APPLICATION OF ENVIRONMENTAL DECISION ANALYSIS FRAMEWORK ON THE E.COLI PROBLEM IN LAKE TUSCALOOSA WATERSHED

by

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A DISSERTATION

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DEDICATION

To God, who has given me the knowledge, strength, and patience.
# LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AFO</td>
<td>Animal feeding operation</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>CAFO</td>
<td>Confined animal feeding operation</td>
</tr>
<tr>
<td>CF</td>
<td>Chicken farm</td>
</tr>
<tr>
<td>cfu</td>
<td>Colony forming unit</td>
</tr>
<tr>
<td>CN</td>
<td>Curve Number</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>cfs</td>
<td>Cubic feet per second</td>
</tr>
<tr>
<td>E. coli</td>
<td><em>Escherichia coli</em></td>
</tr>
<tr>
<td>EDAF</td>
<td>Environmental Decision Analysis Framework</td>
</tr>
<tr>
<td>F</td>
<td>Forest</td>
</tr>
<tr>
<td>ft</td>
<td>Feet</td>
</tr>
<tr>
<td>GSA</td>
<td>Geological Survey of Alabama</td>
</tr>
<tr>
<td>Ia</td>
<td>Initial abstraction</td>
</tr>
<tr>
<td>Kᵩ</td>
<td>Partitioning coefficient</td>
</tr>
<tr>
<td>K₂</td>
<td>Release rate parameter</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>N</td>
<td>Number of microorganisms after death at time t</td>
</tr>
<tr>
<td>N₀</td>
<td>Initial count of microorganisms at time 0</td>
</tr>
<tr>
<td>NRCS</td>
<td>Natural Resources Conservation Service</td>
</tr>
</tbody>
</table>
\( P \) Precipitation

P Pasture

p-value Probability value

Q Flow

R Residential

SCS Soil Conservation Service (now Natural Resources Conservation Service)

SSO Sanitary Sewer Overflow

t_l Lag time

t_c Time of concentration

US EPA United States Environmental Protection Agency

USGS United States Geological Services

\( \mu \) Die-off rate constant (day\(^{-1}\))

\( \alpha \) Significance level
ACKNOWLEDGEMENTS

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CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS .............................................................. iv

ACKNOWLEDGEMENTS ............................................................................................... vi

LIST OF TABLES ............................................................................................................ xv

LIST OF FIGURES ........................................................................................................ xvii

ABSTRACT .................................................................................................................. xxviii

CHAPTERS:

I  INTRODUCTION ........................................................................................................... 1

1.1 Overview ........................................................................................................... 1

1.2 Goal ................................................................................................................... 2

1.2.1 Prediction ................................................................................................. 3

1.2.2 Objectives ................................................................................................ 3

1.2.3 Methods .................................................................................................... 3

1.3 Hypothesis ......................................................................................................... 4

1.3.1 Prediction ................................................................................................. 4

1.3.2 Objectives ................................................................................................ 5

1.3.3 Critical Tests/Measures ............................................................................ 5

1.3.4 Methods .................................................................................................... 7

1.4 Contribution ...................................................................................................... 7

1.5 Methodology ..................................................................................................... 8
2.4.2 Common Reasons behind the Existence of Water, Wastewater, and Stormwater Infrastructure Problems ................................................................. 38

2.4.3 An Example of a Framework System Used in Planning and Managing Infrastructure Projects: The Logical Framework Approach (LFA) ............ 41

2.4.3.1 LFA History .......................................................................................... 42

2.4.3.2 Agencies Using LFA ............................................................................ 42

2.4.3.3 Strengths and Limitations of LFA ....................................................... 43

2.4.4 Summary .................................................................................................. 44

III ENVIRONMENTAL DECISION ANALYSIS FRAMEWORK (EDAF) .......... 45

3.1 Introduction .................................................................................................. 45

3.2 Environmental Decision Analysis Framework (EDAF) ............................... 46

3.2.1 First Layer – Stakeholders ..................................................................... 46

3.2.2 Second Layer – Facets ........................................................................... 48

3.3 Collecting Objectives .................................................................................. 50

3.4 Objectives Hierarchy ................................................................................. 51

3.5 Benefits of EDAF ....................................................................................... 52

3.6 Stage of Lifecycle for Implementing Frameworks to Select Sustainable System(s) .................................................................................................. 52

3.7 Implementing EDAF on the E.coli Problem in Lake Tuscaloosa Watershed ................................................................. 55

3.7.1 Introduction ............................................................................................ 55

3.8 Summary ..................................................................................................... 60

IV DATA ANALYSIS AND OBSERVATIONS ............................................. 61

4.1 Introduction .................................................................................................. 61

4.2 Land Use in the Watershed ........................................................................ 63
4.3 Geology of Lake Tuscaloosa Watershed ........................................................ 64
4.4 Water Quality in Lake Tuscaloosa................................................................. 65
4.5 Example of an Area Affected by E.coli: Bear Creek...................................... 66
4.6 E.coli Sampling in Lake Tuscaloosa by the City of Tuscaloosa................. 68
4.7 Factors Affecting E.coli Observations......................................................... 70
  4.7.1 Precipitation........................................................................................... 71
  4.7.2 Flow ....................................................................................................... 72
  4.7.3 Turbidity ............................................................................................... 74
4.8 Analysis of City Data..................................................................................... 75
  4.8.1 Factorial Experimental Design ................................................................ 76
4.9 Observations in Watershed ......................................................................... 80
  4.9.1 Introduction........................................................................................... 80
  4.9.2 Commercial Chicken Operations in the Watershed................................ 81
  4.9.3 Observations in North River Basin......................................................... 86
    4.9.3.1 Activities Close to a Sampling Station ...................................... 88
    4.9.3.2 Agricultural Activities (Pastures) on North River ..................... 90
  4.9.4 Urban Impact on Lake Tuscaloosa: Carroll’s Creek Basin ................... 94
    4.9.4.1 Sanitary Sewer Overflows in the Basin ..................................... 96
4.10 GSA Sampling in the Watershed ............................................................... 97
4.11 Lake Tuscaloosa Watershed All Data Analysis......................................... 98
  4.11.1 Introduction........................................................................................ 98
  4.11.2 All Watershed Data............................................................................. 99
  4.11.3 Regression Analysis........................................................................... 103
4.12 Summary ............................................................................................................... 105

V FLOW MODEL RESULTS AND ANALYSIS ......................................................... 107

5.1 Introduction ......................................................................................................... 107
5.2 North River Flow Model Results and Analysis .............................................. 107
5.3 Binion Creek Flow Model Results and Analysis ............................................. 114
5.4 Summary ............................................................................................................ 120

VI E.COLI MODEL .................................................................................................. 121

6.1 Introduction ....................................................................................................... 121
6.2 Methodology .................................................................................................... 121
6.3 E.coli Model Calibration .................................................................................. 126
6.4 E.coli Mass Balance Model ............................................................................. 127
   6.4.1 North River ............................................................................................. 127
   6.4.2 Binion Creek .......................................................................................... 130
6.5 Summary .......................................................................................................... 131

VII E.COLI MODEL RESULTS AND ANALYSIS .................................................. 132

7.1 Introduction ....................................................................................................... 132
7.2 Calculation Examples ...................................................................................... 132
   7.2.1 Example of Calculating N_0 ..................................................................... 132
   7.2.2 Example Mass Balance Calculation ....................................................... 134
7.3 North River E.coli Model Results Analysis .................................................... 136
7.4 Binion Creek E.coli Model Results Analysis ................................................... 141
7.5 Investigation of Potential Sources and Need of Controls .............................. 147
   7.5.1 Introduction ............................................................................................. 147
7.5.2 Impact of Wastewater Treatment Plant (WWTP) ................................ 148
7.5.3 Impact of On-site Septic Systems .................................................. 149
7.5.4 Investigating Stormwater Systems .................................................. 149
7.5.5 Investigating Agricultural Activities .................................................. 151
7.5.6 Results and Analysis ...................................................................... 152
  7.5.6.1 North River .............................................................................. 152
  7.5.6.2 Binion Creek ............................................................................ 156
7.5.7 Probability Plots for Different Scenarios Using Logistic Regression .................................................................................................................. 156
7.5.8 Percentage of Time Exceeding the Limit ............................................. 157
7.6 Summary ............................................................................................ 158

VIII CHOOSING CONTROLS USING DECISION ANALYSIS ....................... 160
8.1 Introduction .......................................................................................... 160
8.2 Potential Alternatives to Control E.coli in Lake Tuscaloosa Watershed .... 160
  8.2.1 Introduction .................................................................................... 160
  8.2.2 Animal Access Control Alternatives to Nearby Waterbodies .......... 161
  8.2.3 Manure Management Alternatives .................................................. 162
    8.2.3.1 Incineration .............................................................................. 162
    8.2.3.2 Approved Burial Sites .............................................................. 163
    8.2.3.3 Waste Storage Structure ........................................................... 164
    8.2.3.4 Composting .............................................................................. 164
    8.2.3.5 Filter Strips ............................................................................... 165
  8.3 A Step-by-Step Approach for Selecting Controls ..................................... 167
8.4 Summary ............................................................................................ 178
IX CONCLUSIONS, DISCUSSION, RECOMMENDATIONS, AND FUTURE RESEARCH.............................................................................................................. 180

9.1 Introduction........................................................................................................ 180

9.2 Conclusions...................................................................................................... 181

9.2.1 Dissertation Goal and Related Objectives .............................................. 181

9.2.1.1 Goal Objective #1 ........................................................................ 181

9.2.1.2 Goal Objective #2 ........................................................................ 182

9.2.1.3 Goal Objective #3 ........................................................................ 182

9.2.2 Dissertation Hypothesis and Related Objectives .................................. 183

9.2.2.1 Hypothesis Objective #1................................................................. 184

9.2.2.2 Hypothesis Objective #2................................................................. 184

9.3 Improvements on Framework and Models throughout the Research ........ 189

9.3.1 EDAF ...................................................................................................... 189

9.3.2 Flow and E.coli .................................................................................. 190

9.4 Challenges..................................................................................................... 190

9.5 Recommendations to Develop a Comprehensive Watershed Management Plan for the Lake Tuscaloosa Watershed............................................. 191

9.5.1 On-site Septic Systems ......................................................................... 192

9.5.2 Monitoring and Rehabilitating the Infrastructure .................................. 192

9.5.3 Flow and Precipitation Gauges ............................................................. 193

9.5.4 Water Quality Monitoring and Sampling ........................................... 194

9.5.5 Develop Education and Training Program ......................................... 195

9.6 Future Research Studies............................................................................... 196

9.6.1 Extension and Testing of EDAF ............................................................ 196
9.6.2 Flow and \textit{E.coli} Modeling................................................................. 197
9.6.3 Implementing Controls in Watershed .................................................. 197
9.7 Presentations to Stakeholders ................................................................. 198
  9.7.1 City of Tuscaloosa ............................................................................ 198
  9.7.2 Lower Black Warrior Basin Committee ........................................... 198
9.8 Research Contribution ........................................................................... 199
REFERENCES ................................................................................................. 200
APPENDICES:
A  AERIAL PHOTOS AND LAND USES FOR NORTH RIVER AND BINION CREEK BASINS ........................................................................................................ 213
B  FLOW AND \textit{E.COLI} PLOTS FOR NORTH RIVER AND BINION CREEK BASINS ..................................................................................................................... 244
C  STAKEHOLDER INTERVIEWS ..................................................................... 264
D  FLOW MODEL ............................................................................................. 272
LIST OF TABLES

2.1 Pollutants, Sources, and Consequences from Wastewater and Stormwater ...............16

2.2 Associated Health Risks due to *E.coli* Presence in Water ........................................ 19

2.3 Water Quality Criteria for Swimming in Fresh Waters .............................................. 20

2.4 Examples of Communities Dealing with the Lack of Resources for Operation and Maintenance Resulting in Infrastructure Problems ................................................. 41

3.1 Description of Facets .................................................................................................. 49

3.2 Stakeholder/Facet Matrix ............................................................................................ 50

3.3 List of Stakeholders Concerned about the *E.coli* Problem in Lake Tuscaloosa ........ 56

3.4 Objectives Gathered from Stakeholders ..................................................................... 57

4.1 Factorial design for a $2^2$ .............................................................................................. 77

4.2 Factorial Design for a $2^3$ ............................................................................................. 79

5.1 Observed and Calculated Flow Values at North River ............................................... 111

5.2 Observed and Calculated Flow Values at Binion Creek .............................................. 117

6.1 Spreadsheet Listing the Variables and Units of the Model ........................................ 126

7.1 Model Parameters Used to Calculate the $N_0$ Value for Subbasin GC1 ....................... 133

7.2 Initial *E.coli* Concentrations ($N_0$) in North River Subbasins ................................. 134

7.3 Initial *E.coli* Concentrations ($N_0$) in Binion Creek Subbasins ............................... 134

7.4 Summary of Values to Calculate C in Water for NR8 Subbasin .................................. 135

7.5 Observed and Calculated *E.coli* Data for North River Basin Downstream .............. 136

7.6 Observed and Calculated *E.coli* Data for Binion Creek Basin Downstream ............ 142
LIST OF FIGURES

1.1 Methodology flow chart....................................................................................................... 10

1.2 Interaction between the framework and the project pre-planning phases....................... 11

2.1 Risk aversion....................................................................................................................... 34

2.2 Risk loving......................................................................................................................... 34

2.3 Risk neutral ....................................................................................................................... 35

3.1 Organizational alignment for a project .............................................................................. 48

3.2 Monitoring and evaluation in stages of the project cycle .............................................. 53

3.3 Project life cycle for a building project............................................................................. 53

3.4 Interaction between the framework and the project pre-planning phases..................... 55

3.5 Objectives hierarchy diagram .......................................................................................... 59

4.1 Lake Tuscaloosa.............................................................................................................. 62

4.2 Lake Tuscaloosa watershed ............................................................................................ 62

4.3 Examples of land uses in Lake Tuscaloosa watershed. An aerial photo of a pasture is in a., a forest is in b., a chicken farm is in c. and an urban area is in d......................... 64

4.4 Geological map for the Tuscaloosa Lake watershed prepared by the Geological Survey of Alabama (GSA) in 2005.......................................................... 65

4.5 City of Tuscaloosa sampling sites on Lake Tuscaloosa................................................... 69

4.6 E. coli count time series comparison between northern and southern parts of the lake between October 1998 and January 2007 ................................................................. 70

4.7 E. coli counts at different precipitation values at the northern part of Lake Tuscaloosa................................................................................................................................. 71

4.8 E. coli counts versus precipitation in the southern part of Lake Tuscaloosa................. 72
4.9 Relation between *E. coli* values at northern sampling sites of the lake and flow values recorded at the USGS flow gauges ........................................................................................................ 73

4.10 Plot for turbidity and *E. coli* data at the upper half of the lake ........................................ 75

4.11 Plot for turbidity and *E. coli* data at the lower half of the lake ........................................ 75

4.12 Main effects result for the northern part of the lake ......................................................... 78

4.13 Main effects result for the southern part of the lake ......................................................... 78

4.14 Main effects on *E. coli* values (cfu/100mL) ....................................................................... 80

4.15 The interaction between the means ................................................................................... 80

4.16 The number of chicken houses in the subbasins in the watershed. The dark subbasins are those that contain the commercial chicken operations ................................................. 82

4.17 Chicken farm close to the river in a transition phase between old and new flocks of birds (November 2005) ........................................................................................................... 84

4.18 Partially covered manure pile ........................................................................................... 84

4.19 Chicken farm with partially covered manure piles in Lake Tuscaloosa watershed: a. location of manure pile in the farm, b. a closer shot of the improperly covered piles, and c. location of the farm in relation to the river (November 2005) ................................................. 85

4.20 Chicken farm with partially covered manure in watershed; a. a general shot of the farm with an indication to the location of the manure pile and the location of the pile in relation to the river and b. a close shot of the uncovered manure pile (November 2005) ................................................................................................................... 86

4.21 Site investigation location in relation to the watershed; the green line is the path of the boat ................................................................................................................................. 87

4.22 Path of North River investigation with point A as the starting point and point B as the ending point ................................................................................................................................. 87

4.23 North Hagler road sampling station .................................................................................. 89

4.24 Barn swallow birds’ nests ................................................................................................ 89

