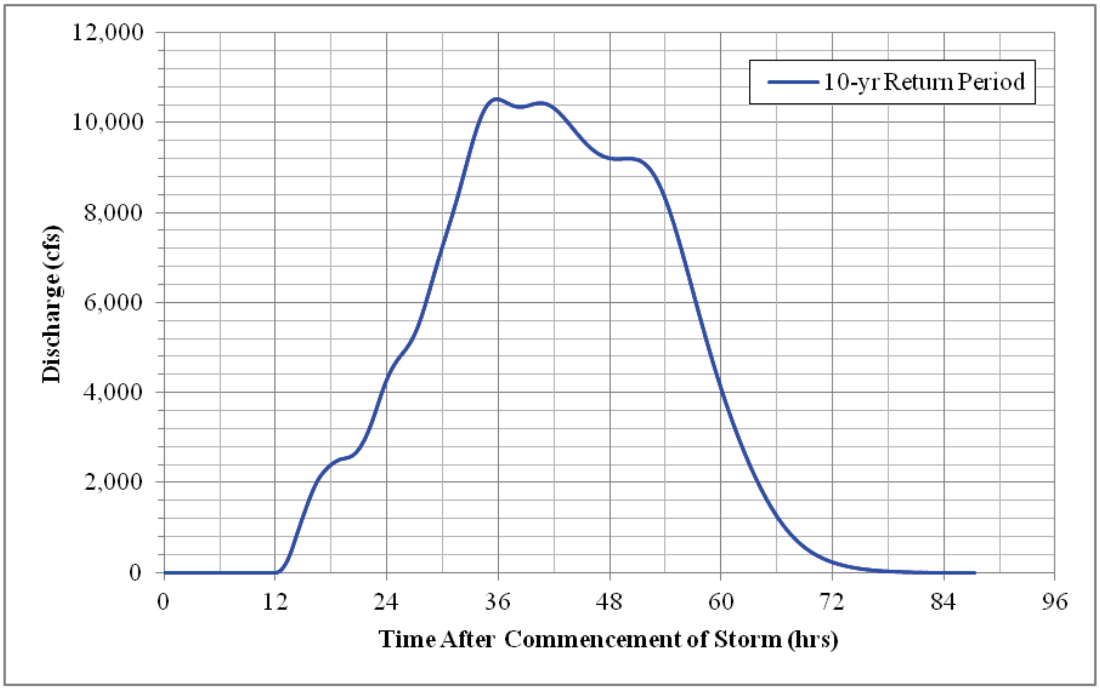

Figure 117: 10-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

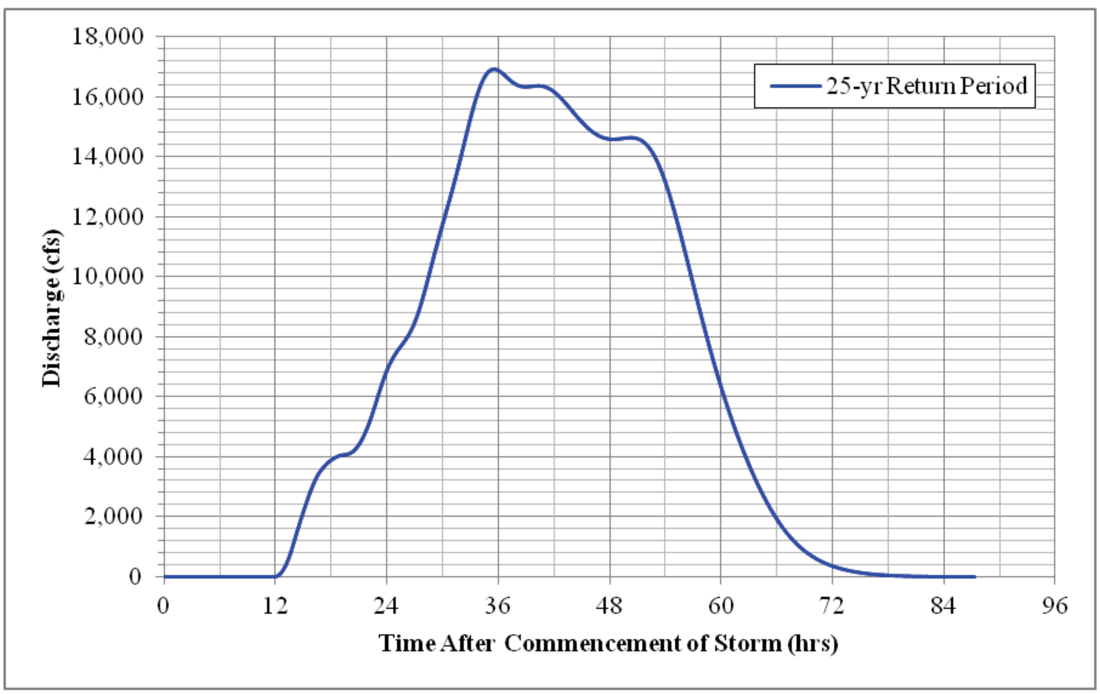

Figure 118: 25-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