4.25 Horses drinking from the river close to the sampling station ........................................... 89

4.26 Animal manure and urine mixed with the soil ................................................................. 90
4.27 Pastures on North River directly on the water .......................................................... 90
4.28 Animal manure and activity on the river bank ......................................................... 91
4.29 Site with high animal activity ................................................................................. 92
4.30 A close shot of the activity and the manure ............................................................. 92
4.31 Runoff from the pasture site .................................................................................. 92
4.32 Different sites on the river bank with manure ......................................................... 93
4.33 Cows from a pasture on North River in the shade ................................................... 93
4.34 Carroll’s Creek basin in Lake Tuscaloosa watershed ............................................... 95
4.35 Carroll’s Creek GSA and City sampling sites, chicken farm, and SSO sites ............. 96
4.36 a. E.coli count during low precipitation and b. E.coli count during high precipitation ............................................................................................................. 98
4.37 Full model effects of season on E.coli counts (C: cold and W: warm) ................. 100
4.38 Full model effects of location on E.coli counts (L: lower and U: upper) ............... 101
4.39 Effect of land use on E.coli counts ......................................................................... 101
4.40 Box-whisker plots of observed E.coli values (log) by land use ............................... 102
4.41 Relationship between number of chicken houses and mean E.coli counts in Lake Tuscaloosa watershed ..................................................................................... 103
4.42 Box-whisker plot of observed E.coli values (log) versus the number of chicken houses ....................................................................................................... 103
4.43 Probability plot of the residuals .............................................................................. 105
5.1 Observed flows in North River at different precipitation events .............................. 108
5.2 Observed flow versus calculated flow for North River ........................................... 109
5.3 Observed and calculated flow distributions .............................................................. 109
5.4 Normal probability plot for residuals ...................................................................... 111
5.5 Residuals versus precipitation ................................................................................. 112
7.13 Residuals versus time.............................................................................................. 145
7.14 Residuals versus calculated values ................................................................. 146
7.15 Flow versus observed *E.coli* values................................................................. 146
7.16 Observed and calculated *E.coli* time series..................................................... 147
7.17 Impact of WWTP subbasin on *E.coli* counts downstream at a 1.06 inch rain event....................................................................................................................... 149
7.18 *E.coli* concentration downstream after implementing controls on all sources of pollution in the basin using the 200 and minimum values................................. 153
7.19 Using the 200 cfu/100mL values to replace the *E.coli* concentration for the scenarios of controlling only the pastures and controlling 50% of chicken farms and all the pastures .................................................................................................................. 154
7.20 Using the minimum value from each precipitation run to replace the *E.coli* concentration for the scenarios of controlling only the pastures and controlling 50% of chicken farms and all the pastures................................................................. 154
7.21 Using the 200 cfu/100mL values to replace the *E.coli* concentration for the scenarios of controlling all the pastures and for controlling all the chicken farms .......... 155
7.22 Using the minimum value from each precipitation run to replace the *E.coli* concentration for the scenarios of controlling all the pastures and all the chicken farms .................................................................................................................. 155
7.23 Using the 200 cfu/100mL value to replace the *E.coli* concentration for the scenarios of controlling the pastures and controlling the chicken farms....................... 156
7.24 Probability plot for implementation of different control scenarios in both North River and Binion Creek basins .............................................................................. 157
7.25 Percentage of rains the *E.coli* levels in the lake would exceed the 200 cfu/100mL limit........................................................................................................................ 158
8.1 Reducing *E.coli* utility curve .............................................................................. 170
8.2 Reducing phosphorus (P) utility curve ................................................................. 170
8.3 Reducing nitrogen (N) utility curve......................................................................... 171
8.4 Reducing sediment utility curve ........................................................................... 171
8.5 Reducing air pollution utility curve ................................................................. 172
8.6 Minimizing cost utility curve ........................................................................ 172
9.1 Current and suggested locations for flow and rain gauges in the Lake Tuscaloosa
watershed: (Red) The current flow gauges, (Green) the suggested flow gauges, and
(Brown) the suggested locations for precipitation gauges ................................. 194
A.1 NR0 subbasin aerial photo ........................................................................... 214
A.2 LK1 subbasin aerial photo .......................................................................... 214
A.3 TD1 subbasin aerial photo .......................................................................... 215
A.4 HC1 subbasin aerial photo .......................................................................... 216
A.5 LY1 subbasin aerial photo .......................................................................... 216
A.6 BR2 and BR1 subbasins aerial photo .............................................................. 217
A.7 GC1 subbasin aerial photo .......................................................................... 218
A.8 NR9 subbasin aerial photo .......................................................................... 218
A.9 LB1 subbasin aerial photo .......................................................................... 219
A.10 CA2, CA1, and NR8 subbasins aerial photo .................................................. 220
A.11 EC1 and NR7 subbasins aerial photo ............................................................ 221
A.12 CL4, CL3, and BS1 subbasins aerial photo ................................................... 222
A.13 CL2 and DC1 subbasins aerial photo ............................................................ 223
A.14 CL1, DCT, NR6, RB1, and SPC subbasins aerial photo ................................. 224
A.15 LC1, CE4, and CE3 subbasins aerial photo ................................................... 226
A.16 BY1, CE2, CE1, and NT2 subbasins aerial photo .......................................... 227
A.17 TC2 subbasin aerial photo .......................................................................... 228
A.18 TC1 subbasin aerial photo .......................................................................... 229
A.19 BE1 subbasin aerial photo .......................................................................... 229
A.20 NR5 subbasin aerial photo ................................................................. 230
A.21 FC1 and NR4 subbasins aerial photo ............................................... 231
A.22 NR3 subbasin aerial photo ............................................................... 232
A.23 BO2 and BO1 subbasins aerial photo ............................................. 233
A.24 NR2, GB1, and NT1 subbasins aerial photo .................................... 234
A.25 CP1 subbasin aerial photo ............................................................... 235
A.26 NR1 subbasin aerial photo ............................................................... 236
A.27 BC3 subbasin aerial photo ............................................................... 237
A.28 BC2 subbasin aerial photo ............................................................... 237
A.29 BT2 subbasin aerial photo ............................................................... 238
A.30 BT1 subbasin aerial photo ............................................................... 239
A.31 BT6 subbasin aerial photo ............................................................... 240
A.32 BT4 and BT5 subbasins aerial photo .............................................. 241
A.33 BT3 subbasin aerial photo ............................................................... 242
A.34 BC1 subbasin aerial photo ............................................................... 243
A.35 001 subbasin aerial photo ............................................................... 244
B.1 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (NR0) .............. 245
B.2 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (LK1) .............. 245
B.3 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (TD1) .............. 245
B.4 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (HC1) .............. 246
B.5 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (LY1) .............. 246
B.6 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (BR2) .............. 246
B.7 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (BR1) .............. 246
B.8 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (GC1) .......... 247
B.9 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR9) .......... 247
B10. Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (LB1) .......... 247
B.11 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CA2) .......... 248
B.12 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CA1) .......... 248
B.13 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR8) .......... 248
B.14 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (EC1) .......... 249
B.15 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR7) .......... 249
B.16 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CL4) .......... 249
B.17 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CL3) .......... 250
B.18 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BS1) .......... 250
B.19 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CL2) .......... 250
B.20 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (DC1) .......... 251
B.21 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (DCT) .......... 251
B.22 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CL1) .......... 251
B.23 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR6) .......... 252
B.24 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (RB1) .......... 252
B.25 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (SPC) .......... 252
B.26 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (LC1) .......... 253
B.27 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CE4) .......... 253
B.28 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CE3) .......... 253
B.29 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CE2) .......... 254
B.30 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CE1) .......... 254
B.31 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BY1).......... 254
B.32 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NT2).......... 255
B.33 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (TC2).......... 255
B.34 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (TC1).......... 255
B.35 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BE1).......... 256
B.36 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NR5).......... 256
B.37 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (FC1).......... 256
B.38 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NR4).......... 257
B.39 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NR3).......... 257
B.40 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BO2).......... 257
B.41 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BO1).......... 258
B.42 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NR2).......... 258
B.43 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (GB1).......... 258
B.44 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NT1).......... 259
B.45 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (CP1).......... 259
B.46 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (NR1).......... 259
B.47 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BC3).......... 260
B.48 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BC2).......... 260
B.49 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BT2).......... 261
B.50 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BT1).......... 261
B.51 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BT6).......... 261
B.52 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BT4).......... 262
B.53 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BT5).......... 262
B.54 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BT3) ........... 262
B.55 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (BC1) ........... 263
B.56 Plot (a) precipitation versus flow and plot (b) is flow versus \textit{E.coli} (001) ............ 263
D.1 Parameters option in the pull-down menu ............................................................... 275
D.2 Subbasin area entry .................................................................................................. 276
D.3 Loss values entry...................................................................................................... 277
D.4 Creating an optimization trial in HEC-HMS ......................................................... 280
D.5 Editing optimization trials....................................................................................... 280
D.6 Methods to choose from in the objective function ............................................... 281
D.7 Parameters to choose from for calibration ......................................................... 282
D.8 Curve number parameter window ........................................................................ 283
D.9 SCS lag parameter window .................................................................................. 283
D.10 Initial abstraction parameter window ................................................................... 284
D.11 Results of the simulation without calibration .................................................. 285
D.12 Results of simulation with calibration ............................................................... 285
D.13 North River basin in the watershed .................................................................... 287
D.15 Flow and precipitation time series for North River during 2005 ....................... 288
D.16 North River basin from upstream to station NR5 (J17) ....................................... 289
D.17 North River basin from NR5 (J17) to downstream ............................................. 290
D.18 Binion Creek basin in Lake Tuscaloosa watershed ......................................... 296
D.19 Flow and precipitation from January 1998 until January 2007 ......................... 296
D.20 Flow and precipitation during year 2005 ......................................................... 297
ABSTRACT

A great deal of complexity in decision making arises from the necessity of incorporating a multidisciplinary set of theories with interdisciplinary methodological approaches in order to address all of the data, information, stakeholders, and constraints involved in many problems. This dissertation research was conducted to develop an environmental decision analysis framework (EDAF) that aids in the pre-planning stages of environmental projects and eases this complexity in decision making in order to choose robust and sustainable alternatives. This framework is based on a multiobjective model that assists in identifying and managing risk and uncertainty and includes non-financial objectives in the decision-making process.

This framework was utilized to examine the problems associated with elevated \textit{E.coli} levels in Lake Tuscaloosa. This lake is an artificial impoundment that serves as a public water supply located in the State of Alabama. Recent studies and monitoring of the lake have shown high levels of \textit{E.coli} bacteria in the upper parts of the lake during periods of high stream flow. These high levels of \textit{E.coli} have been identified as a concern for many different interested parties in the area. The city is under pressure to strengthen its management, monitoring, and control of the existing and future pollutant sources around the lake that are within its jurisdiction. Additionally, the city has to consider other sources of bacteria in the watershed outside of its jurisdiction as potential causes of these elevated bacteria levels.
The decision analysis framework and modeling schemes developed as part of this research examines flow and *E. coli* sources and transport issues, along with potential solutions. The framework at the pre-panning stage assisted in organizing the information that helped in the analysis of the problem and in choosing solutions. Developing a strategy to maintain the *E. coli* levels below the permissible limits in the watershed was made possible by implementing this EDAF.
CHAPTER I
INTRODUCTION

1.1 Overview

A great deal of complexity in decision making arises from the necessity to incorporate an interdisciplinary set of theories and methodological approaches in order to address all the data, information, stakeholders, and constraints involved in many problems (Klashner and Sabet 2005). The *E.coli* contamination levels in Lake Tuscaloosa are one such problem. Many researchers argue that in order to achieve long-term financial objectives, decision makers need to pay more attention to measuring non-financial measures (Eccles 1991; Geanuracus 1997; Johnson and Kaplan 1987; Kaplan and Norton 1996A, 1996B; Neely 1999). Janssen and Goldsworthy (1996) and Kummu et al. (2007) discuss and emphasize the importance of interdisciplinary research in integrating, developing, and improving the solutions presented to communities.

In order to include these measures in the decision analysis process, they need to be supported with data. Sometimes seeking additional data can cause problems, such as delays in making the decision, along with waiting to obtain the needed data and to perform the analyses. After additional data is obtained, the results can be quite different than expected. Data may be hard to obtain, expensive, or sensitive, and/or the respondents may misrepresent information. All of these are categorized as uncertainty (Keeney 1982).
These issues may cause decision delays and affect the project outcome (Harris 1998). The issues addressed above have raised the need to develop a framework that helps organize the data and information for any project in order to choose alternatives under consideration that are suitable and sustainable for the community (Reich and Kapeliuk 2005).

In this research, an Environmental Decision Analysis Framework (EDAF) was developed that recognizes this decision-making complexity and was implemented at the early stages of an *E.coli* contamination project: the City of Tuscaloosa, Alabama, was concerned about high levels of *E.coli* bacteria in the northern parts of Lake Tuscaloosa. This lake is the major drinking source for many cities in the area. It is also a major attraction for residential, commercial, and industrial developers.

The City of Tuscaloosa is currently facing a challenging situation: dealing with increased development pressure around the lake and surrounding watershed and protecting the lake from various pollutants, especially bacteria and nutrients. The city is under pressure to strengthen its management, monitoring, and control of existing and future pollutant sources (mostly land development) around the lake that are in its jurisdiction. Additionally, the city has to consider other sources of bacteria in the watershed outside of its jurisdiction as potential causes of these elevated bacteria levels.

### 1.2 Goal

The goal is to explore the use of an Environmental Decision Analysis Framework to inform and extend the evaluation of management practices to protect Lake Tuscaloosa.
1.2.1 Prediction

The framework considers the stakeholders’ conflicting needs and concerns and ranks the possible alternative solutions. The attributes of concern include sustainability, robustness, cost, and public health (water contact recreation, water supply, fishing, etc.).

1.2.2 Objectives

- To enhance environmental management methods to better address the issues that cause projects to fail.
- To calculate the potential benefit of implementing control practices on Lake Tuscaloosa *E.coli* levels.
- To develop utility curves relating the possible range of outcomes for each control practice alternative and determine the utility value associated with each option.

1.2.3 Methods

- Conducting interviews with stakeholders to understand their needs and concerns.
- Developing a hierarchy of the objectives that correlates between different objectives.
- Including these objectives in the decision-making process for choosing suitable solutions.
- Using decision analysis methods to develop trade-offs.
- Using utility theory to develop the utility curves.
1.3 Hypothesis

An appropriate environmental decision analysis framework, based on multiobjective decision analysis theory, can be an effective analytical/management tool, even on projects characterized by limited or incomplete data. This tool can also address a variety of stakeholders’ conflicting objectives. Moreover, the framework can be used on projects that are politically volatile, as each step is well documented and stakeholder input is used at various critical steps in the process, allowing for robust outcome(s).

1.3.1 Prediction

The framework can successfully assist in the collection, management, and analysis of the available data for a crucial water quality project. This dissertation examined the *E.coli* bacteria problem in the Lake Tuscaloosa watershed. There are limited data describing all aspects of this problem and a wide spectrum of stakeholders with conflicting objectives. Additionally, water quality and quantity is one of the highest public health priorities on the City of Tuscaloosa’s agenda. The results from data analysis and modeling efforts conducted during this research have assisted the city in identifying the sources of the *E.coli* pollution and provided means for better determining their impact on downstream water quality. Furthermore, this process has resulted in a short list of the most suitable and available solutions that can be implemented to solve this problem and achieve the desired water quality in the Lake.
1.3.2 Objectives

- To use the Environmental Data Analysis Framework (EDAF) to organize the collected data in a useful scheme that addresses the conflicting objectives of the different stakeholders and ranks the most management alternatives most likely to be successful.

- To implement the framework on a project characterized by limited/incomplete data and having high public interest (the *E.coli* problem in Lake Tuscaloosa).
  - To analyze the available *E.coli* data for the watershed to identify locations, seasons, and flows associated with different *E.coli* levels in the waterbodies.
  - To identify the likely activities that contribute to high *E.coli* levels in the watershed.
  - To develop a calibrated hydrology/hydraulic model for the watershed to quantify variations in seasonal flows from different parts of the watershed and to determine travel times from these different areas to the Lake.
  - To develop and calibrate a fate and transport model for the *E.coli* bacteria in the watershed, providing assistance for identifying potential source locations.

1.3.3 Critical Tests/Measures

- Data analysis:
  - The One-Way ANOVA test was used on the available data concerning *E.coli* versus factors such as land use, turbidity, and precipitation to evaluate
the significance of these parameters with an $\alpha$ of 0.05 (95% confidence interval). If the p-value was less than 0.05, then the test was significant and at least one level of the tested factor was significantly different from the others.

- Regression analyses, step wise and logistic, were used to build models to identify and study the impact of different land uses on \(E. coli\) levels in the watershed as a function of the identified significant factors.

- Factorial designs were developed to determine which factors (independent variables) and their interactions have significant effects on the \(E. coli\) levels in the watershed. These statistical models were used in conjunction with the physical models to describe sources and the transport of \(E. coli\) in the watershed.

- Tests and allowable errors in the flow and fate and transport models:
  - One-Way ANOVA tests were used on the observed and calculated flow and \(E. coli\) data to evaluate the significance of the calculated data at an $\alpha$ of 0.05 (95% confidence interval). If the p-value was less than 0.05, then the test was significant.
  - Error analysis (residual tests), such as Pearson’s r test and bias test, were conducted on the calculated flow data.

- Decision analysis theory was used to correlate the objectives of the stakeholders and the alternatives that are identified from the developed models. The utility curves and trade-offs were used to calculate the utility values, using a multiobjective utility function.
Based on the above analyses, the null hypothesis was that the EDAF will not provide additional insight and will not identify potential solutions any more useful than what the current studies have shown.

1.3.4 Methods

- Implementing the EDAF on the *E.coli* bacteria problem in the Lake Tuscaloosa watershed.
- Using GIS and aerial photographs, along with prior descriptions of watershed activities, to identify potential significant sources of contamination in the watershed.
- Using HEC-HMS to simulate runoff from the different subwatersheds.
- Using fate and transport models to calculate *E.coli* contributions from different subwatershed areas.
- Using the calibrated models to predict the Lake Tuscaloosa *E.coli* levels associated with different management options.

1.4 Contribution

The significant contributions of this research are:

- developing an integrated holistic pre-planning approach for determining the attributes to include in the planning phase,
- identifying the significant lower and/or upper bounds that are acceptable for that facet within the confines of environmental engineering, specifically looking at *E.coli*, and
- assisting the City of Tuscaloosa in developing a sustainable and robust plan to control the *E. coli* bacteria problem in the watershed.

### 1.5 Methodology

Methodology is an important component in research. It shows the flow of information and ideas from one stage to another, as presented in Figure 1.1. The research starts with an idea or a motivation for the research. This is followed by researching the background of what has been done and then identifying the gaps that could support the ideas and the motivation for the research. In this research, there are three parts in the background: the need for the framework, information about the pollutant (*E. coli*), and the use of decision analysis in selecting controls.

Once the background was established, the first stage of developing and implementing the framework began. This stage identified the various components of the framework for the *E. coli* problem in the Lake Tuscaloosa watershed. This stage was considered a junction point, because the data and observations for the *E. coli* problem in the Lake Tuscaloosa watershed were already available, having been collected over the past several years, but the data had never been analyzed to aid in identifying the sources of the problem. Therefore, the available data were studied and analyzed in a succeeding project stage.

Using the analyzed data and associated observations, an understanding of the dynamics and mechanisms of fate and transport of *E. coli* in the area of study needed to be established through the use of a set of interacting models. The results from the modeling established an understanding of the sources of *E. coli* in the watershed and the relative
benefits of alternative management options within the context of community planning and development.

After the sources of *E.coli* were identified and the dynamics of the system were understood, the management alternatives to control and manage the sources of the bacteria were chosen. This stage connects back to the framework, where the framework facets are used to describe the attribute categories of each alternative being examined. Decision analysis procedures were then used to rank the controls in meeting the conflicting objectives. Once this stage was accomplished, the research interpretations and conclusions were prepared. These conclusions were tied back to the idea and motivation stage to demonstrate the connection with the research, with the goal that the hypothesis and objectives were critically examined. Additionally, this stage included suggestions to improve the framework and ways to take this research forward.

The interaction between the framework and the different phases of the project is presented in Figure 1.2 as a diagram. In this figure, the framework assists in informing the different phases of the project at the pre-planning stage (discussed in Chapter III, section 3.6). This interaction between the framework and the problem pre-planning phases leads to the development of a robust and sustainable execution strategy.
Figure 1.1 Methodology flow chart.
Figure 1.2 Interaction between the framework and the project pre-planning phases.

1.6 Dissertation Organization

This dissertation is organized systematically according to the flow of information as described in the methodology section. This introduction presents the underlying goal, the hypothesis, related objectives, and the contributions of this research to science and humanity. Chapter II is the literature review which provides the needed background information required at different stages in the dissertation. The literature review chapter is divided into three sections. The first section discusses the background of *E.coli* bacteria. The second section discusses decision analysis and how it can be used for this type of problem. The third section contains a discussion about the reasons behind the failure of water, wastewater, and stormwater infrastructure systems.
The development of the framework is discussed and described in Chapter III, building on the material presented in the literature review. In Chapter IV, the analysis methodology used to examine the available *E. coli* data in Lake Tuscaloosa watershed is presented. The analysis of the flow model is discussed in Chapter V. The *E. coli* fate and transport model, along with the analysis, is discussed in Chapters VI and VII, respectively. Modeling is necessary to identify the sources of *E. coli* in the watershed, and the effects of the management options considered. The potential controls to be implemented to control the sources of the *E. coli* contamination are discussed in Chapter VIII. The conclusions and recommendations are presented in Chapter IX.
CHAPTER II
LITERATURE REVIEW

2.1 Introduction

The literature review for this dissertation examines three major topics: 1) waterborne \textit{E.coli} bacteria, 2) decision analysis, and 3) environmental infrastructure problems. Each topic is covered in a separate section below. Further supporting literature is provided in the technical chapters throughout this dissertation in order to provide additional support for the research. The first section discusses \textit{E.coli} bacteria found in water, the pollutant of concern in this research. The second section examines decision analysis processes. This part discusses the background for choosing alternative controls, considering uncertainty and using expected utility theory. The third section discusses the environmental infrastructure problems that cause systems to fail. The development of more robust decision analysis framework will aid in the pre-planning stages of environmental projects. These topics are the basis for the framework that was developed during this research and is discussed in Chapter III.

2.2 Waterborne \textit{E.coli} Bacteria

2.2.1 Introduction

Watersheds can be large areas of land that include many different types of activities that cause point (municipal and industrial sources) and nonpoint (urban,
agricultural, forestry, mining, etc., sources) pollution discharges into the waterbody of concern. Trying to study and analyze the watershed’s different components and sources of pollution and their risks is a difficult task (Pitt et al. 1993).

Waterbodies can include lakes, rivers, and creeks and can have many designated beneficial uses. The general public uses these waters for recreational purposes such as skiing, fishing, boating, and swimming. Natural uses are protected through maintaining acceptable biological integrity and the integrity of the eco-system in the watershed. From a municipal engineering point of view, these waters can be used as a drinking water supply and as drainage corridors for flood prevention (Pitt 2007). The National Water Quality Inventory (NWQI) in 2000 summarized the quality of different waterbodies in the US. The report indicated that 40% of rivers, 45% of lakes, and 50% of estuaries are not suitable for swimming and fishing, the suitability for which is one of the primary goals identified in the 1972 Clean Water Act (US EPA 2000). The report determined that the primary sources of impairment are runoff from agricultural lands, wastewater treatment plants, and hydrologic modifications such as channelization and dredging. The data from the report indicated that around 50% of the rivers were impaired due to agricultural activities and around 12% due to urban runoff and storm sewers. The data also indicated that around 40% of the lakes were impaired due to agricultural activities and around 20% due to urban runoff and storm sewers (US EPA 2000).