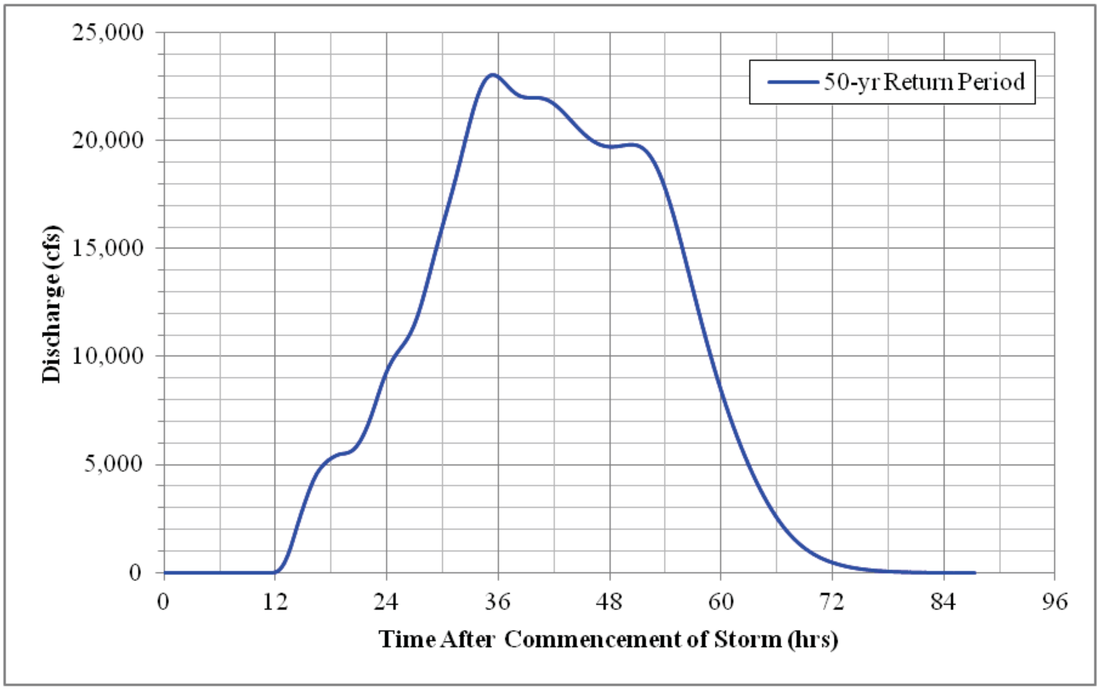

Figure 119: 50-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

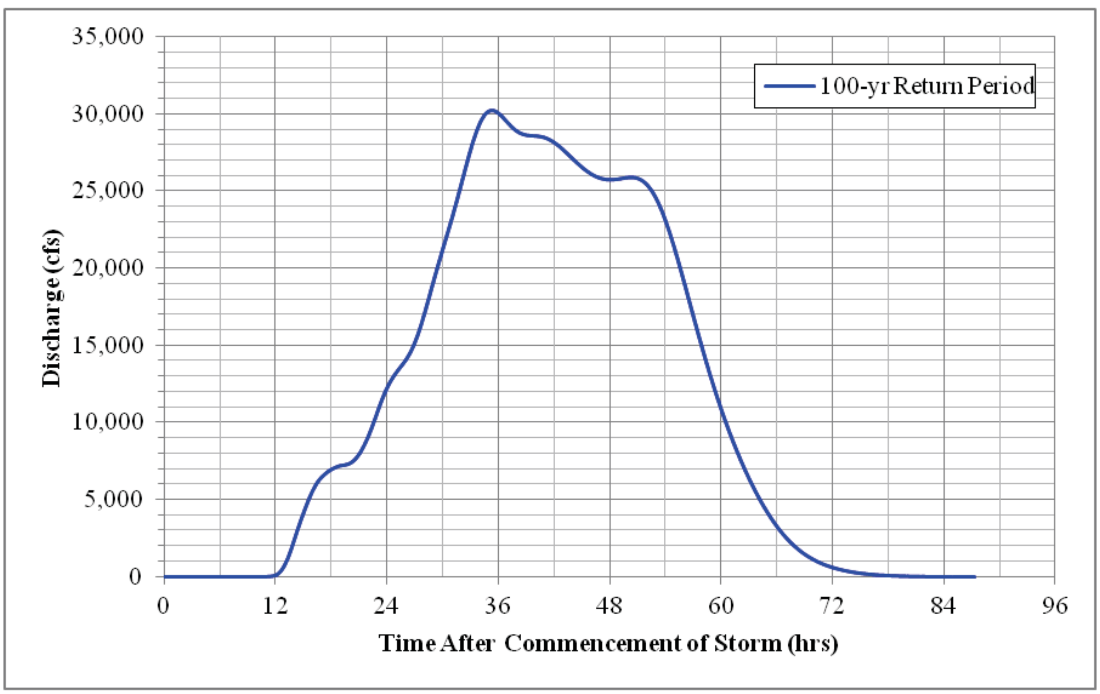

Figure 120: 100-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

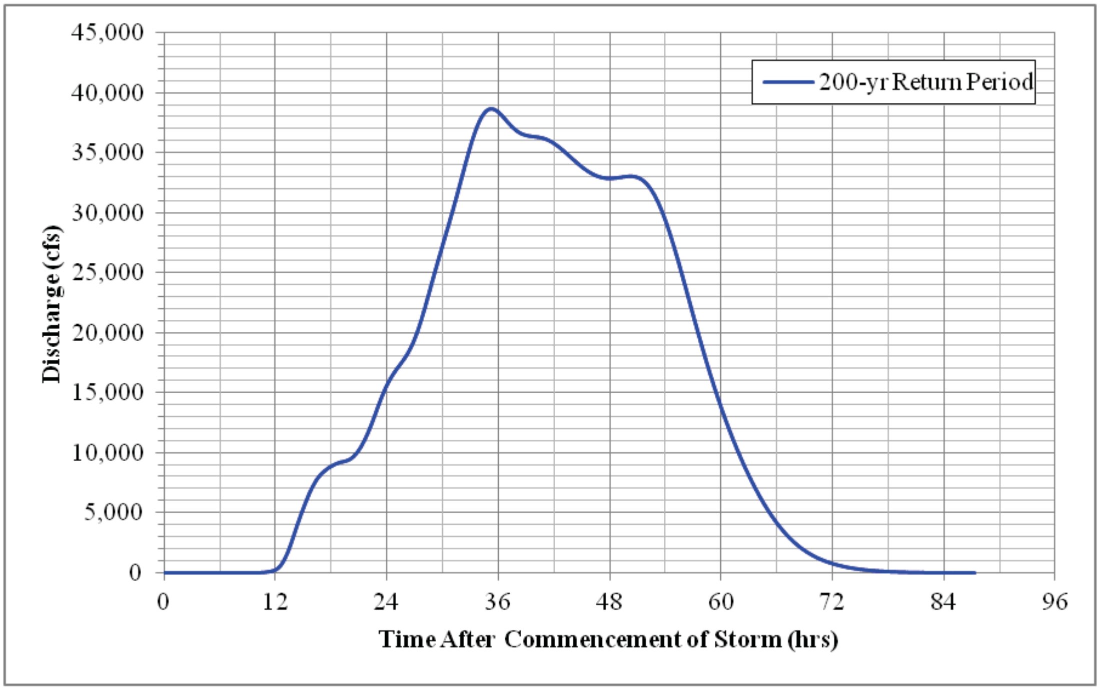

Figure 121: 200-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

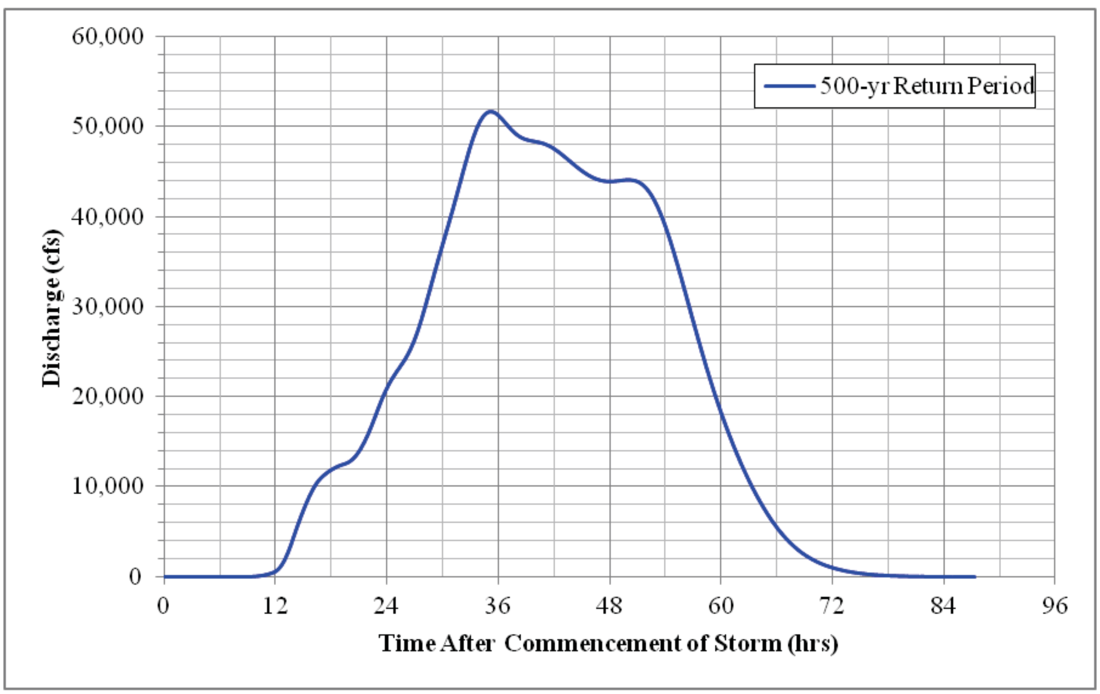