Stormwater discharges into urban receiving waters are a negative quality indicator and cause high levels of concern among officials and the public. Stormwater is one of the major pollutant sources affecting the nation’s waters, along with agricultural runoff. Pollutants in stormwater include organic, inorganic, chemical, and biological
contaminants and can be liquid, solid, or gaseous in form (Field et al. 2004; US EPA 2001). These pollutants negatively affect the quality of waterbodies, increasing the risk to human health and ecological and environmental systems. The information in Table 2.1 identifies the different pollutants found in waterbodies, their sources, and their consequences to humans and the environment (Field et al. 2004).

Agricultural runoff is the surface water that leaves agricultural areas, such as fields and feedlot operations, due to excessive precipitation or irrigation, and it is considered a nonpoint pollution source (Vellidis et al. 2003). Agricultural runoff has been identified as the primary source of pollutants for United States inland waterbodies and the third major source of pollution to estuaries (US EPA 2002). One of the primary pollutants is soil erosion. This eroded soil (sediment), a pollutant itself, transports other pollutants into the receiving waters. These pollutants can be nutrients, pesticides, herbicides, and animal manure (Vellidis et al. 2003). Animal manure is composed of bacteria and other microorganisms and may contain pathogens that can impact human health and environmental and ecological systems.

Detecting and quantifying pathogens in receiving waters it is not an easy task. These processes require technologies, experience, and financial support. The collection and detection of pathogenic bacteria is one to three times more expensive than detecting inorganic or organic contaminants (Pachepsky et al. 2006).
### Table 2.1 Pollutants, Sources, and Consequences from Wastewater and Stormwater

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Sources</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria (e.g., <em>E. coli</em>, enterococci)</td>
<td>Human and animal waste</td>
<td>Shellfish bed closures, beach closures, public health problems</td>
</tr>
<tr>
<td>Viruses</td>
<td>Human and animal waste</td>
<td>Public health problems</td>
</tr>
<tr>
<td>Parasitic protozoa (e.g., Giardia, Cryptosporidium)</td>
<td>Human and animal waste</td>
<td>Shellfish bed closures, drinking water contamination, adverse public health effects</td>
</tr>
<tr>
<td>Trash and floatables</td>
<td>Anthropogenic activities</td>
<td>Aesthetic impairment, devaluation of property, odors, beach closures</td>
</tr>
<tr>
<td>Toxic organic compounds</td>
<td>Human activities (mainly automobile use and power plants), landscape area maintenance</td>
<td>Sediment toxicity, aquatic life impairment, fish kills</td>
</tr>
<tr>
<td>Metals</td>
<td>Construction, cars, anthropogenic activities</td>
<td>Aquatic life impairment</td>
</tr>
<tr>
<td>Oil and grease</td>
<td>Cars, machines, construction</td>
<td>Adverse public health effects</td>
</tr>
<tr>
<td>Biochemical oxygen demand</td>
<td>Human and animal waste, natural organic debris</td>
<td>Reduced oxygen levels and fish kills</td>
</tr>
<tr>
<td>Solids deposits (sediments)</td>
<td>Anthropogenic activities, mainly construction site erosion and stream bank erosion due to high flows</td>
<td>Aquatic habitat impairment, Shellfish bed closures, flooding from sediment clogged drainage</td>
</tr>
<tr>
<td>Nutrients (e.g., nitrogen, Phosphorus)</td>
<td>Farms, gardens, landscape</td>
<td>Eutrophication, algal blooms, aesthetic impairment, odors</td>
</tr>
<tr>
<td>Synthetic organic chemicals</td>
<td>Anthropogenic activities</td>
<td>Nervous system problems, blood diseases, liver and kidney damage, cancer</td>
</tr>
<tr>
<td>Biologically active chemicals</td>
<td>Human waste</td>
<td>Health problems such as increased cancer and antibiotic-resistant bacteria</td>
</tr>
</tbody>
</table>

#### 2.2.2 *E. coli*

Waterborne pathogens have been one of the leading causes of impairment in waterbodies (US EPA 2000). These pathogens are microorganisms that are harmful to humans and may cause diseases and health risks, as indicated previously in Table 2.1. These pathogens include viruses, bacteria, and protozoa (US EPA 2000). Detecting and quantifying these pathogens for treatment is both difficult and expensive (Pachepsky et al. 2006); therefore, indicator bacteria are used as surrogates for the actual pathogens,
because they are plentiful and can be easily and rapidly detected. Currently used indicator bacteria (\textit{E.coli} and enterococci) are assumed to originate mostly from warm blooded fecal discharges, with minimal other sources. Historically, their presence in urban receiving waters is usually assumed to be indicative of the presence of poorly treated sewage. In addition, indicator bacteria have been selected because they are most sensitive to disinfection and other conventional treatment processes. If these indicator bacteria are not detected in treatment plant effluents, it is assumed that the more sensitive pathogens have also been removed (US EPA 1986). These indicator bacteria include fecal coliforms, \textit{E.coli}, enterococci, and others. The main focus of this dissertation is on the contamination of public water supplies with bacteria, mainly \textit{E.coli}.

\textit{E.coli} can persist in soils for relatively long periods after being discharged with the feces of animals. They can then be transported to receiving waters during rains. These bacteria can persist in warm soils having appropriate nutrients, promoting recolonization and growth (Whitman et al. 2006). Additionally, \textit{E.coli} can persist in streams and stream sediments. High concentrations can be found at stormwater outfalls and are lowest at the headwaters of streams (Byappanahalli and Fujioka 2004; Whitman and Nevers 2003).

Many factors can affect the presence and movement of \textit{E.coli} through a watershed, such as the presence of activities in the watershed associated with concentrations of animals or wastewater treatment and disposal; even the wind direction can have an impact, with onshore winds causing an increase in \textit{E.coli} count in shallow near-shore waters (Whitman et al. 2006).
2.2.2.1 Indicator Organism Water Quality Standards

*E. coli* are currently the basis for most microbiological water quality standards and health risks in fresh water (Geldreich 1976; Geldreich and Kenner 1969; US EPA 1986). The use of indicator bacteria is necessary due to the lack of measurement technology, the lack of trained analytical professionals, and the high costs associated with detecting specific pathogens. In addition, there are a great number of waterborne pathogens of interest, and the difficulties of evaluating all of them are very great. Even with newly developing and improving tools and methods for pathogens, the use of indicators is likely to continue for some time in the future. It is also important to understand that the use of the total forms of *E. coli* do not indicate the presence of the toxic form of *E. coli* (O157:H7), but indicate the presence of fecal matter and possible associated pathogens such as cryptosporidium.

In a Hong Kong swimming beach study, *E. coli* were found to be the best indicator of swimmer illness, particularly in gastroenteritis and skin symptoms. The study found that the geometric mean of 180 cfu/100 mL (*E. coli* measuring unit, colony forming units (cfu) per known volume of sample (100 mL)) of *E. coli* count was the threshold between acceptable and barely acceptable beaches for swimming and direct contact interaction with the water (Cheung et al. 1990). The following Table 2.2 shows the associated health risks from that study.
Table 2.2 Associated Health Risks due to *E.coli* Presence in Water

<table>
<thead>
<tr>
<th>Rank</th>
<th>Rate of gastroenteritis and skin illness (per 1000 swimmers)</th>
<th>Seasonal geometric mean <em>E.coli</em> density (per 100mL)</th>
<th>No. of swimming beaches in category during study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>Acceptable</td>
<td>10</td>
<td>180</td>
<td>19</td>
</tr>
<tr>
<td>Barely acceptable</td>
<td>15</td>
<td>610</td>
<td>7</td>
</tr>
<tr>
<td>Unacceptable</td>
<td>&gt;15</td>
<td>&gt;610</td>
<td>7</td>
</tr>
</tbody>
</table>

The Santa Monica Bay Restoration Project investigated the adverse health effects on swimmers in oceans affected by discharges from separate storm drains (SMBRP 1996). The study detailed the outcome of having an *E.coli* count of more than 320 cfu/100 mL. The increased risk of an ear ache was 46%, and the number of excess cases per 10,000 swimmers was 149. The increased risk of nasal congestion was 24%, and the number of excess cases per 10,000 swimmers was 211.

In 1986, the US EPA developed water quality criteria for recreational waters, water supplies, and fish consumption. It is quantified upon “the relationship between the density of an indicator in the water and the potential human health risks involved in the water’s recreational use” (US EPA 1986, 10). A US EPA study showed that *E.coli* and enterococci bacteria were the best indicators for human health risks in marine and fresh waters and their test results could be returned in one day instead of two. In addition to the single sample limit for the designated bathing beach area, the limit should not exceed 126 *E.coli*/100 mL for an average of 5 samples equally spaced over a 30 day period. The US EPA water quality criteria for swimming in fresh waters for *E.coli* for a single sample limit are shown in Table 2.3.
Table 2.3 Water Quality Criteria for Swimming in Fresh Waters

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Single Sample Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designated bathing beach area</td>
<td>235 $E. coli/100$ mL</td>
</tr>
<tr>
<td>Moderate full body contact recreation</td>
<td>298 $E. coli/100$ mL</td>
</tr>
<tr>
<td>Lightly used full body contact recreation</td>
<td>406 $E. coli/100$ mL</td>
</tr>
<tr>
<td>Infrequently used full body contact recreation</td>
<td>576 $E. coli/100$ mL</td>
</tr>
<tr>
<td>Fish/Shellfish consumption by human</td>
<td>610 $E. coli/100$ mL</td>
</tr>
</tbody>
</table>

The City of Tuscaloosa uses a slightly more stringent $E. coli$ criterion than the US EPA for designated bathing beach areas (200 cfu/100 mL versus 235 cfu/100 mL).

2.2.2.2 $E. coli$ Impact on Human Health

$E. coli$ are identified as one of the leading causes of health problems in receiving waters. There are two main routes of $E. coli$ into the human body. The first is by consuming food being irrigated by polluted water, inadequately cooked contaminated meat, or unpasteurized milk and drinks. The second is by drinking water or coming into direct contact with water polluted by $E. coli$ (Easton et al. 2005).

There are hundreds of strains of $E. coli$; most of them are harmless and some are beneficial. The strains that are responsible for the food- and water-borne disease outbreaks are those that produce Shiga toxin. They are so named because the toxin looks identical to bacteria known as Shigella dysenteria type 1 (Griffin and Tauxe 1991).

The most understood $E. coli$ strain that produces the Shiga toxin is $E. coli$ O157:H7 (Easton et al. 2005). This strain produces toxins that cause damage to the endothelial cells in the kidneys, pancreas, brain, and other organs (Clark 2005). $E. coli$ O157:H7 are responsible in the US for around 2,100 hospitalized cases, and around 61 people die due
to *E. coli* infections annually. The damage to public health caused by *E. coli* O157:H7 costs the US around $405 million a year (2003 dollars) (Clark 2005).

2.2.2.3 Impact on Fish

People go to lakes, rivers, or creeks to enjoy fishing for sport, for consumption, or both. Pollution caused by *E. coli* contaminates many species in the waterbody, including fish (Apun et al. 1999; Fattal et al. 1992; Novotny et al. 2004; Pal and Das Gupta 1992) that then pose a potential health risk to humans when consumed; it is assumed that high counts of *E. coli* in such waterbodies indicates the likely presence of actual pathogens in the edible portions of the fish (Fattal et al. 1992). Researchers (Apun et al. 1999; Pal and Das Gupta 1992; Fattal et al. 1992) found that *E. coli* is retained in the intestines, skin, and liver of the fish, but none is retained in the fishes’ muscle.

2.2.2.4 Potential Sources of *E. coli*

*E. coli* can be introduced to the environment in various ways, such as failing on-site septic systems, failing sewer systems (sanitary sewer overflows (SSOs)), discharges of poorly treated sewage, contaminated urban stormwater, runoff from pastures and feedlots, and human fecal discharge from boats (Aslan-Yilmaz et al. 2004; Dietz et al. 2004; O’Shea and Field 1992). The occurrence of *E. coli* in natural waters can be from sources other than sewage and animal waste. Whitman et al. (2006) found that once *E. coli* is established in the soil, the soil can be a continuous source of bacteria for the nearby streams and can have long-lasting influences on the water quality in the watershed.
The US EPA conducted the Nationwide Urban Runoff Program (NURP) to characterize stormwater quality (US EPA 1983). During this extensive study, non-stormwater discharges were found to contribute some of the pollutants being discharged from separate storm drainage systems. These sources included inappropriate sanitary sewage contamination in the storm drainage system that resulted in high bacterial contamination. These discharges are continuous during both dry and wet weather (Pitt et al. 1993). There were many early studies conducted examining inappropriate discharges into storm drainage systems, including studies in Washtenaw County (Ann Arbor) in Michigan, Fort Worth in Texas, Sacramento in California, and Toronto and Ottawa in Canada. Pitt (2007) summarized these and many other case studies of inappropriate discharges. Studies to detect and correct these inappropriate discharges are now required by the NPDES Stormwater Permit program for all municipalities.

*E.coli* from human sources

Failing sanitary sewer systems may contribute to the *E.coli* problem observed in watersheds. The failure takes many different forms. It can be due to aging and degradation in the network which causes sewage to leak from the pipes. It can be caused by back up and overflow in the system, especially during storm events. Failure of any component in the system, such as pumps, can cause *E.coli* contamination (Utley 2007).

Failing on-site septic systems are believed to be a major contributor of increased microbiological contamination (*E.coli*) in both coastal and inland waterways (Abdullah 1995; Lipp et al. 2001; Parveen et al. 1999). On-site septic systems mainly consist of a septic tank that receives the sewage coming from the household. In this tank, the solids
settle and the grease and lighter material floats to the top. The separated liquid flows out of the tank through a pipe into the leach field. The leach field removes the contamination from the effluent flowing out of the septic tank through a grid of buried perforated pipes. This removal is conducted by letting the effluent leach out and be absorbed by the surrounding soil. If the leach field fails (usually due to clogging when solids leave the septic tank due to infrequent cleaning), then poorly treated septage can rise to the ground surface and flow to surface receiving waters, becoming a direct source of contamination.

Septic systems are located in nonsewered urban and rural areas (Geary and Gardner 1998). In the US, more than 25% of people use septic systems (Rubin 2002; Scandura and Sobsey 1997). The annual failure rate for septic tanks in the United States is between 1 and 5% each year (De Walle 1981). This rate differs from one location to another depending on many factors, such as the unsuitability of soil conditions, improper design and installation, or improper operation and maintenance (Schueler 2000).

_E.coli_ from animal sources

Studies by many researchers found that the presence of animals on open fields near waterbodies and the spreading of animal manure without proper treatment on fields have greatly contributed to water contamination by _E.coli_ (Bradley et al. 2001; Cizek et al. 1994; Fischer et al. 2001; Khaleel et al. 1980). In 1992, an incident in Swaziland caused about 40,000 people to get sick from an _E.coli_ outbreak after 3 months of drought in a region hundreds of kilometers downstream from an agricultural area (Effler et al. 2001).
The United States’ poultry industry is the largest in the world in terms of production and the second in terms of export. Additionally, the US is a major worldwide egg producer (USDA 2008). In the State of Alabama, the 3rd largest poultry producing state, the poultry industry has an annual total economic impact of $8 billion, which accounts for 63% of the total Alabama farm income. This industry provides around 78,000 jobs to the State (Alabama Poultry and Egg Association 2008).

This poultry industry, within the State of Alabama, produces more than 735 million birds a year. These birds produce around 1.7 million tons of manure and litter (ACES 2008). Poultry manure, a byproduct from chicken farms, is used as a fertilizer for agricultural purposes, especially cattle pastures (Bush et al. 2003). This manure contains nutrients that can improve the physical and chemical properties of the soil. This fertilizer and the grazing cattle can have a negative impact on the quality of nearby waterbodies (Fisher and Endale 1999). The US EPA estimated in 1999 that about 940 million tons of manure was generated from livestock and poultry operations. Around 80% of this manure was from beef and dairy operations (US EPA 1999A). Other animals located near the waterbodies contribute to the *E.coli* problem if their waste is not managed properly. These animals can be wild, such as deer, mice, geese, pigeons, etc., or domestic, such as horses, pigs, and dogs.

2.2.3 Summary

This review of research concerning waterborne *E.coli* bacteria summarized the sources and potential health impacts of waterborne *E.coli*. It also presented the water quality standards for *E.coli* that have been established to reduce health risks associated
with use of surface waters, including the local *E. coli* permissible limit established by the City of Tuscaloosa for Lake Tuscaloosa. The literature shows that *E. coli* sources can be a wide range of point and non-point sources. These sources can include urban stormwater, sewage, and agricultural sources, amongst others. Managing a large watershed, such as the Lake Tuscaloosa watershed, with multiple land uses and ongoing development requires a robust approach. This method should assist in collecting and managing data in order to perform analyses to identify the sources behind the *E. coli* levels observed in the Lake. Additionally, the method should aid in selecting the most appropriate controls that will be robust and sustainable to reduce the *E. coli* levels in the Lake. The following section of this literature review summarizes decision analysis methods that have been used for such large and complex problems.

### 2.3 Decision Analysis

#### 2.3.1 Introduction

Usually, problems are not clearly identified and structured for the decision maker to immediately identify suitable solutions (Mintzberg 1973; Mintzberg et al. 1976; Sayles 1964). The decision maker is led to a solution depending upon the influence of the source, the interest of the decision maker, the perceived payoffs of taking action, the associated uncertainty, and finally the perceived probability of successful implementation of the decision (Mintzberg et al. 1976).

Developing decisions is a difficult task due to errors and uncertainty in information which commonly result in projects’ failure to meet their goals and objectives (Ewusi-Mensah 2003). Therefore, better quantitative models are needed by decision
makers to improve the quality of decisions (Power and Sharda 2005). Usually, a decision maker tries to maximize the utility or value function in order to choose the most preferred decision. Simon (1978) considers an individual’s decisions as non-optimal and difficult because of limited access to information which might lead to unnecessary conflicts, especially in cases of uncertainty.

2.3.2 Risk and Uncertainty

Risk and uncertainty are frequently used in decision analysis, especially now when problems are more complex and decisions must be made faster and with limited resources. Ellsberg (1988) states that the degree of uncertainty, or the reliability of probability estimates, must be included in the decision process. Wilson and Crouch (1987) state that the risk assessor should obtain any type of information that would help in obtaining a number between 0 and 1 to estimate the risk and to be as precise as possible (Hansson 1994). There is an increased awareness by decision makers of the importance of dealing with both risk and uncertainty (Beck 1987; Duchense et al. 2001; Methot and Pleau 1997; Rousseau et al. 2001; Schutze et al. 2004; Willems 2000). It is the responsibility of decision makers to understand these risks and uncertainties and try to navigate through them (Keeney and Raiffa 1976). In order to understand these key elements, both terms are defined to distinguish between them and to build a basic understanding.

Knight (1935), in his locus classicus, states that the term ‘risk’ has two definitions, according to the situation. The first is “a quantity susceptible of measurement” and the second is “something distinctly not of this character” (Knight
1935, 13). Alexander (1975) relates risk to complete probabilistic knowledge and uncertainty as partial probabilistic knowledge. Hansson (1994) states that uncertainty applies to cases of non-quantifiable type, and risk applies to the quantifiable type.

In one of the most influential books on decision theory, *Games and Decisions*, certainty, uncertainty, and risk are defined as follows (Luce and Raiffa 1957, 13):

- **Certainty**: “If each action is known to lead invariably to a specific outcome.”

- **Uncertainty**: “If either action or both has as its consequence as set of possible specific outcomes, but where the probabilities of these outcomes are completely unknown or are not even meaningful.”

- **Risk**: “If each action leads to one of a set of possible specific outcomes, each outcome occurring with a known probability. The probabilities are assumed to be known to the decision maker.”

### 2.3.2.1 Why Uncertainty?

Most everyday reasoning and decision making are based on uncertain premises. Most of our actions are based on guesses, often requiring explicit weighing of conflicting evidence (Shafer 1990). Uncertainty cannot be avoided, but it can be reduced and managed by considering all relevant data. Uncertainties exist due to several factors such as: 1) little or no data available, 2) expensive and/or time-consuming data collection, 3) acts of God such as earthquakes and droughts, 4) the movement of populations, 5) priorities and their level of importance at different stages of the life cycle, and 6) indirect effects from politicians and organizations (Keeney 1982).
Decision makers note that stakeholders fail to appreciate the rationale for their final decision when unexpected impacts (or surprise responses) occur or accusations of manipulating data for a desired result are made (Charnley 2000; Cranor 1997; Gerrard 2000; Krimsky and Plough 1988; Lynn 1990; Thompson 1983). Therefore, understanding the different data relationships is important in informing decision makers and other stakeholders for better decision making (Stahl and Cimorelli 2005).

Environmental decision making, at policy organizations such as the US EPA, is constrained by limited time and resources. Policy analysts within the organization tend to limit uncertainty considerations in their analyses to cope with these limitations. Therefore, limiting or ignoring uncertainties may result in unpleasant policy surprises (USDE 2004; US EPA 1998; US EPA 1999B; US EPA 2005). It is important for decision makers to know how defensible a chosen policy option is over other options when the uncertainties of the data are considered (Stahl and Cimorelli 2005). This is similar to the E.coli problem in Lake Tuscaloosa, where policy makers made decisions that were not supported by adequate evidence with available data having a high level of uncertainty. The decisions that were made were politically comfortable and tended to shift the blame to agencies that were assumed to be capable of correcting the problem. However, it is likely that these decisions will result in very little improvement in Lake Tuscaloosa water quality.
2.3.3 Utility Theory

Utility theory is a successful method that assists decision makers when they manage uncertainty and risk in information during the decision analysis process. Using utility theory can lead to higher levels of confidence when making decisions.

These preferences in terms of utility are defined by an individual comparing two bundles and determining that one bundle \((x_1, x_2)\) is preferable to another bundle \((y_1, y_2)\), which means that bundle \(x\) has a higher utility than bundle \(y\). The preferences of the individual are the fundamental description used for analyzing choice, and the simplest way to describe it is through utility (Varian 1987). Utility function assigns a number to every possible bundle, with the highly preferred bundles having higher scores. The previous example can be presented as \((x_1, x_2) > (y_1, y_2)\) if and only if \(u(x_1, x_2) > u(y_1, y_2)\).

2.3.3.1 Utility Function

Managing decision making under uncertainty modifies the decision analysis structure. This modification includes the addition of utility functions to the process. Utility functions are based on probabilities and are used as the bases in decision analysis (Varian 1987). Utility theory is used to quantify the values of decision makers for consequences.

The best way to clarify utility functions is through an example from *Decision Theory* by Hansson (1994). The example has two mutually exclusive conditions such as rain or shine, hot or cold, etc. Let \(x_1\) and \(x_2\) represent consumption in states 1 and 2.
\( p_1 \) and \( p_2 \) be the probabilities for states 1 and 2. Note that these two are mutually exclusive; therefore, only one of them can happen at a time. This is presented as:

\[
p_2 = 1 - p_1. \tag{eq. 2.1}
\]

The utility function can be written as:

\[
u(x_1, x_2, p_1, p_2). \tag{eq. 2.2}
\]

The utility function can be presented in different ways. Here, two types are discussed. The first is expected utility, and the second is Cobb-Douglas. The primary difference is the mathematical representation of these two theories. The expected value is presented as:

\[
(x_1, x_2, p_1, p_2) = p_1 x_1 + p_2 x_2. \tag{eq. 2.3}
\]

The Cobb-Douglas utility function is presented as:

\[
u(x_1, x_2, p, 1-p) = (x_1^p)(x_2^{1-p}). \tag{eq. 2.4}
\]

This above function can be transferred into a logarithmic one:

\[
\ln u(x_1, x_2, p_1, p_2) = p_1 \ln x_1 + p_2 \ln x_2. \tag{eq. 2.5}
\]

A main mathematical characteristic of the utility function is that it can be differentiated twice. The properties of this differentiation are \( u(x) \) is defined for \( c > 0 \); the first derivative is \( u'(x) > 0 \) and second derivative is \( u''(x) < 0 \), and the latter of the two derivatives is risk aversion. Since the expected utility theory is the one of concern, further discussion is in the following section.

### 2.3.3.2 Expected Utility Theory

Expected utility theory plays a major role in uncertainty and incomplete information assessment, and remains the dominant approach for modeling risky and uncertain decision making. Many models for decision-making under uncertainty have
been developed, and they are all based upon the expected utility theory (Hansson 1994). The expected utility has proven to be a “pretty good” approximation to individuals’ true preferences (Plott 1996).

Our world is not ideal; it cannot be treated as an ideal gas, frictionless planes, or a vacuum (Simon et al. 1987). Expected utility theory is an old mathematical probability theory, also called probability-weighted utility theory. Probabilities and utilities can be used to calculate the expected utility of each alternative. The alternatives with higher expected utilities should be preferred (Keeney 1982).

Background of expected utility theory

Expected utility theory dates back to the 17th century during the development of the modern probability theory. Blaise Pascal and Pierre de Fermat assumed that the attractiveness of a lottery payoff \((x_1, x_2, \ldots, x_n)\) with probabilities \((p_1, p_2, \ldots, p_n)\) can be expressed by its given expected value

\[
x(\text{bar}) = \Sigma (x_i.p_i).
\] (eq. 2.6)

This equation represents the average utility, or the expected utility, of \(x\).

In 1782, Nicholas Bernoulli studied individuals’ tendency to evaluate expected value, and he illustrated this tendency in an example called the St. Petersburg paradox. This example is based on tossing a coin repeatedly until it is tails. If the first attempt is tails, the person gains $1, $2 for two tosses, $4 for three tosses, $8 for four tosses, and so on. Therefore, the probability of winning is \(\frac{1}{2}\) to win $1, \(\frac{1}{4}\) to win $2, etc.; so it should be preferred to any finite gain (List and Haigh 2005).
The cousin of Nicholas, Daniel Bernoulli, offered a solution to the paradox. Essentially, he outlined the intuitive reason why people pay only a small amount for a game with infinite mathematical expectation. Daniel argued that a gain of $100 was not necessarily worth more than twice as much as a gain of $50. The utility function $u(x)$ that he suggested was logarithmic, which illustrated diminishing increases in utility for equal increments in wealth. It does in fact show that expected utility is limited.

$$u(x) = b \ln \left( \frac{\alpha + x}{\alpha} \right) \quad (\text{eq. 2.7})$$

$$du(x)/dx = b / (\alpha + x) \quad (\text{eq. 2.8})$$

$$d^2u(x) / dx^2 < 0 \quad (\text{eq. 2.9})$$

John von Neumann and Oskar Morgenstern proved that there exists a utility index such that the ordering of lotteries based on their expected utilities fully coincides with the person’s actual preferences (List and Haigh 2005). Von Neumann – Morgenstern utility function can be presented as:

$$u(CEi) = \Sigma (pi.u(xi)) \quad (\text{eq. 2.10})$$

where CE is the certainty equivalent, pi is the probability, and u(xi) is the utility function.

The Von Neumann – Morgenstern utility function can be obtained by: 1) asking decision makers for the certainty equivalent (CE) for each risky alternative that they face; 2) arbitrarily setting the utility scale from 0 (the least favorable) to 1 (the most favorable); and 3) based on the decision makers’ CEs, applying the utility rule to calculate utility levels for alternatives.

The expected utility function can be also expressed in a convenient equation as:

$$u(x1, x2, p1, p2) = p1 \ u(x1) + p2 \ u(x2). \quad (\text{eq. 2.11})$$
This equation illustrates that the weighted sum of some function of consumption in each state, $u(c_1)$ and $u(c_2)$, where the weights are given by the probabilities. The expected value of the utility would be $u(c) = c$. Any monotonic (multiply or divide or log) transformation of an expected utility function describes the same preferences.

2.3.3.3 Utility Curves

The utility curves indicate the individuals’ attitude toward risk for a certain attribute and quantify the preferences that exist over the total range. These curves are important in quantifying alternatives when uncertain consequences exist. The shape of the utility curve can be determined using knowledge of the attribute. These curves are usually theoretically defined and constructed through a series of questions that determine the points on the utility curve. The highest preferred utility has a value of 1, and the least preferred utility has a value of 0.

Types of utility curves

There are three types of utility curves. These types of utility curves are defined according to the individual’s behavior in taking risk. The first type of utility curve described is risk aversion. It indicates that an individual does not prefer to take risks and that the expected benefit of risk is less than the utility generated by the expected value (mean) of the variable being evaluated. The risk aversion property states that the utility function is concave; for example, the marginal utility of wealth decreases as wealth increases, as demonstrated in Figure 2.1.
Figure 2.1 Risk aversion.

The second type of utility curve is risk loving. A risk-loving individual is one whose expected utility of a risk is greater than the utility of the most likely outcome. Risk loving is opposite to risk aversion. The risk-loving utility is again demonstrated using wealth as an example in Figure 2.2.

Figure 2.2 Risk loving.

The third type of utility curve is risk neutral. The relationship between the expected utility and some variable is linear. The risk-neutral individual is one for whom
the expected benefit of a risk and utility of the expected outcome are the same.

Continuing with the example of wealth, the risk neutral utility is shown in Figure 2.3.

![Risk Neutral Utility Curve](image)

**Figure 2.3 Risk neutral.**

The way in which a problem is framed strongly affects the choices and preferences used to develop the utility curves. If a problem is described in terms of possible gains, for example, people tend to be risk averse, but if the same problem is described in terms of losses relative to a possible maximum gain, they tend to be risk loving. If people use predefined subjective probabilities and utilities to make choices, they are not be affected by the description of the problem (Shafer 1990).

Developing utility curves is not an easy thing to do, because deep understanding and knowledge about the problem and the desired outcome of the decision process is necessary. Developing utility curves for a project can provide tremendous help from similar projects in the same field of study, which may alleviate some of the difficulty associated with developing utility curves for future projects.
2.3.3.4 Multiobjective Decision Making

Usually, more than one objective is included in decision making. The sections above examined single objective examples. Those mathematics are expanded here to include additional objectives. Keeney and Raiffa (1976) developed a multiobjective utility assessment method on the basis of traditional economic ideas about utility. This method is intended to help people make tradeoffs between different objectives. These tradeoffs are mainly between value and certainty, but many problems involve tradeoffs between competing values. Their solution also contains techniques for getting people to specify in simple ways how they want to make these tradeoffs (Shafer 1990). For further information about this topic, Von Winterfeldt and Edwards (1986).

A multiobjective utility function is a mathematical expression that summarizes attributes’ utility functions and the trade-offs between them. The mathematical form of the multiobjective utility function is established by verifying several reasonable assumptions regarding preferences:

\[
 u(x_1, x_2, \ldots, x_n) = \sum k_i v_i(x_i), \tag{eq. 2.12}
\]

where \( x_i \) is the level of the \( i \)th attributes, \( u(x_i) \) is the utility of the \( i \)th individual attribute, \( v \) is the multiobjective utility, \( k_i \) is the trade-off constant for \( i \)th attribute, and \( \sum k_i = 1 \).

Using the multiobjective utility helps decision makers to weigh the different alternatives against one another to reach optimal requirements for solutions.

2.3.4 Summary

This section about decision analysis summarized its theory and mathematical background. It is the mathematical backbone for the developed framework used in this
research’s analysis of the Lake Tuscaloosa watershed *E.coli* contamination. This framework provides a structure for managing uncertainty and choosing sustainable alternatives. This section also discussed the development of utility curves and their importance as a tool for quantifying alternatives when uncertain consequences exist. Because decisions often involve multiple objectives, the multiobjective decision-making theory was discussed. Further discussion about this theory and its implementation is discussed in the technical chapter regarding choosing between alternatives (Chapter VIII).

### 2.4 Environmental Infrastructure Problems

2.4.1 Introduction

Since the dawn of civilization, tribes and later formal governments have attempted to solve water, wastewater, and stormwater infrastructure problems (UN-Water 2005). Solutions are complex, because the task of solving problems has multiple stages, resources to construct the physical infrastructure are expensive, and lessons learned during one project are not necessarily applicable to other projects (Alfaqih et al. 2006).

Water is one of the most vital elements for life, and almost every civilization across the globe is facing serious problems with its water and water-related infrastructure systems. In many communities, water supplies, especially for drinking water, are either depleting or becoming polluted. Too often these problems are compounded by the lack of reliable wastewater and/or stormwater infrastructure systems that provide proper collection and treatment (UN-Water 2005). Collectively, these problems cause health concerns and impact the quality of life and the surrounding environment (WHO 2003A).
Many communities are greatly affected by improper or neglected water, wastewater, and stormwater infrastructure systems. Despite the best of intentions, these systems are not often sustainable. These systems, after implementation, may operate at a reduced capacity or break down completely. This is due mainly to the implemented management systems that fail to provide efficient, robust, and sustainable operation and maintenance for these systems (WHO 2003B).

2.4.2 Common Reasons behind the Existence of Water, Wastewater, and Stormwater Infrastructure Problems

The Norwegian Agency for Development Cooperation (NORAD) states why infrastructure systems fail:

“Inadequate planning is a persistent fundamental problem. Planning documents are often specific and clear as to the physical and financial inputs, personnel, activities, and expected physical results. But thorough assessment of the overall objectives, the target groups, and the external factors which determine success or failure is often lacking” (NORAD 1990, 3).

The World Health Organization (WHO) and the United Nations Children’s Fund (UNICEF) summarized the main reasons for failure as high population growth, limited funding, poor operation and maintenance, and the continuance of the ineffective “business as usual” approaches (WHO and UNICEF 1992). UNICEF (1995) affirmed that cultural and social issues are important parameters to be considered in making decisions. Researchers and aid organizations only consider social, economic, and environmental aspects in a project (Kakade et al. 2001).

Butterworth and Soussan (2001) stated that even though there are many projects and investments in the water and sanitation sector, there are many people without these
services. Even if the systems exist, they commonly function inadequately, resulting in systems that do not serve the needs of the population (UNEP 2002). In many cases, infrastructure systems age and replacement becomes necessary but is not possible due to lack of funds or knowledge.

Oldfield (2006), in his survey of non-government organization (NGO) leaders, found that the most appealing systems to the donors supporting the technologies and resources are not necessarily the right ones for the receptor community, even though the solution may show very good results initially. Oldfield stated that the best practice was the one that combined local knowledge of the community with innovative technology and sound sustainable design. The NGO leaders agreed that the best technological solution was the one that is based on social sustainability.

Butterworth and Soussan (2001), UNEP (2002), WHO (2003B), and Oldfield (2006), in their surveys and studies, established a list of general reasons behind systems’ failure, including the following:

- Poor community involvement.
- Financial and economic issues.
- Lack of resources (material, machinery, manpower) for operation and maintenance.
- Lack of education about water and sanitary issues.
- Social and cultural issues.
- Lack of professional and skilled individuals.
- Poor enforcement of laws and regulations.
- Inadequate or non existing policies.
- Balancing between developing new systems and maintaining old ones.

- Unavailability of supporting infrastructure.

- Lack of data and information to support decisions.

The above reasons were found in different communities around the world. Table 2.4 shows examples of the impact of the lack of resources on operations and maintenance for implemented wastewater systems in different communities. More examples of water, wastewater, and stormwater problems worldwide can be found in a report by the United Nations Environmental Program (UNEP) issued in 2002.
Table 2.4 Examples of Communities Dealing with the Lack of Resources for Operation and Maintenance Resulting in Infrastructure Problems

<table>
<thead>
<tr>
<th>Continent</th>
<th>Country</th>
<th>Infrastructure Issue</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>Nigeria</td>
<td>The wastewater treatment plant is poorly operated and maintained and suffers from multiple electrical and mechanical breakdowns due to lack of parts.</td>
<td>(UNEP 2002)</td>
</tr>
<tr>
<td>Egypt</td>
<td></td>
<td>The treated wastewater does not meet the national and international effluent standards due to excessive raw sewage volumes (greater than the anticipated plant capacities).</td>
<td>(UNEP 2002)</td>
</tr>
<tr>
<td>Asia</td>
<td>Jordan</td>
<td>The biggest domestic wastewater treatment plant, As-Samra, is over load. It treats both domestic and industrial wastes. This plant has a hydraulic load design capacity of 68,000 m$^3$/day, but the actual load is 236,000 m$^3$/day.</td>
<td>(Alfaqih 2007)</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>In Tianjin, only 21% of wastewater is treated, and the rest is discharged untreated into nearby waterbodies. The cost of treating this polluted water is higher than transporting water from other sources.</td>
<td>(Bhatia and Falkenmark 1993)</td>
</tr>
<tr>
<td>South America</td>
<td>Guatemala</td>
<td>There are 27 wastewater treatment plants that are poorly designed, lack spare parts, and are poorly operated and maintained. Only 4 of the 27 plants are in full operation, and the total treated combined flow is only 0.1 m$^3$/s.</td>
<td>(UNEP 2002)</td>
</tr>
<tr>
<td>Europe</td>
<td>Ukraine</td>
<td>22% of the wastewater system is in a critical condition, 46% of the pump units needed replacement, and 25% of the installations in treatment plants had exceeded their technical life time.</td>
<td>(EPR 1998)</td>
</tr>
<tr>
<td></td>
<td>France, UK, Germany, Netherlands</td>
<td>These countries have combined sewer systems. During rainfall, combined sewage is only partially treated.</td>
<td>(UNEP 2002)</td>
</tr>
<tr>
<td>North America</td>
<td>USA</td>
<td>Atlanta has raw sewage spilled into local waterways. There are more than 1,000 combined sewage systems in the US, and many billions of dollars are being spent to minimize discharges of poorly treated combined sewer overflows (CSOs). Many separate sewer systems also experience overflows (SSOs) of poorly treated combined sewage during wet weather.</td>
<td>(Lavelle 2007)</td>
</tr>
</tbody>
</table>

2.4.3 An Example of a Framework System Used in Planning and Managing Infrastructure Projects: The Logical Framework Approach (LFA)

There are many planning and management tools that have been developed by companies and organizations to assist in analyzing complex infrastructure problems, but the one most commonly used is the Logical Framework Approach (LFA). LFA is a...
project management tool that is used in different stages of the project, such as planning, execution, and evaluation. It is based on the method of objective-oriented planning (Oertengren 2004). LFA involves the analysis of stakeholders, problems, objectives, and strategies in the project (Bakewell and Garbutt 2005).

2.4.3.1 LFA History

In the 1960s, the United States Agency for International Development (USAID) sought the development of a method that would help the agency manage its projects. The method and concepts were adopted from a similar one used in the military that was then chosen by the National Aeronautics and Space Administration (NASA). The method is based on having a “strong central authority and control around a relatively clear set of goals” (Gasper 2000, 4; Hailey and Sorgenfrei 2004.). After being implemented by USAID, European funding agencies adopted the LFA and has required that it be the standard for grants applications since the 1970s (Oertengren 2004).

2.4.3.2 Agencies Using LFA

LFA is very popular and used extensively by international development agencies, and it is the method that any project or program is frequently uses for evaluation and assessment. LFA is used by the United Nations (UN), the United States Agency for International Development (USAID), the German Development Agency (GTZ), the United Kingdom Department for International Development (DFID), the Canadian International Development Agency (CIDA), the Swedish International Development Cooperation Agency (Sida), the Norwegian Agency for Development Cooperation
(NORAD), and many other local, regional, and international development agencies (Bakewell and Garbutt 2005).

2.4.3.3 Strengths and Limitations of LFA

The LFA is widely used, but as with any system in use since the 1960s, it has proven to have both strengths and limitations. The primary strengths of the LFA are its ability to (Wageningen-International 2006, 1):

- “Analyze the existing situation during project preparation,
- Establish a logical hierarchy of means by which objectives will be reached,
- Identify potential project risks,
- Establish how outputs and outcomes can be monitored and evaluated, and
- Present project summary.”

On the other hand, the following limitations of the LFA have been identified (Bakewell and Garbutt 2005; Wageningen-International 2006, 1):

- “Being used too rigidly, leading people into a ‘blueprint’ approach to project design,
- Limited attention to problems of uncertainty where a learning or adaptive approach to project design and management is required,
- The project designers tend to focus on economic indicators rather than on people’s experiences, and they tend to ignore qualitative data in favor of quantitative data, and
- A tendency for poorly-thought-through sets of activities and objectives to be entered into a Participatory Planning Monitoring (PPM) Table, giving the appearance of a logical framework when in fact the key elements of the analytical process have been skipped.”