Figure 122: 500-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

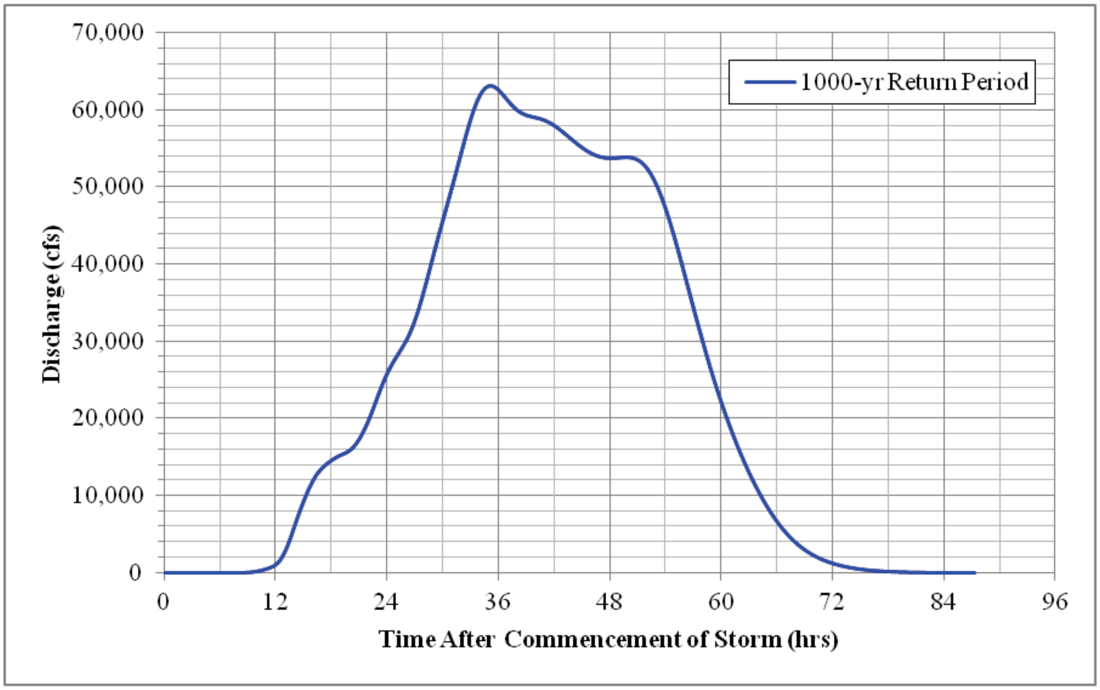

Figure 123: 1000-yr Frequency Storm Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000