These limitations need to be considered in the planning and management stages of the infrastructure systems to produce robust and sustainable systems.

2.4.4 Summary

This review of environmental infrastructure problems summarized some reasons behind the failure of water, wastewater, and stormwater infrastructures. These reasons for failure have affected the sustainability of the infrastructure elements and have impacted the stakeholders in various ways, such as, but not limited to, health, economics, and the environment. Additionally, the frameworks commonly used in the planning stages have many limitations, such as their inability to account for uncertainty in the data as well as the difficulty of including non-financial objectives in the analyses.

A decision analysis framework was therefore developed as part of this dissertation research to address these reasons for failure, thereby converting them into reasons for success (discussed further in Chapter III). The decision analysis framework is based on a multiobjective model that assists in identifying and managing risk and uncertainty and includes non-financial objectives in the decision-making process. The development of this flexible framework allows for better analysis during the pre-planning stage of infrastructure projects such as the management of failing water infrastructure systems.
CHAPTER III

ENVIRONMENTAL DECISION ANALYSIS FRAMEWORK (EDAF)

3.1 Introduction

Several problems were mentioned in Chapter II regarding the planning, implementing, and operating of water, wastewater, and stormwater infrastructure systems. The following is a summary of these problems:

- Lack of community involvement and participation in the decision-making process for the infrastructure problem under consideration;
- Lack of building comprehensive “big pictures” about the area under consideration, not only in terms of economics, but also in terms of public health, education and training, environmental and ecological factors, resources, regulations, ancillary infrastructure, and social and cultural issues; and
- Dealing with uncertainty in the available data.

These problems are considered reasons for systems’ failure or unsuitability of the infrastructure systems. This has raised the need to develop a framework that addresses these problems in order to develop systems that are robust and sustainable for the community under consideration.

A framework is a suitable structure to address and organize different factors of the project and the relationships between them to achieve sustainable solutions (Sprague
and Carlson 1982). Reich and Kapeliuk (2005) addressed the need for such a framework that organizes different types of information to ease the complexity of the decision analysis required to achieve robust and sustainable infrastructure systems.

### 3.2 Environmental Decision Analysis Framework (EDAF)

The framework developed as part of this dissertation research is labeled the Environmental Decision Analysis Framework (EDAF). This framework was developed as part of this dissertation research. EDAF addresses these reasons for failure in the early stages of the project and converts them into reasons for success (facets). The framework includes these facets in the early planning and designing stages of systems, which increases the chances of the project’s success and minimizes the risks.

The framework assists decision makers in identifying stakeholders’ objectives and addresses the issues of stakeholders’ priorities to help in the selection of robust and sustainable infrastructure systems. It also facilitates stakeholder objective traceability through the project assessment phase of environmental engineering management.

The EDAF consists of layers of information. Hence, each layer increases the understanding of the problem, which in turn increases the chances for the success of the infrastructure system. There are two main layers in the framework. The first one is the stakeholders, and the second one is the facets.

#### 3.2.1 First Layer – Stakeholders

Planning methodology has changed over the years from a one-man show, where one person (the decision maker) would be the thinker, planner, and designer for the
people, to one in which both people and planners come together to develop successful systems (Timmermans 1997).

Stakeholders are a critical success factor for the approval and implementation of any infrastructure system. A stakeholder is anyone who has an impact on the project or is affected by it (Sharp et al. 1999). The involvement of stakeholders during the initial phases of project planning is very important (Gibson et al. 2006). Stakeholders may be, for example, owners, users, designers, politicians, operators, organizations, facilitators, builders, and neighbors. The list can be large or small, depending on the project and its impact on the community at large.

Stakeholders have different objectives that they would like to achieve. These objectives, when identified, are crucial for the success of the project. The stakeholders, in order to achieve a successful and sustainable output from the framework, should share and express various information, needs, and concerns with the decision makers through various methods of communication, such as interviews, surveys, media, etc. This sharing of information to reach a common ground of uniformly defined and understood project objectives is called alignment (Griffith and Gibson 2001).

Griffith and Gibson (2001) discussed the importance of stakeholders’ alignment in projects. Stakeholders need to be represented and aligned throughout the various phases of the project. This can be achieved by the different decision-making organizational sectors, represented by the different organizational hierarchy personnel from each sector. Figure 3.1 shows an example of organizational alignment. This alignment clarifies the objectives of every level in the decision-making organization at every phase of the project.
3.2.2 Second layer – Facets

The previously addressed problems that caused systems to fail are categorized and grouped into eight facets. These facets are public health, education and training, finance and economic, environment and ecology, resources, ancillary infrastructure, social and culture, and regulatory. Table 3.1 contains the descriptions of these facets.

Figure 3.1 Organizational alignment for a project. (Used with permission)
Table 3.1 Description of Facets

<table>
<thead>
<tr>
<th>Facet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Health</td>
<td>Protects people from diseases and pollutants that would negatively affect their health, promotes the need for a sanitary environment throughout the community, and educates people about personal hygiene in an effort to maintain their health.</td>
</tr>
<tr>
<td>Education and Training</td>
<td>Indicates the level of literacy in the society and its ability to learn different skills at a certain level within a manageable time, to develop good reasoning and judgment of surrounding problems, and to be trained and train others to spread knowledge.</td>
</tr>
<tr>
<td>Finance and Economic</td>
<td>Deals with the status of the project in terms of the current economic situation of the area; economic benefits to the stakeholders and to the area in general; the raising, allocation, and expenditure of funds over the life of the project; and the financial risks.</td>
</tr>
<tr>
<td>Environment and Ecology</td>
<td>Determines physical, chemical, and biological interactions between the different components of the environment, e.g. flora and fauna, and their impact on one another.</td>
</tr>
<tr>
<td>Resources</td>
<td>Includes materials, money, man power, and machinery. These resources are the factors that will take the project from an idea to reality.</td>
</tr>
<tr>
<td>Ancillary Infrastructure</td>
<td>Identifies the current utilities and facilities available in the area of the project such as electricity, roads, water and sanitary networks, telecommunications, hospitals, and schools in the community.</td>
</tr>
<tr>
<td>Social and Cultural</td>
<td>Identifies the characteristics of the society and what constitutes their “foot print.” Deals with the different interactions between various levels in the society, such as local customs and habits, religious beliefs, gender roles, social status, and prejudices.</td>
</tr>
<tr>
<td>Regulatory</td>
<td>Deals with the laws and regulations that are currently in effect in the project area addressing environmental problems. It also includes the standards and requirements for proper implementation. The policy makers have a big effect on these regulatory problems in terms of addressing and putting them into effect.</td>
</tr>
</tbody>
</table>

The stakeholders’ layer is linked with the facets layer in order to identify and describe the objectives of each stakeholder for each facet. The developed matrix of facets and stakeholders is shown in Table 3.2.
Table 3.2 Stakeholder/Facet Matrix

<table>
<thead>
<tr>
<th>Stakeholder*</th>
<th>Facet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Public Health</td>
</tr>
<tr>
<td></td>
<td>Financial &amp; Economic</td>
</tr>
<tr>
<td></td>
<td>Environmental &amp; Ecology</td>
</tr>
<tr>
<td></td>
<td>Education &amp; Training</td>
</tr>
<tr>
<td></td>
<td>Ancillary Infrastructure</td>
</tr>
<tr>
<td></td>
<td>Regulatory</td>
</tr>
<tr>
<td></td>
<td>Resources</td>
</tr>
<tr>
<td></td>
<td>Social &amp; Cultural</td>
</tr>
</tbody>
</table>

User
Owner
Designer
Politician
Neighbor
Donor
Investor

* This stakeholder list is just an example of stakeholders

3.3 Collecting Objectives

The above discussion targets the structuring of the framework and its components. This section explains the method of collecting and filling the matrix with the collected information. The EDAF is based on stakeholders’ objectives toward the problem under consideration. In order to collect these objectives, visits and interviews with the stakeholders should be conducted. The first step of the interview is to explain the study and the importance of this task. The second step is to explain the matrix and the meaning of each facet.

The stakeholders present objectives for each one of the facets during an interview. Some facets may have multiple, one, or no objective(s) for that stakeholder. After collecting the objectives from all the stakeholders, the objectives under the same facet from all the stakeholders are compiled. The complete list of objectives under each facet is revised, and similar objectives are combined in order to come up with a workable list of
distinct objectives. This final list of objectives is the workable definition for the facet for the problem under consideration. An example of these objectives is in Section 3.7.

3.4 Objectives Hierarchy

The collected objectives from the stakeholders are organized and mapped into a hierarchy. This hierarchy shows the different levels and details of the objectives. It provides a lot of insight about the problem at the surface level. Additionally, it shows the connections between different objectives. The hierarchy shows the analyst why s/he needs to care about the problem under consideration and what set of criteria or alternatives would best fit the problem (Clemen and Reilly 2001). This hierarchy may show new alternatives that were not considered previously.

The objectives hierarchy consists of levels, where each objective breaks down into a set of other subobjectives until reaching the lowest, most basic level. An example of the objective hierarchy is in Section 3.7.

After collecting and organizing the stakeholders’ objectives for each facet and collecting and analyzing the data for the problem under consideration, a list of potential solutions for the problem can be identified and described. An important consideration is that there are likely no solutions that can deal with all the objectives for all the facets. Therefore, potential systems are tested against each facet to analyze its impact on that facet’s objectives. The impacts of these potential solutions are analyzed through multiobjective decision analysis.
3.5 Benefits of EDAF

The usage of the EDAF allows water, wastewater, and stormwater infrastructure systems to achieve the goals of the Water and Sanitation Program (WSP) of the World Bank. These goals are summarized as: “achieving sustainable and effectively used water and sanitation systems through methods that are replicable” (Mikkelsen 1995, 69; PROWWESS 1990).

By using the EDAF, the stakeholders’ objectives are included in the initial stages of planning and designing systems, which will improve the chances of developing robust and sustainable systems. These developed systems will be used more effectively by the community, because it is part of the decision-making process from the beginning, and the final solution reflects the unique needs of that particular community. Further, these systems can be transferred to other areas with similar problems, after modifying them to reflect key features of the new community.

3.6 Stage of Lifecycle for Implementing Frameworks to Select Sustainable System(s)

Selecting sustainable systems to be implemented is a main goal for any project. The listing of potential systems as solutions occurs during the early stages of the project lifecycle. The project lifecycle activities, as stated by Hvidt (1987) and DANIDA (1992), include: 1) project identification, 2) pre-appraisal (preparation and analysis), 3) feasibility study, 4) appraisal, 5) negotiation and agreement, 6) project commencement, 7) implementation, 8) monitoring and reviews, 9) transfer to normal administration, 10) project completion, 11) project evaluation, and 12) impact evaluation. The Food and
Agriculture Organization (FAO) (1990) has a similar cycle for its projects. The lifecycle is shown in Figure 3.2.

![Figure 3.2 Monitoring and evaluation in stages of the project cycle.](image)

Cho and Gibson (2001) stated the detailed activities for the building project lifecycle; these activities are 1) project assessment/feasibility, 2) programming, 3) schematic design, 4) design development, 5) construction documents, and 6) construction. The activities are shown in Figure 3.3.

![Figure 3.3 Project life cycle for a building project.](image)

The most important activity in the project lifecycle is project assessment/feasibility (Cho and Gibson 2001) or, according to DANIDA, the project identification and pre-appraisal (both terms can be considered pre-planning). This is where different potential system(s) are chosen for the project. The outcome of this activity affects the entire project and leads to its success or failure. Therefore, selection of solution(s) should be considered carefully at this stage. If this activity is not clearly...
defined and performed, it causes the project to fall short in every succeeding aspect, such as cost, schedule, operations, and the life of the system/asset (Cho 2000; Cho et al. 1999; Cho and Gibson 2001; Gibson et al. 1997; Merrow and Yarossi 1994; O’Connor and Vickroy 1986).

The framework, along with its different components, is used to organize the existing data and the objectives for the different phases of the project at the pre-planning stage. The result from this interaction is to produce a robust and sustainable execution strategy for the problem under consideration. This interaction is presented in Figure 3.4.

The project pre-planning phases are baseline description, targeted studies, vulnerability, and generating possible controls/strategies. In the baseline description phase, the problem is identified and described (*E.coli* problem in Lake Tuscaloosa watershed). The relevant stakeholders are identified. The available data and information are gathered. The boundary conditions for the problem are set. This phase is discussed in section 3.7, the beginning of Chapter IV, and Appendices A and C.

The targeted study phase includes the analysis of the available data and the relationship between the different parameters. It identifies the key components and issues of the problem. This phase includes the development and execution of the models. Additionally, it includes the analysis of the modeling results. This phase is discussed in Chapters IV, V, VI, and Appendices B and D.

The vulnerability phase includes the use of the models and the data analysis to analyze the various sources of the problem and to identify contributing sources. This phase is discussed in Chapter VII. The final phase, generating possible controls/strategies, identifies the potential controls that can be implemented to address the
problem. It also discusses the different management strategies that need to be implemented to improve the analysis. This phase also includes the use of multiobjective decision analysis to choose between the various potential controls. This is discussed in Chapter VIII and IX.

Figure 3.4 Interaction between the framework and the project pre-planning phases.

3.7 Implementing EDAF on the *E.coli* Problem in Lake Tuscaloosa Watershed

3.7.1 Introduction

Previously, a description of the framework and its components were discussed. The framework was implemented on the *E.coli* problem in the Lake Tuscaloosa Watershed. A complete description of the watershed and the problem is detailed in Chapter IV. As discussed in Chapter II, *E.coli* contamination can come from various locations within the watershed. The watershed is a very dynamic system that needs to be
studied in order to make robust and sustainable decisions. Many times a comprehensive understanding is not possible. Therefore, the EDAF facilitates this understanding.

The EDAF assisted in gathering various information and data about the problem through contacting and interviewing different stakeholders. The list of stakeholders concerned about the Lake’s problems covered a wide spectrum of organizations or groups who affect or are affected by the problem and is contained in Table 3.3.

Table 3.3 List of Stakeholders Concerned about the *E.coli* Problem in Lake Tuscaloosa

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residents around the lake</td>
<td>Consider the lake as an attraction point</td>
</tr>
<tr>
<td>Commercial and residential developers around the lake</td>
<td>Consider the lake as an attraction point</td>
</tr>
<tr>
<td>General public using the lake for recreation purposes</td>
<td>Use the lake for fishing, swimming, skiing, boating, etc.</td>
</tr>
<tr>
<td>City of Tuscaloosa (Water and Wastewater Management)</td>
<td>Use the lake as a water supply for the City of Tuscaloosa</td>
</tr>
<tr>
<td>City of Tuscaloosa (City Council)</td>
<td>Work with different entities to sustain the lake quality</td>
</tr>
<tr>
<td></td>
<td>Sustain the lake as an economic attraction for different types of development</td>
</tr>
<tr>
<td>General public consuming the lake’s water</td>
<td>Expect clean water from the faucet</td>
</tr>
<tr>
<td>Geological Survey of Alabama (GSA)</td>
<td>Has geological and environmental information about the watershed</td>
</tr>
<tr>
<td>City of Northport (Water and Wastewater Management)</td>
<td>Use the upper part of the lake as a water supply for the City of Northport</td>
</tr>
<tr>
<td>Farmers (Cattle/Agriculture)</td>
<td>Have land and property in the watershed</td>
</tr>
<tr>
<td>Chicken farms</td>
<td>Located in the watershed</td>
</tr>
<tr>
<td>Forest areas (Forest Management)</td>
<td>Located in the watershed</td>
</tr>
<tr>
<td>Residents in the upper watershed</td>
<td>Consider the lake as an attraction point</td>
</tr>
<tr>
<td>Cities in the watershed (Berry) (Berry wastewater management)</td>
<td>The wastewater plant is located near the North River in the watershed</td>
</tr>
<tr>
<td>Environmental and Ecological watchdogs (Black Warrior River Keepers and Alabama Department of Environmental Management)</td>
<td>Monitor pollutants discharged into the lake Work with different entities to eliminate different pollution sources</td>
</tr>
<tr>
<td>Politicians</td>
<td>Make sure their voters use and enjoy the lake water freely with no pollutant restrictions</td>
</tr>
<tr>
<td>Local and National Engineers</td>
<td>Provide information and suggestions about the problem</td>
</tr>
</tbody>
</table>
During the interviews with the stakeholders, multiple activities associated with the project were achieved, such as gathering additional information about the watershed, accessing data, identifying the stakeholders’ objectives, and validating the list of facets in the EDAF. For example, the Black Warrior River Keepers provided aerial photos. The contact reports for these interviews are presented in Appendix C.

Every stakeholder gave a list of objectives; some stakeholders did not have any objectives for some facets. The stakeholders agreed that the mentioned facets covered their needs and concerns; it also helped them in generating more objectives. After collecting these objectives from an individual stakeholder, they were put on a spreadsheet under each facet with other stakeholders’ related objectives. A long list of objectives was generated. Afterwards, similar objectives were combined and the list was shortened to a few objectives for each facet. The final list of objectives for each facet is shown in Table 3.4.

<table>
<thead>
<tr>
<th>FACETS</th>
<th>OBJECTIVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Health</td>
<td>Make water safe (no E.coli threat) for different public uses</td>
</tr>
<tr>
<td></td>
<td>(swim, ski, fish, boat)</td>
</tr>
<tr>
<td></td>
<td>Protect lake and waterbodies from pollutants (E.coli)</td>
</tr>
<tr>
<td></td>
<td>Inform the public about what to do in case of an E.coli outbreak</td>
</tr>
<tr>
<td>Finance &amp; Economic</td>
<td>Maintain a long term investment in the watershed, especially around the lake</td>
</tr>
<tr>
<td></td>
<td>Increase budget to operate efficiently to reduce E.coli threats</td>
</tr>
<tr>
<td></td>
<td>Increase number of companies and investments in the area</td>
</tr>
<tr>
<td></td>
<td>Not to drive away investors/companies/homeowners due to E.coli threats and</td>
</tr>
<tr>
<td></td>
<td>associated bad public relations</td>
</tr>
<tr>
<td>Environment &amp; Ecology</td>
<td>Reduce water quality threats from E.coli on fish and other species</td>
</tr>
<tr>
<td></td>
<td>Sustain the watershed as a recreation focal point</td>
</tr>
<tr>
<td></td>
<td>Formulate ordinances to protect environment and ecology from E.coli</td>
</tr>
<tr>
<td></td>
<td>Manage the hot spots of high E.coli sources into the watershed</td>
</tr>
</tbody>
</table>
Table 3.4 (cont.)

<table>
<thead>
<tr>
<th>Resources</th>
<th>Allocate manpower to enforce and protect watershed from <em>E.coli</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Allocate equipment to enforce and protect watershed from <em>E.coli</em></td>
</tr>
<tr>
<td></td>
<td>Allocate outside expertise to help in protecting the watershed from <em>E.coli</em></td>
</tr>
<tr>
<td>Education &amp; Training</td>
<td>Educate the public about the watershed and its importance, both locally and regionally</td>
</tr>
<tr>
<td></td>
<td>Keep the lake’s website and media updated with information concerning <em>E.coli</em> counts and threats</td>
</tr>
<tr>
<td></td>
<td>Improve training sessions for workers and public personnel responsible for the lake and the watershed</td>
</tr>
<tr>
<td></td>
<td>Educate landowners about protecting the watershed from potential pollutants, such as <em>E.coli</em>, generated from their properties</td>
</tr>
<tr>
<td></td>
<td>Educate and inform policy makers and government officials about the lake and the potential <em>E.coli</em> threats</td>
</tr>
<tr>
<td>Ancillary Infrastructure</td>
<td>Increase number of homes connected to a sewer system to reduce the <em>E.coli</em> threat</td>
</tr>
<tr>
<td></td>
<td>Register all on-site septic systems in the watershed to allocate any <em>E.coli</em> issues</td>
</tr>
<tr>
<td></td>
<td>Reduce failures of pumps and sewer systems</td>
</tr>
<tr>
<td></td>
<td>Place Best Management Practices at sources of pollution to reduce <em>E.coli</em> runoff</td>
</tr>
<tr>
<td>Social &amp; Cultural</td>
<td>Decrease number of people not using the lake due to <em>E.coli</em> water pollution</td>
</tr>
<tr>
<td></td>
<td>Work with Residents/Public to change practices that may cause <em>E.coli</em> pollution to the water</td>
</tr>
<tr>
<td></td>
<td>Change cultural habits that are potential sources of <em>E.coli</em></td>
</tr>
<tr>
<td>Regulatory</td>
<td>Increase City's zoning control to protect waterbodies from potential <em>E.coli</em> sources</td>
</tr>
<tr>
<td></td>
<td>Encourage different government entities to work together to protect the watershed from <em>E.coli</em> threats</td>
</tr>
<tr>
<td></td>
<td>Ease regulations on <em>E.coli</em> non-contributing sources</td>
</tr>
<tr>
<td></td>
<td>Introduce stricter regulation on <em>E.coli</em> contributing sources</td>
</tr>
<tr>
<td></td>
<td>Introduce stricter regulations to protect public health</td>
</tr>
</tbody>
</table>

These were then organized in an objective hierarchy diagram that shows the relationships between the different objectives. This diagram is shown in Figure 3.5.
Maximize watershed protection from harmful bacterial pollution

Maximize public health
- Minimize public health risk
- Maximize use of waterbodies
  - Inform the public about E-coli outbreaks and methods of protection
  - Prevent pollution from sources
- Identify sources of pollution
  - Agriculture activities
  - SSOs
  - Scattered individual incidents

Sound Environment and Ecology
- Minimize threat to fish and other species
- Sustain watershed as research/recreation focal point
  - Media
  - Meetings
- Maximize interest by environmentalists, ecologists and nature lovers

Social and Cultural
- Minimize no. of people not using the lake due to water pollution
- Change cultural habits in public activities that would to E-coli pollution

Robust Economic and Financial
- Maximize investments in watershed and surroundings
  - Have more investments
  - Positive public relations

Fair Regulatory
- Minimize financial impact on agriculture activities
  - Keep agriculture activities
- Maximize cooperation from public
  - Minimize expenditure on preventable issues

Maximize Ancillary Infrastructure
- Maximize no. of households connected to sewer system
  - Maximize education and training to agriculture practices
  - Improve training for workers and public personnel
- Minimize network failures
  - Maximize Agriculture solutions
  - Allocate resources to manage, control, and maintain infrastructure
- Maximize cooperation
  - Maximize number of registered septic tanks
  - Maximize regulation enforcement

Maximize Agriculture solutions
- Maximize number of registered septic tanks
  - Minimize expenditure on preventable issues
- Maximize regulation enforcement

Maximize different govt and non-gov entities working together
- Increase cities’ zoning control
  - Allocate resources to protect and enforce regulations

Figure 3.5 Objectives hierarchy diagram.
3.8 Summary

This chapter discussed the EDAF and its components. It also described the method of identifying the stakeholders and interviewing them for the purposes of identifying their needs and concerns and obtaining any available data. Additional support is presented in Appendix C. The interviews with the stakeholders identified their objectives and allowed access to further information and data. These interviews filled gaps in knowledge between what was identified as the main source of the problem and newly identified potential problems. The range of stakeholders, objectives, and data has broadened and has become richer. These provide the foundation for analysis to properly address stakeholders’ objectives and ensure adequate data and representation that will lead to the achievement of sustainable and robust solutions.
CHAPTER IV
DATA ANALYSIS AND OBSERVATIONS

4.1 Introduction

Lake Tuscaloosa, shown in Figure 4.1, is an artificial impoundment that serves as a public water supply. It is located in Tuscaloosa County, in the State of Alabama in the Southeastern United States. The Lake, which was constructed on North River in 1970, serves as the major public water supply for the surrounding communities and is an important recreational water body in an area lacking in natural lakes. The lake is especially used during warm weather when people travel to the lake for swimming, skiing, fishing, or just enjoying the scenery.

The watershed, Figure 4.2, covers an area of approximately 425 sq. miles. The lake covers an area of approximately 5885 acres with a capacity of 40 billion gallons. This region normally has high rainfall (long term average of about 55 inches per year) but is currently undergoing a severe drought, with about half of the normal rainfall during the last rain year (2007). Even with this low recent rainfall, Lake Tuscaloosa has proven to be a reliable and sustainable water supply for the area. The reliability of this water supply has been an important component for the economy in the area. In the last few years, the City of Tuscaloosa has been a major target for industrial development. One of the leaders in car manufacturing, Daimler, produces three models of Mercedes cars (M, R, and G) at its Tuscaloosa factory. Also, there is the JVC electronics factory, an oil refinery, a steel
plant, BFGoodrich tires, and many more local and international companies. It also houses the University of Alabama campus that currently has around 23,000 students and plans to expand to 28,000 in a few years.

The lake was originally surrounded by forests and early in its life had limited commercial and residential development around its perimeter. Recently, developers have started to more intensely develop around the lake due to its potential for attracting people and retailers.

The City of Tuscaloosa is currently facing a challenging situation in dealing with increased urban development around the lake and in the watershed while trying to protect
the lake from various pollutants (especially bacteria and nutrients). The city is therefore under pressure to strengthen its management, monitoring, and control of existing and future pollutant sources (mostly land development) around the lake that are in its jurisdiction. Additionally, the city has to consider other sources in the watershed outside of its jurisdiction as potential pollutant sources that are adversely affecting the water quality of the lake.

### 4.2 Land Use in the Watershed

Land use is an important factor in the analysis and assessment of the *E.coli* sources. The watershed includes forests, old quarries, and residential, commercial, agricultural (pastures, chicken farms, and cattle), and recreational uses. The primary land use in the watershed is forest lands.

The following set of photos in Figure 4.3 shows examples of land uses in the watershed. Picture (a) is an example of pasture land, (b) is an example of a forest, (c) is an example of a chicken farm, and (d) is an example of a residential area. These pictures are aerial photos of the watershed that were obtained from United States Geological Services (USGS 2002) website and from Google Earth®. The land uses in the watershed were determined according to these aerial photos. A complete description of the land use for every subbasin in the watershed is presented in Appendix A. A brief description of the subbasins in North River and Binion Creek basins, along with aerial photos, is also presented in Appendix A.
Figure 4.3 Examples of land uses in Lake Tuscaloosa watershed. An aerial photo of a pasture is in a., a forest is in b., a chicken farm is in c. and an urban area is in d.

The land uses determined by the aerial photos were confirmed through more detailed selected aerial photos that were obtained from the Black Warrior River Keepers, out of Birmingham, Alabama, and through some physical site visits.

4.3 Geology of Lake Tuscaloosa Watershed

The geology of the Lake Tuscaloosa watershed, shown in Figure 4.4, consists of two dominant types of rock. The eastern part is Pottsville formation and the western part is Coker formation. The Pottsville formation (light blue in Figure 4.4) consists of light to dark-gray, fine-grained to coarsely conglomeratic sandstone and subordinate amounts of gray shale, siltstone, limestone, coal, and underclay. The permeability in this formation is low to moderate (Geyer and Welshusen 1992). The water travels relatively quickly and directly to the nearest stream outlet once it hits formation layer (O’Neil et al. 2005). The Coker formation (dark green in Figure 4.4) consist of light-gray to moderate-reddish-orange, poorly sorted, clayey, gravelly fine to very coarse sand, with interbeds of grayish-green to moderate-red sandy clay and well-sorted medium quartz sand. Gravels consist mostly of quartz and quartzite and range in size from very fine pebbles to large cobbles (Alabama Clean Water Partnership 2005). This formation tends to allow water to
percolate better and will naturally treat the water as an interflow before it enters the stream channel and flows into the lake (O’Neil et al. 2005).

Figure 4.4 Geological map for the Tuscaloosa Lake watershed prepared by the Geological Survey of Alabama (GSA) in 2005.

4.4 Water Quality in Lake Tuscaloosa

The Alabama Department of Environmental Management (ADEM) has monitored lake water quality during 1998 and 2002 (ADEM 2004). These studies indicated that the lower part of the lake was between oligotrophic (unproductive) and mesotrophic (moderate productive) nutrient levels. The middle and upper parts of the lake showed
mesotrophic to eutrophic (very productive) conditions, especially in late summer. In water quality terms, when the water system has oligotrophic conditions, the lake is infertile and unproductive for algae and is therefore a good water supply (low turbidity, low tastes and odors). On the other hand, when the system is eutrophic, it is highly fertile and has a high productivity of algae, indicating that the water source is undesirable as a water supply (taste and odor problems are more common and the water is more turbid).

Recent studies and monitoring of the lake have shown a couple of problems in the lake’s water quality. The first problem is sedimentation, as the lake has lost around 11% of its original storage capacity since being built in the 1970s (Sledge 2007). The second problem, which is the main concern in this research, is the high levels of *E.coli* bacteria, especially in the northern parts of the lake (near the main river entrances) during periods of high stream flow (O’Neil et al. 2005). These high levels of *E.coli* have been identified as a concern by many different stakeholders in the area. Additionally, the main river entering the lake, North River, located at the northern part of the lake, is on the US EPA 303(d) list due to sedimentation and habitat alteration problems (but not for bacteria).

### 4.5 Example of an Area Affected by *E.coli*: Bear Creek

The Centers for Disease Control and Prevention (CDC) report annually about areas that have been affected by *E.coli* outbreaks in their waters. In Alabama, as an example, Bear Creek’s water quality has reached critical levels (above the permissible limits). Authorities restricted the public’s general use of the waterway for swimming and fishing. These restrictions have not been incorporated in Lake Tuscaloosa watershed to date.
The Bear Creek watershed is located in the Northwest portion of the State of Alabama. The watershed is a wonderful location for wildlife viewing and natural scenes. It is located in the Tennessee Valley and flows across three states, Alabama, Mississippi, and Tennessee. This watershed has been an important part of the history and heritage of the local people. The information in this section is mainly from a documentary by Alabama Public Television (APT) (Philips 2006) and the Alabama Nonpoint Source Pollution Program (ANSPP) (ANSPP 2001).

According to Philips (2006) and ANSPP (2001), in 1984, serious contamination by *E.coli* bacteria was detected by the Tennessee Valley Authority (TVA). As a result, the waterways in the watershed were closed to all human use. These excess pollution levels started to occur after many agricultural practices were started in that area.

The main source of the problem was from agricultural practices in the watershed. The farmers did not realize that they were contributing to the problem. They kept on doing what they had been doing for years, such as spreading chicken manure, without treatment, for fertilizer on the fields. Since the problem was across different counties and states, it was important that all the stakeholders work together in order to help solve the problem. A key factor for their success was education about the problem and the impacts on themselves and on their surroundings. Toward the end of the 90’s waste management planning has been required for animal feeding operations. An agency such as NRCS began working with farmers on educating them about dealing with this waste.

Many practices were implemented to reduce the manure runoff in the waterways. Some of these were alternative livestock watering systems combined with forested buffers to keep animals out of the water, the installation of manure composting facilities
that can be operated by the farmers, and finally artificial wetland treatment systems. All of these helped to reduce the pollution in the waterways and improve its quality. Additionally, the farmers needed to become familiar with the solutions and be able to use them efficiently. Therefore, the farmers were educated about their operation and maintenance. Also, the TVA invested a lot of resources, such as finances and expertise, to assist in solving the problem. Furthermore, it was important for the stakeholders to develop and understand the tradeoffs between agricultural activities and their impact on the environment and their natural resources.

4.6 \textit{E.coli} Sampling in Lake Tuscaloosa by the City of Tuscaloosa

The City of Tuscaloosa has been monitoring the lake since 1998. The period between 1970, when the lake was built, and 1998 has no monitoring data. Starting in October of 1998, samples have been taken every month to check the quality of the water, mainly for \textit{E.coli}. The city collects the samples from 32 locations, shown as diamonds (green) on the map, distributed all around the lake perimeter, as shown in Figure 4.5. These sites were selected as the city can only sample within its jurisdiction and not over the entire watershed. To date, no adverse health effects have been reported to the local public health department. Local planning efforts, as part of a new lake’s division, will likely include additional attention to events impacting public health.
Figure 4.5 City of Tuscaloosa sampling sites on Lake Tuscaloosa.

*E.coli* time series plots of the average count values at sites 24-27, located in the northern part of the lake, are compared to the average counts at sites 1-5, located in the southern part of the lake, as shown on Figure 4.6. Sites 24, 25, 26, and 27 are located on North River, the main water source of the lake. Site 27 is the furthest from the lake and 24 is the closest. From the city’s *E.coli* data, the maximum *E.coli* value found in the lake was 9,590 cfu/100 mL, found at the Iron Bridge sampling location (site 18) on Binion
Creek in November 2004. The time series shows that the sites located near the southern part of the lake (downstream), on average, have lower *E.coli* counts than the sites at the northern part (upstream). The points below are averages for the sites, if individual values were used the sites would have more extreme values.

![Figure 4.6 *E.coli* count time series comparison between northern and southern parts of the lake between October 1998 and January 2007.](image)

**4.7 Factors Affecting *E.coli* Observations**

This section illustrates the parameters collected by the City of Tuscaloosa that may have an impact on *E.coli* counts in the watershed. Parameters are recorded or measured during water quality sampling to test for *E.coli*. These factors are precipitation, flow, turbidity, and water usage rates. The following discussion shows the relationship between these factors and the *E.coli* counts.
4.7.1 Precipitation

Precipitation is an important factor in the movement of *E. coli* from its source into the closest waterbody. Overland flowing sheetflow runoff, caused by precipitation, is responsible for transporting much of the land-based *E. coli* to the receiving waters. In addition, increased stream and river flows are much more efficient in transporting the *E. coli* down the watershed and into Lake Tuscaloosa. The relationship between precipitation and *E. coli* in the northern part of Lake Tuscaloosa (which receives most of the flow from the upstream watershed area) is directly proportional, as the presence of high *E. coli* values is correlated to high precipitation in that area of the Lake.

The precipitation data used for this research were obtained from the National Weather Services (NWS). The *E. coli* data from the City of Tuscaloosa’s sampling sites for the lake’s northern part are plotted against the corresponding amounts of precipitations in Figure 4.7. The *E. coli* counts are from sites in North River (sites 24 through 27) and Binion Creek (sites 18, 19, and 20).

![Figure 4.7 E. coli counts at different precipitation values at the northern part of Lake Tuscaloosa.](image-url)
Observations showed that the southern part of the Lake does not experience the high E.coli values that the northern part of the Lake experiences. The E.coli values in the southern part of the Lake during the same precipitation periods are lower. The majority (99%) of the data observations are below the city’s E.coli limit of 200 cfu/100 mL, as shown in Figure 4.8. The sites presented in this plot are 1 through 17. Rationale examining of these observations is discussed in Section 4.8.

![E.coli counts versus precipitation in the southern part of Lake Tuscaloosa.](image)

4.7.2 Flow

Stream and river flows in the watershed affect the transport of bacteria to the Lake. The water has a different impact on the fate of the bacteria based on the travel time in the watershed and the velocity of the water. Bacterial renewal and uptake occurs through settling, sedimentation, and die-off; longer flow times result in less bacteria entering the Lake from upstream sources. The only available information for flow comes from three sites in the northern part of the lake area (Figure 4.5). The first location is a
downstream location in North River; the second is a downstream location in Binion Creek; and the third is located in a central watershed area in Turkey Creek. These flow stations are operated by the USGS. These USGS stations are located upstream from the city’s sampling sites.

A plot of the flow and *E. coli* data for the northern part of the Lake was constructed, as shown in Figure 4.9. The stations’ flow readings were plotted against the average *E. coli* values for both the North River and Binion Creek sampling stations. The plot shows a correlation between flow and *E. coli*: whenever flow increases, the *E. coli* counts also increase at these sites.

The ANOVA testing of the data shows a significant correlation between *E. coli* and flow, with a p-value < 0.05. The normality assumption holds with an Anderson Darling value > 1.

![Figure 4.9 Relation between E.coli values at northern sampling sites of the lake and flow values recorded at the USGS flow gauges.](image)

Figure 4.9 Relation between *E. coli* values at northern sampling sites of the lake and flow values recorded at the USGS flow gauges.
4.7.3 Turbidity

Turbidity is an indication of the amount of particulate matter suspended in the water, which usually causes cloudiness. Its’ unit of measure is nephelometric turbidity units (ntu), and it is measured by directing a beam of light into a water sample (USGS 2002). *E.coli* and turbidity are directly proportional in the upper part of the Lake, as shown on Figure 4.10, where high values of *E.coli* are associated with high turbidity values (USGS 2002). However, Figure 4.11 shows a weaker correlation between these two parameters for the lower portion of the Lake. This data was collected by the City of Tuscaloosa during its periodic water quality inspection of the lake in its jurisdiction. A one-way ANOVA test on the log of the data for the upper part resulted in a p-value <0.05 and an R^2 value of 95%. The Lognormal Anderson Darling output gave a value of 3.78, which meant that this data fits a lognormal distribution.

The one-way ANOVA tests on the data from the lower part of the Lake resulted in a p-value <0.05 and an R^2 value of 71%. The Lognormal Anderson Darling output gave a value of 3.319. The values at the upper Lake fitted the lognormal distribution better than the lower Lake. Comparing the *E.coli* data on these graphs for the same scale shows that the lower Lake has lower turbidity and *E.coli* values than the upper Lake.
Figure 4.10 Plot for turbidity and *E.coli* data at the upper part of the lake.

Figure 4.11 Plot for turbidity and *E.coli* data at the lower part of the lake.

### 4.8 Analysis of City Data

The data provided by the city was further statistically analyzed using a factorial experimental design. This design simultaneously examines the effects of two or more factors, and their interactions, on the observed outcomes.
4.8.1 Factorial Experimental Design

This design is discussed further in Berthouex and Brown (1994), Box et al. (1978), and in Montgomery (2005). The factorial design test is performed to:

— “Screen a set of factors (independent variables) and learn which produces an effect,”
— Estimate the magnitude of effects produced by experimental factors,
— Develop an empirical model, and
— Develop a mechanistic model” (Berthouex and Brown 1994, 2).

The primary benefit of the test for this research is screening factors to determine effect.

The test was performed on the data provided by the city for the sampling sites located throughout the lake from October 1998 until January 2007. The two main factors under investigation that affect the E.coli value are the precipitation (P) and the season (S). For precipitation, 1.0 inches of rain was selected as the division between small and large rains. It was noticed that high E.coli counts were measured for rains that were at this depth or larger. The second factor examined is season, where the year has been divided into two seasons: warm and cold. The warm season is from April through September, and the cold season is from October through March. Additionally, the Lake area was divided into 2 parts, northern and southern, to identify the areas highly impacted by E.coli. The border line between these two parts was identified geographically by the Tierce Patton Bridge, which dissects the lake close to its midpoint. The factorial analyses were conducted on each set of Lake data separately.

After identifying the two main factors for the tests, the values were assigned a (+) or (-) to indicate the levels of these factors for the different bacteria data observations.
For precipitation, all the values above 1.0 inch were given (+) and the values below were given (-). For season, the warm weather was given (+) and the cold weather was given (-). Table 4.1 shows the signs for the ranges within each factor. This factorial design is a full $2^2$ assessment, because it tests two factors at two levels each.