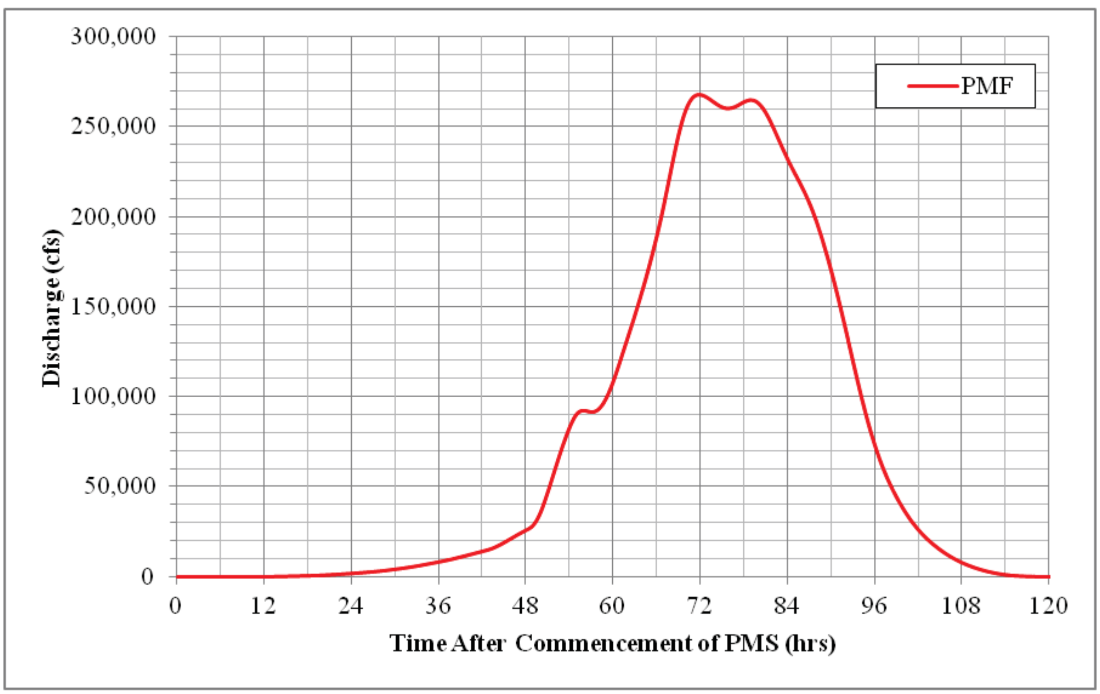

Figure 124: PMF Outflow Hydrograph – Banister River Analysis – Location Corresponding to FFA Comparison Point – USGS 02077000