Table 4.1 Factorial Design for a $2^2$

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low</th>
<th>High</th>
<th>Coded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>&lt;1.0</td>
<td>$\geq$1.0</td>
<td>-</td>
</tr>
<tr>
<td>Season</td>
<td>Cold</td>
<td>Warm</td>
<td>-</td>
</tr>
</tbody>
</table>

The results from running the factorial test for the northern and southern parts of the lake are shown on Figures 4.12 and 4.13. These plots show that the cold season was significant (p-value <0.05) and had a greater effect on high $E. coli$ counts than the warm season. The main reason for this result is that the collected samples during cold weather were on or directly after rain events, increasing the chances of having high $E. coli$ counts. On the other hand, during warm weather, the majority of the samples were collected during dry periods and not after rain events. As shown on Figure 4.12, the precipitation value of $\geq$1.0 inch has a greater effect on high $E. coli$ counts than when the precipitation is <1.0 inch. The same results were obtained when the analyses were conducted for the lower part of the lake, as shown in Figure 4.13. The test also showed that precipitation has a larger effect on high $E. coli$ levels in the Lake than season. Additionally; the tests also showed that there were no significant interactions between the means of precipitation and season.
Because of the prior results, location was added to the factorial design, where the impact of the northern part versus the southern part was tested in addition to the precipitation and season. The northern part was given (+) and the southern part was given (-). Since there are now three factors, the test is a full $2^3$ factorial. Table 4.2 shows the signs for the ranges for each factor.
Table 4.2 Factorial Design for a $2^3$

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low</th>
<th>High</th>
<th>Coded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>&lt;1.0</td>
<td>≥1.0</td>
<td>-</td>
</tr>
<tr>
<td>Season</td>
<td>Cold</td>
<td>Warm</td>
<td>-</td>
</tr>
<tr>
<td>Location</td>
<td>South of Lake</td>
<td>North of Lake</td>
<td>-</td>
</tr>
</tbody>
</table>

The results from conducting this factorial test are shown on Figure 4.14 and indicated similar results as the previous two factor model. For the location test, the northern part had a higher effect on the *E.coli* values than the southern part of the Lake. Additionally, there is an interaction between precipitation and location, as shown in Figure 4.15. In the upper part of the Lake, the higher precipitation has a greater effect on the *E.coli* counts than in the lower part of the lake. The p-value for the season, precipitation, location, season with location, and precipitation with location was <0.05. The interaction for season with precipitation and season had a p-value >0.05. This indicated that location has a big impact on the *E.coli* count around the lake.

Further, these tests indicate that more data needs to be collected at more frequent time periods and during different weather events from the sampling sites, especially from the northern part.
4.9 Observations in Watershed

4.9.1 Introduction

The factorial experimental design showed that precipitation >1.0 inch and locations in the northern part of the lake resulted in the highest *E.coli* counts in the lake.
Therefore, further qualitative and quantitative investigations took place in this area to narrow the sources of the bacteria. The first investigation examined the chicken farm industry in the watershed. The second investigation involved going upstream by boat in North River to see the activities along the banks of the river. The third investigation was a search of public health records of the cities adjacent to the lake to find out if any of them had reported sewage leaks into the creeks that flow to the lake.

4.9.2 Commercial Chicken Operations in the Watershed

Detailed site investigations of the commercial chicken operations would require site access which was not sought during this research. The site data were approximated based on aerial photographs for these initial analyses. Follow-up detailed site studies would be needed to verify these assumptions and to develop effective manure management operations during the next steps in the process. This section shows some aerial photos of chicken farms located in the Lake Tuscaloosa watershed. These photos were obtained from the Black Warrior River Keepers. They were taken in November 2005. These farms are potential contributing sources of \textit{E. coli} in the watershed. There are 12 chicken farms located in the watershed. These farms combined have 54 chicken houses. The number of chicken houses and the affected subbasins are shown on Figure 4.16.
Figure 4.16 The number of chicken houses in the subbasins in the watershed. The dark subbasins are those that contain the commercial chicken operations.

The commercial chicken operations in the watershed are operated under animal feeding operations (AFO) regulations. This AFO operation category does not require annual inspections on the farms, and the regulations are less strict than the farms that operate and are considered confined animal feeding operations (CAFOs). The chicken farms in the watershed include both layer (egg production) and broiler (meat production) chickens. All of the farms in the watershed have less than 125,000 chickens, which is the cutoff number that would require them to operate under the more stringent CAFO regulations.
The average dimensions of a chicken house are 40-50 ft wide, 400-600 ft long, with 8 ft high (for the sidewalls). The average flock size for each chicken house is between 24,000 and 28,000 birds. The average period each flock stays at the farm is between 4 and 6 weeks. This results in about 8 turnovers per year. If a farm has 3 broiler houses that hold 25,000 birds each. Each bird weighs on average 4.5 lbs. The farm turns over 6 flocks per year. The farm produces around 1,010 tons of market weight birds with around 500 tons of manure and litter.

At each flock turnover, the farmers clean the chicken houses and take out all the manure and the upper bedding. Every year the farmers fully clean the houses and replace the entire bedding material in the houses. The bedding material consists of saw dust. The produced manure from the chicken operations is usually collected, dried and then spread on fields as a fertilizer for pastures and crops.

The following pictures present some of the chicken operations in the watershed. In Figure 4.17, the chicken farm was in a transition phase, when the chicken houses were being cleaned out and being readied for new chicks. At the upper right corner of the photo, there is new sawdust that will be placed in the chicken house. The circle is suspected to be an improperly covered pile of chicken manure cleaned from the chicken house (Figure 4.18). The arrow points to the nearby river.
Figure 4.17 Chicken farm close to the river in a transition phase between old and new flocks of birds (November 2005).

Figure 4.18 Partially covered manure pile.

Another example of suspected improperly covered manure piles appears at another chicken farm in the watershed. The first photo a. in Figure 4.19 shows the location of the manure piles on the chicken farm. The second photo b. is a close-up of
these piles, where the manure is only partially covered by a tarp. The third photo c. shows the location of the farm in relation to the river and the drainage pathway.

Figure 4.19 Chicken farm with partially covered manure piles in Lake Tuscaloosa watershed: a. location of manure pile in the farm, b. a closer shot of the improperly covered piles, and c. location of the farm in relation to the river (November 2005).

Another example of incompletely covered manure in the watershed is in Figure 4.20. This example is different than the previous two, as this manure pile is not covered at all. The photo of the farm is shown in Figure 4.20 a. In this photo, a red circle shows the manure pile, and the arrow indicates the location of the pile in relation to the river. Part b. of the photo shows a close-up of the manure pile.
Figure 4.20 Chicken farm with partially covered manure in watershed; a. a general shot of the farm with an indication to the location of the manure pile and the location of the pile in relation to the river and b. a close shot of the uncovered manure pile (November 2005).

There are additional aerial photos of chicken farms in the watershed that do not use proper methods to manage and dispose of the manure.

4.9.3 Observations in North River Basin

An investigation of the activities on North River was conducted in June 2007. The site investigation location, in relation to the watershed, is shown in Figure 4.21. Figure 4.22 contain an aerial photo of the investigation path and the surrounding areas.
Figure 4.21 Site investigation location in relation to the watershed; the green line is the path of the boat.

Figure 4.22 Path of North River investigation with point A as the starting point and point B as the ending point.
The main objective of this investigation was to have a closer look at the activities on the river banks and the surrounding area that might be potential sources of \textit{E. coli}. A boat was used as the method of transportation. Pictures were taken throughout the investigation to document these activities. The covered distance was around 5 miles from point A to point B.

The whole Southeastern United States has been suffering from severe drought, and peak drought conditions occurred during this survey. The levels in the lakes and rivers were below their normal levels. For example, Lake Tuscaloosa and North River were 2 to 3 feet below their normal flow levels during this survey. Shallow water hindered extending the survey beyond point B.

\textit{4.9.3.1 Activities Close to a Sampling Station}

The North Hagler road crossing is one of the sampling stations for the City of Tuscaloosa on North River (Figure 4.23). The sign on that day was green, indicating that \textit{E. coli} levels are below the city’s limit and direct contact with the water is safe. If the \textit{E. coli} levels are above the city’s limit, then the green sign is exchanged for a red one. There are two probable sources of \textit{E. coli} near this sampling station: barn swallow birds (Figure 4.24) living underneath the bridge, and animals in the pasture across from the station (Figure 4.25). The animals from the pasture have direct access to the river. These animals’ manure and urine can be seen on the river bank mixed with the soil in Figure 4.26.
Figure 4.23 North Hagler road sampling station.

Figure 4.24 Barn swallow birds’ nests.

Figure 4.25 Horses drinking from the river close to the sampling station.
Figure 4.26 Animal manure and urine mixed with the soil.

4.9.3.2 Agricultural Activities (Pastures) on North River

The area adjacent to the river has much agriculture activity, mainly pastures. These pastures are directly on the river with no fencing to keep animals from accessing the water. Figure 4.27 shows examples of these pastures.

Figure 4.27 Pastures on North River directly on the water.

During the boat survey, the smell of manure was strong and distinctive. Additionally, the lower branches of the trees were all at one height, indicating that there were large numbers of animals in the area eating the leaves. Many stops were taken to
investigate animal activity and manure on the river bank. Figure 4.28 was from one of these stops.

One site showed high cattle activity. For a distance of 30 to 40 feet, the site was full of cow manure. At the time the pictures were taken, the manure was fresh; also, there was runoff coming from the pasture area. Figures 4.29 through 4.31 document this activity.
Figure 4.29 Site with high animal activity.

Figure 4.30 A close shot of the activity and the manure.

Figure 4.31 Runoff from the pasture site.
Additional sites nearby had similar cattle activity (Figure 4.32).

Figure 4.32 Different sites on the river bank with manure.

Throughout the investigation, there were no cows observed on the river banks due to the heat. Some cows were found within the trees in the shade near the river (Figure 4.33).

Figure 4.33 Cows from a pasture on North River in the shade.

This investigation trip was important in order to have a closer look at the situation on North River and the potential sources of E.coli. This short trip up the river gave an indication of what might be occurring on a larger scale further up in the watershed, since more pasture land is located upstream. Similar investigations should be conducted in the
whole watershed to have a clear understanding of the activities and their impact on water quality.

4.9.4 Urban Impact on Lake Tuscaloosa: Carroll’s Creek Basin

Carroll’s Creek basin, Figure 4.34, is located in the southern part of the watershed in Tuscaloosa County, with an area of 12,408 acres (19.39 mi²). This basin is located in two cities, Tuscaloosa and Northport. The majority of the basin is in the Northport area; only the part close to Lake Tuscaloosa is within the City of Tuscaloosa’ limit.

Carroll’s Creek has three main types of land uses, residential, forest, and agricultural. In the creek watershed closest to the lake, and within both Tuscaloosa and Northport city limits, is residential and forest lands. In the middle section of the basin, there is a chicken farm. The upstream part is agricultural and forest.

The City of Tuscaloosa, in its efforts to protect Lake Tuscaloosa, has sampling stations to test the lake’s water quality. These stations are within the city’s limits. In Carroll’s Creek basin, the city has two stations, one at Carroll’s Creek mouth and the other at Carroll’s Creek Island. The sampling stations are shown in Figure 4.35.
The factorial test, section 4.8, showed that the lower part of the lake had a smaller association with high *E. coli* counts in Lake Tuscaloosa compared to the upper area of the Lake. This result was based on the city’s samples from 1998 until 2007. The *E. coli* values at the Carroll’s Creek stations were below the city’s *E. coli* limit (200 cfu/100mL), except for one reading in April of 2003 at 350 cfu/100mL.

In the 2005 Geological Survey of Alabama (GSA) report (O’Neil et al. 2005), Carroll’s Creek basin sampling results showed *E. coli* counts above the city’s limit during low flows in the middle section of the creek near the residential area and chicken farm. During high flows, all of the sampling stations had *E. coli* counts above the city’s limit.
and reached its peak near the residential areas. The main reason for this is discussed in the next section. The sampling stations for GSA and the city are in Figure 4.35. These aerial maps were taken from Google Earth® in 2007.

![Map of Carroll's Creek GSA and City sampling sites, chicken farm, and SSO sites.](image)

Figure 4.35 Carroll’s Creek GSA and City sampling sites, chicken farm, and SSO sites.

### 4.9.4.1 Sanitary Sewer Overflows in the Basin

Sanitary Sewer Overflows (SSOs) occur during stormwater events when wastewater is mixed with infiltrating stormwater, causing excessive flows that bypass the treatment plant or overflow at other locations in the collection system. Other causes of sanitary sewage overflow discharges can be failure in one of the wastewater network components, such as the pumps. Aging of the system can cause cracks in the pipes and manholes to leak into the stormwater collection system, which is directly connected to the waterbody. In our case, overflow moves into Carroll’s Creek and then afterwards into Lake Tuscaloosa.
There have been several reported incidents of SSOs in Carroll’s Creek in the last few years. The latest action was taken against the City of Northport in July 2007 under Alabama Department of Environmental Management (ADEM) Consent Order No. 07-139-CWP. This order was issued for Northport to take action against violations of the Alabama Water Pollution Control Act.

The SSO list contained 3 reported violations in 2006 at sites T1, T2, and T3, shown in Figure 4.35. The first violation incident was in February 2006, where 42,000 gal of raw sewage was discharged into the creek due to lightning that cut the power off at the sewage pumps. The second incident was in March 2006, where a wastewater hose ruptured and leaked 2,000 gallons of sewage. The third incident was in July 2006, where 30,000 gal of sewage was released due to failure of the wastewater pump. The location of these violations is mapped in Figure 4.35. The City of Northport is currently working on replacing and renewing the sanitary wastewater collection system in that area.

4.10 GSA Sampling in the Watershed

The GSA, in 2005, investigated the \( E.\text{coli} \) problem in the Lake Tuscaloosa watershed. They sampled during two periods representing both high and low precipitation. The GSA collected samples from 232 stations during precipitation events. Out of these 232 stations, there were 33 stations whose water dried up during dry weather sampling; therefore, dry weather samples were not available at all locations.

The GSA divided the watershed into subbasins and color coded these basins according to the \( E.\text{coli} \) count found during sampling. These counts were divided into two categories, 1 to 200 (City’s limit), and greater than 201 cfu/100 mL (exceeding the City’s
During periods of low precipitation, the majority of the watershed *E.coli* counts were between 1 and 200 cfu/100 mL (Figure 4.36 a.). During high precipitation, the *E.coli* counts throughout the watershed were much higher than during the low precipitation observation period (Figure 4.36 b.).

**Figure 4.36 a.** *E.coli* count during low precipitation and **b.** *E.coli* count during high precipitation.

### 4.11 Lake Tuscaloosa Watershed All Data Analysis

#### 4.11.1 Introduction

The observations in the watershed and the sampling by the GSA have identified the potential areas of concern. In order to test these observations with the available data, the entire city’s data from 1998 until 2007 and the GSA data from the watershed in 2005 were analyzed. The data set included the sites, precipitation values, season (warm or
cold), location (northern or southern), land use, and number of chicken houses in the basin.

4.11.2 All Watershed Data

An ANOVA test was performed on the data. ANOVA is a general technique to test the hypothesis that the means among two or more groups are equal. The data is assumed to be independent and with ~3000 data points, the law of large numbers is used to satisfy the normality assumption. Equal variance is checked using Bartlett’s and Levene’s tests. The ANOVA was run using the general linear model. The response variable was \( E. coli \). The determination point of significance was the p-value < 0.05 to the levels of \( E. coli \).

Using all the data, the models showed that only precipitation and land use were significant (p-value<0.05) when determining the levels of \( E. coli \). The season and the location were not significant when examining \( E. coli \) levels in the watershed’s streams.

The season variable, even though not significant, showed that warmer periods had higher \( E. coli \) mean values than cold periods, as shown in Figure 4.37. Previously, the analysis of the city’s data showed that season was significant and cold had a higher mean value than warm. The main reason for this result is that many collected samples during cold weather were on or directly after large rain events. Therefore, this increased the chances of having high \( E. coli \) counts. On the other hand, during warm weather, the majority of the samples were collected during dry periods and not after rain events.

This watershed analysis of all the data shows that warmer weather had a higher \( E. coli \) mean count than colder weather, whereas, when using the city’s data, colder
weather samples had higher *E. coli* mean counts than the warmer season samples. It is obvious that a consistent sampling method during wet and dry periods within the seasons needs to be developed for data collection, and the effects of large rains need to be considered.

![Main Effects Plot (data means) for *E. coli*](image)

**Figure 4.37** Full model effects of season on *E. coli* counts (C: cold and W: warm).

The location variable, even though not significant when examining watershed *E. coli* data, showed that the northern part of the watershed generally had higher *E. coli* mean values than the southern watershed area, as shown in Figure 4.38. In the previous analysis of the city’s data, location within the city’s sampling area on the Lake was significant. The analysis showed that the northern part of the lake had a higher mean effect on *E. coli* counts than the lower part of the Lake. The main reason for this location variability in the analysis is the addition of Carroll’s Creek basin data (southern part) to the analysis. There are known unusual conditions in this basin; SSO events and wastewater infrastructure system failures have been reported. If this unusual data is removed and the ANOVA test is run again, the location becomes significant with a p-value <0.05.
Figure 4.38 Full model effects of location on *E.coli* counts (L: lower and U: upper).

The main effects plot for land use, Figure 4.39, shows that the forest, pasture, and chicken farms (F,P,C) have the highest mean values of *E.coli*. The majority of these pastures and chicken farms are located in the North River and Binion Creek basins. The box plot of the land uses (Figure 4.40) shows the range of *E.coli* values for each land use. The land use categories F,P, and C had the highest means.

Figure 4.39 Effect of land use on *E.coli* counts.
Figure 4.40 Box-whisker plots of observed *E.coli* values (log) by land use

The number of chicken farm houses in a subbasin is plotted against the mean of *E.coli* counts measured at that subbasin (Figure 4.41). This figure shows an increasing number in the mean *E.coli* counts relative to the number of chicken houses. The box plot of the number of chicken houses (Figure 4.42) shows the range of *E.coli* values with different numbers of chicken houses within each subbasin of the watershed (see Appendix A).
Figure 4.41 Relationship between number of chicken houses and mean *E.coli* counts in Lake Tuscaloosa Watershed.

Figure 4.42 Box-whisker plot of observed *E.coli* values (log) versus the number of chicken houses.

4.11.3 Regression Analysis

Regression analysis was used to analyze the different land uses which were shown to be significant in the ANOVA analysis. After considering the available data, the model was used to address the different land uses and their impact on *E.coli* levels. The regression model includes the areas of each land use as a percentage of the subbasin (not
acres). The types of land uses considered are forest, pasture, and urban residential. Chicken farms were also added as a land use. The chicken farms are represented by the number of houses in each farm in a subbasin. The flow from each subbasin (cfs) is also added to the analysis.

First, a stepwise regression was conducted on the variables to find out which variables were significant and which ones were not. The results from the ANOVA analysis identified that only two variables were significant, the pasture percentage and the number of chicken houses. The p-value for pastures was 0.007 and for chicken farms was 0.000; both of these values were <0.05. The second step was to do a regression analysis on all the variables to identify the parameters of the regression equation. Even when including all the variables, the only significant variables were pastures and chicken farms. The p-value for pastures was 0.003 and for chicken farms was 0.000. Both of these p-values were < 0.05. The probability plot of the residuals (Figure 4.43) has a p-value <0.05, which indicates that the values are significant and not random. The results from considering the chicken farms and pasture in the regression model gave the following equation:

\[ E_{coli} = 460 + 1784 (P) + 235 (CF), \]  

(eq. 4.1)

where (P) is the percentage of pasture land and (CF) is the number of chicken farm houses in the subbasin.
This regression equation was used in the investigation to choose control analysis in Chapter VIII. The most important value was the constant (460). This value was used because if controls were implemented on a pasture or chicken farm, then their *E.coli* contribution was the constant. This represented an irreducible *E.coli* value for the area that cannot be further reduced.

### 4.12 Summary

This chapter discussed three main topics. The first topic was an introduction to the Lake Tuscaloosa watershed’s location, land uses, geology, water quality, etc. The second topic presented different activities that were observed in the watershed. These activities were documented by photos that were taken by air and by boat. The third topic discussed the statistical analyses that were conducted on the available data provided by the City of Tuscaloosa and the GSA.
The results from the data analyses indicated that the upper areas of the watershed are very likely contributing to the *E.coli* problem in the Lake, especially during rain events that are greater than 1 inch. It also indicated that agricultural activities seem to be a major contributor to the *E.coli* problem in the Lake Tuscaloosa watershed. The observations in the watershed showed some activities that may be considered potential sources for *E.coli*. These activities include animal manure near the river banks and partially covered manure at the chicken farm sites. These observations need to be further verified by modeling the system, as discussed in the coming chapters.
CHAPTER V

FLOW MODEL RESULTS AND ANALYSIS

5.1 Introduction

The modeling setup for both North River and Binion Creek basins is discussed in Appendix D. That Appendix includes the background, assumptions, and calculations to model the flow. This chapter discusses the results from the flow models. The results are compared to the observed readings and the errors are calculated. The results from the calibrated flow models are used in the E.coli model as an input. Therefore, it is important to obtain results as close as possible to the observed readings.

5.2 North River Flow Model Results and Analysis

In the North River basin, the results from the HEC-HMS model were compared to the historical flow data. The flow model was run from October 1998 until January 2007. The precipitation was plotted against the observed flows in Figure 5.1. This plot shows the spread of the data over the various precipitation events.
Figure 5.1 Observed flows in North River at different precipitation events.

The observed flow values were plotted against the calculated flow values in Figure 5.2. This plot showed that there is a correlation between both flows. The $R^2$ value was 0.55. The p-value for North River data, at a 95% confidence interval, is <0.05. Since the plot is not forced into the origin, a regression analysis is performed to indicate the significance of the intercept. The p-value for the intercept is 0.51 (>0.05). This indicates that the constant could be removed from the model; however, this is not a common practice.
Figure 5.2 Observed flow versus calculated flow for North River.

Further analyses were conducted on the calculated and the observed flows. The first test compared the distribution of both values. Both distributions had a similar trend, but the distribution for the calculated one had a slightly larger variance and mean. The distribution is shown in Figure 5.3.

Figure 5.3 Observed and calculated flow distributions.
The second test was Pearson’s ‘r’ test. This test measures the linear relationship between the two flows, which ranges from -1 to +1. A value closer to +1 indicates a positive linear relationship between both of them. The ‘r’ value from the test was 0.65. This indicated that there was a close correlation between the two flows.

Another conducted test was to examine the residuals; it was based on the difference between the observed and calculated values:

\[
Q'i = Qi + Ei, \quad \text{(eq. 5.1)}
\]

\[
Ei = Q'i - Qi, \quad \text{(eq. 5.2)}
\]

where \(Q'i\) is calculated flow, \(Qi\) is observed flow, and \(Ei\) is error. Bias is calculated from the error value according to the following equation. The sum is for the data from \(i=1\) to \(i=n\).

\[
\text{Bias} = \frac{1}{n} \sum Ei, \quad \text{(eq. 5.3)}
\]

where \(n\) equals the number of events.

The bias tested for both flows showed a positive bias with a value of 65.69. The positive bias value indicated an overestimate in the calculated flow. Table 5.1 shows the observed and calculated flow values for the precipitation readings of interest in this research. These values were chosen because they were the ones that matched the *E.coli* sampling data for the year 2005. The residual plots for the data are presented in four plots. The first plot is a probability plot of the residuals (Figure 5.4). The normal probability plot for the residuals has a p-value of 0.119 (>0.05) indicating it is normally distributed. The second plot shows the residuals versus precipitation (Figure 5.5). This plot shows an even band for the residuals at the middle area of the plot. The third plot is residual versus time (Figure 5.6). Similar to Figure 5.5, the plot shows an even band. The
fourth plot is the residual versus the calculated flow values plot (Figure 5.7). This plot shows that the calculated values are as expected to be produced by the model and that the residuals are all small compared to the calculated values.

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (in)</th>
<th>Observed Flow (cfs)</th>
<th>Calculated Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/14/2005</td>
<td>1.07</td>
<td>1520</td>
<td>1105</td>
</tr>
<tr>
<td>2/9/2005</td>
<td>1.05</td>
<td>862</td>
<td>822</td>
</tr>
<tr>
<td>3/8/2005</td>
<td>1.66</td>
<td>292</td>
<td>508</td>
</tr>
<tr>
<td>4/7/2005</td>
<td>2.72</td>
<td>7211</td>
<td>7678</td>
</tr>
<tr>
<td>4/12/2005</td>
<td>0.86</td>
<td>429</td>
<td>438</td>
</tr>
<tr>
<td>4/26/2005</td>
<td>1.06</td>
<td>164</td>
<td>198</td>
</tr>
<tr>
<td>5/15/2005</td>
<td>0.7</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>7/11/2005</td>
<td>3.2</td>
<td>2816</td>
<td>2385</td>
</tr>
<tr>
<td>8/11/2005</td>
<td>1.3</td>
<td>90</td>
<td>113</td>
</tr>
</tbody>
</table>

Figure 5.4 Normal probability plot for residuals.
Figure 5.5 Residuals versus precipitation.

Figure 5.6 Residuals versus date.
Figure 5.7 Residuals versus calculated flow.

Figure 5.8 shows the time series of the flow during the period of study. The calculated flow shows a close trend with the observed flow. Most of the calculated flow values are very close to the observed values.

Since the downstream calculated values were not statistically different from the observed values, the North River flow model for the subbasins in the river was assumed
to reasonably represent the observed values. Therefore, the flow model is used in the
*E.coli* model.

5.3 Binion Creek Flow Model Results and Analysis

In Binion Creek, as in North River, there is only one flow measuring location. The subbasins of the creek do not have historical flow data. Therefore, the comparison was for the generated flow values from the model at this one downstream location. After running the HEC-HMS model for Binion Creek Basin for precipitation values between October 1998 and January 2007, the precipitation values were plotted against the observed flow values in Figure 5.9. The plot shows the spread of the data over the various precipitation events.

![Figure 5.9 Observed flow in Binion Creek at different precipitation events (1999-2006).](image)

Observed flow values were plotted against the calculated flow (Figure 5.10). This plot shows that there is a close correlation between both flows. The $R^2$ value was 0.88. The p-value for Binion Creek data, at a 95% confidence interval, is ($<0.05$). Similar to
North River, the plot is not forced into the origin. A regression analysis is performed to indicate the significance of the intercept. The p-value for the intercept is <0.05. This indicates that the constant in the regression model cannot be removed from the model.

![Observed versus calculated flow for Binion Creek.](image)

Further analyses were conducted on the calculated flow against the observed flow. The first test compared the distribution of both flows. Both distributions had a similar trend, but the distribution for the calculated one had smaller variance and mean. The distributions are shown in Figure 5.11.
Figure 5.11 Observed and calculated flow distributions.

The Pearson ‘r’ test for the observed and calculated ranked values gave a p-value <0.005 and a Pearson ‘r’ value of 0.95. This indicated a close correlation between the two flow sets. Additionally, the bias value for the differences between the observed and calculated flow was -19.36. The negative bias value meant that the calculated flow values were underestimated. Table 5.2 shows the observed and calculated flow values for the precipitation readings of interest in this research.

The residual plots for the data are presented in four plots (similar to North River). The first plot is the probability plot of the residuals (Figure 5.12). The normal probability plot for the residuals has a p-value of 0.658 (>0.05) indicating that the residuals are normally distributed. The second plot is of residuals versus precipitation (Figure 5.13). The plot shows an even band for the residuals at the middle area of the plot, along with two outlier values which could not be predicted by the model. The third plot is residual versus time (Figure 5.14). Similar to Figure 5.13, the plot showed an even band with two outlier values. The fourth plot is the residual versus the calculated flow values (Figure
This plot shows that the calculated values are as expected to be produced by the model and that the residuals are all small compared to the calculated values.

Table 5.2 Observed and Calculated Flow Values at Binion Creek

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (in)</th>
<th>Observed Flow (cfs)</th>
<th>Calculated Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/14/2005</td>
<td>1.07</td>
<td>264</td>
<td>232</td>
</tr>
<tr>
<td>2/9/2005</td>
<td>1.05</td>
<td>209</td>
<td>227</td>
</tr>
<tr>
<td>3/8/2005</td>
<td>1.66</td>
<td>122</td>
<td>216</td>
</tr>
<tr>
<td>4/7/2005</td>
<td>2.72</td>
<td>1070</td>
<td>943</td>
</tr>
<tr>
<td>4/12/2005</td>
<td>0.86</td>
<td>177</td>
<td>186</td>
</tr>
<tr>
<td>4/26/2005</td>
<td>1.06</td>
<td>103</td>
<td>138</td>
</tr>
<tr>
<td>5/15/2005</td>
<td>0.7</td>
<td>46</td>
<td>91</td>
</tr>
<tr>
<td>7/11/2005</td>
<td>3.2</td>
<td>332</td>
<td>468</td>
</tr>
<tr>
<td>8/11/2005</td>
<td>1.3</td>
<td>51</td>
<td>138</td>
</tr>
</tbody>
</table>

Figure 5.12 Normal probability plot for residuals.
Figure 5.13 Residuals versus precipitation.

Figure 5.14 Residuals versus date.
Figure 5.15 Residuals versus calculated flow values.

Figure 5.16 shows the time series of the observed and calculated flows during the period of study. The calculated flows closely follow the observed flows.

Figure 5.16 Binion Creek observed and calculated flow time series.

Since the downstream calculated values were statistically indifferent from the observed values, the Binion Creek flow model for the subbasins in the creek was
assumed to closely represent the observed values. Therefore, these flow results are used in the *E.coli* model.

5.4 Summary

The results from the flow models for North River and Binion Creek are close to the observed readings at the flow gauges. Trying to calibrate the flow of an entire basin from one point at the mouth of the basin can result in a lot of uncertainty. This calibration may be close to the observed value at the one location, but it does not necessarily represent the flows at other locations in the subbasin. Additional flow data collection stations are therefore recommended for additional watershed locations. As mentioned previously, there are many parameters affecting flow simulations, such as the size of the basin. The smaller the basin, the better results can be obtained. Additionally, the more information collected, the less the uncertainty, and the better the simulation results become. Appendix B shows precipitation versus flow plots for each subbasin for both North River and Binion Creek.

The flows from these simulations for the different subbasins are used to model the *E.coli* in North River and Binion Creek basins. The modeling is discussed in Chapter VI.
CHAPTER VI

E.COLI MODEL

6.1 Introduction

Information about E.coli in the watershed is limited, as seen with the flow model. There has not been continuous monitoring of E.coli in the watershed except within the lake. Approximately monthly E.coli measurements have been made by the City of Tuscaloosa at 32 locations since 1998. The only comprehensive E.coli sampling for the watershed was conducted by GSA in 2005. However, this data is sufficient to examine various trends and to quantify expected variabilities of the data. The E.coli modeling in the watershed discussed in this chapter is based on the literature from Pachepsky et al. (2006) and Thomann and Mueller (1987).

6.2 Methodology

The first step in modeling E.coli transport in the watershed is to map the transport path (similar to the flow model) that the E.coli may take as it moves downstream through the watershed. Mapping is important to establish the mass balance equations for the basin. Mass balance assumptions state that mass cannot be created or destroyed in a closed system and must therefore be transferred (Thomann and Mueller 1997). The mass balance equation used for each map segment is:

\[ M_{\text{in}} = M_{\text{out}}, \]  

(eq. 6.1)
where \( M_{\text{in}} \) is the mass/load coming from different subbasins entering a subbasin and \( M_{\text{out}} \) is the mass/load leaving the subbasin.

The load was calculated by multiplying the \textit{E.coli} concentration by the flow from that subbasin. The equation is as follows:

\[
M_{\text{in}} = \sum_{i=1}^{n} Q_i C_i, \quad \text{(eq. 6.2)}
\]

where \( Q_i \) is flow from subbasins (cfs) that was calculated in the flow modeling section, \( C_i \) is the \textit{E.coli} concentration in the subbasin (cfu/100mL), and \( n \) is the number of subbasins in a basin.

Since the flow is in English units (cfs) and the \textit{E.coli} concentration is in metric units (cfu/100mL), a conversion factor was used. The final unit result was cfu/sec. The conversion factor number is 283.3. This number came from the following unit conversion equation.

\[
\frac{\text{ft}^3}{\text{sec}} \times \frac{\text{cfu}}{100\text{mL}} \times \frac{1000\text{mL}}{\text{L}} \times \frac{28.32\text{L}}{1\text{ft}^3} = 283.3
\]

Therefore, the final form of the equation looks as follows.

\[
Min = \sum_{i=1}^{n} Q_i C_i \times 283.3 \quad \text{(eq. 6.3)}
\]

Once the mass balance equations are set for the basin, the unknown values needed in the model are the \textit{E.coli} concentrations and the loss functions parameters. The flow data were obtained from the watershed flow model. This concentration is determined from the \textit{E.coli} model. The only \textit{E.coli} concentration data available for the subbasins in the watershed are measures taken during the GSA sampling period in 2005. Trying to build a model from these data points was challenging because of the limited data for each
sampling location of interest. Additionally, modeling bacteria includes multiple interactions between the bacteria and the surrounding environment, such as the available predators, soil pH, moisture content, temperature, etc. This interaction affects their growth and die-off rates, which makes modeling bacteria a difficult task (Pachepsky et al. 2006). This die-off is incorporated in the model discussed below.

Two phases are needed to calculate the *E.coli* concentration in the model. The first phase takes the known concentration at a subbasin and finds an initial average amount of *E.coli* in that subbasin. These values become the seed/initial *E.coli* value from that subbasin for the second phase. In the second phase, the procedure is opposite to the first one, where the seed value is used to calculate the *E.coli* concentration at a subbasin under different precipitation events.

Before starting to list the different equations for calculating the *E.coli* concentration, it is important to understand the fate and transport of *E.coli*. The first step is the release of *E.coli* from the source or host. This is when *E.coli* start their journey. *E.coli* microorganisms at the initial stages face a high mortality rate, and more than 95% of the original count dies a short period (1 to 3 days) after leaving the host. This mortality depends on the survival conditions for the microorganisms, such as the temperature, moisture, and amount of nutrients available (Pachepsky et al. 2006). If good conditions are available, then the microorganisms can survive and multiply. The *E.coli* becomes part of the upper soil layer, where good survival conditions prevail. When a storm event occurs, the soil particles, along with the attached *E.coli* microorganisms, are released from the soil layer and runoff to the closest waterbody, unless there is a control to stop them. Once the microorganisms reach the waterbody, they start to settle and become part...
of the bottom sediment. This supports the correlation between turbidity and *E. coli* that was discussed earlier.

These above *E. coli* fate and transport stages and their relevant equations are discussed in Pachepsky et al. (2006). The following discussion maps these equations and the input into each of them.

The first phase of the survival and inactivation of the microorganisms is modeled using an exponential equation suggested by Chick in 1908 and presented by Thomann and Mueller (1997). This equation describes the survival rate of the microorganisms using a die-off (disappearance) rate constant.

\[
N = N_0 \exp(-\mu t), \quad \text{(eq. 6.4)}
\]

where \(N\) is the number of microorganisms after death at time \(t\), \(N_0\) is the initial count of microorganisms at time 0, and \(\mu\) is the die-off rate constant (day\(^{-1}\)). The die-off rate constant ranges between 0.1 and 1 per day. The initial count of microorganisms \((N_0)\) has a unit of cfu/g of soil.

The release of manure-borne microorganisms from the soil layer during rain events can be simulated exponentially. Many models have been suggested, but the one used is the bacteria fate model developed for this research used the equation developed by Bicknell et al. (1997).

\[
\Delta M_R = M_s [1 - \exp(-k_2 \Delta Q)], \quad \text{(eq. 6.5)}
\]

where \(\Delta M_R\) is the count of microorganisms released during a runoff event (cfu/g), \(M_s\) is the count of microorganisms in the storage layer of soil (cfu/g), \(\Delta Q\) is the runoff yield during runoff event (cm), and \(k_2\) is the release rate parameter (cm\(^{-1}\)). This value ranges between 2 (for pasture) and 5 (impervious areas), depending on the land use.
The $\Delta Q$ value needs to be converted from cfs to cm. In order to achieve this unit, the following equations were used.

\[
\frac{\text{Flow(cfs)}}{A(\text{ft}^2)} = \frac{ft}{\text{sec}}, \quad (\text{eq. 6.6})
\]

\[
\frac{ft}{\text{sec}} \times 3600 \frac{\text{sec}}{hr} \times 24 \frac{hr}{hr} \times 30.48 \frac{cm}{ft}, \quad (\text{eq. 6.7})
\]

where $A$ is the subbasin area in ft$^2$.

Next, the concentrations of the \textit{E.coli} in the water are calculated by using the following linear isotherm equation (Bicknell et al. 1997; Sadeghi and Arnold 2002). Since the unit of $C$ is cfu/mL, in order to make it cfu/100mL the $C$ value is divided by 100.

\[
C = \frac{S}{k_d}, \quad (\text{eq. 6.8})
\]

where $C$ is the concentration of \textit{E.coli} in water cfu/mL, $S$ is the amount of microorganisms in the runoff (cfu/g), and $k_d$ is the partitioning coefficient (mL/g) with a value between 10 and 70 mL/g.

The model described above determines the concentration of \textit{E.coli} in the water after being released from a contaminated surface source. In order to calculate the initial microorganism number, the process is reversed, using equation 6.8 first and going to equation 6.4. This step is presented in Table 6.1. The forward model table is similar to the one presented below; the only difference is the organization of the parameters.
Table 6.1 Spreadsheet Listing the Variables and Units of the Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C water</td>
<td>cfu/100mL</td>
<td>E. coli count in water</td>
</tr>
<tr>
<td>C water</td>
<td>cfu/mL</td>
<td></td>
</tr>
<tr>
<td>Q subbasin</td>
<td>ft</td>
<td>Subbasin flow</td>
</tr>
<tr>
<td>A subbasin</td>
<td>sq ft</td>
<td></td>
</tr>
<tr>
<td>DQ</td>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>Kd</td>
<td>mL/g</td>
<td>The partitioning coefficient values are</td>
</tr>
<tr>
<td></td>
<td></td>
<td>between 10 to 70 mL/g</td>
</tr>
<tr>
<td>S</td>
<td>cfu/g</td>
<td>Amount of microorganisms in Runoff</td>
</tr>
<tr>
<td>K2</td>
<td>/cm</td>
<td>Ranges from 2/cm for pasture and 3/cm for</td>
</tr>
<tr>
<td></td>
<td></td>
<td>impervious</td>
</tr>
<tr>
<td>DMr</td>
<td>cfu/g</td>
<td>Count of microorganisms released during a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>runoff event</td>
</tr>
<tr>
<td>Ms</td>
<td>cfu/g</td>
<td>Count of microorganisms in manure storage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>layer of soil</td>
</tr>
<tr>
<td>N</td>
<td>cfu/g</td>
<td>Count of microorganisms after dry off</td>
</tr>
<tr>
<td>a</td>
<td>/day</td>
<td>Ranges from 0.1 to 1/day</td>
</tr>
<tr>
<td>t</td>
<td>Day</td>
<td></td>
</tr>
<tr>
<td>Nu</td>
<td>cfu/g</td>
<td>Original count of microorganisms</td>
</tr>
</tbody>
</table>

The calculated concentrations, along with the flow from the subbasin, are the values that are entered into the mass balance model presented in equation 6.3. These calculations of concentrations and the mass balance model are developed in Excel. The spreadsheets were developed for every precipitation event under consideration. The E.coli values produced from the mass balance equations were compared with the actual readings downstream in order to calibrate and verify the model.

6.3 E.coli Model Calibration

In the E.coli model, there are many variables that are uncertain. The first of these variables are in equation 4, the decay time (t) for the microorganisms and the dieoff rate $\mu$. The second is the $k_2$ value in equation 6.5. The third is the $k_d$ value in equation
6.8. Finally, there is uncertainty in modeling the flow values for the subbasins. Each one of these variables impacts the calculated *E. coli* concentrations in the model.

Each subbasin is calibrated separately in the model in order to observe its impact downstream. Also, the calibrations were conducted for every precipitation event separately. The majority of the variables in the model are obtained from the literature, such as the $K_d$, $\mu$, and $K_2$. However, they do not have as much impact on the concentration as the decay time.

If the decay time is shorter, then the microorganisms’ concentration in the water is larger than if the decay time is longer, due to the die-off of the bacteria that occurs with time. The $(t)$ variable may increase due to natural causes, such as obstacles in the waterways causing ponding, that are seldom considered during typical hydraulic river flow modeling during large events.

### 6.4 *E. coli* Mass Balance Model

#### 6.4.1 North River

North River basin is divided into many subbasins. The main subbasins are the ones on North River, indicated by NR, and the adjacent subbasins that flow into the main ones are indicated by their creek or stream initials. Each NR segment is considered a phase in the mass balance equations. The value at each segment is the reading of the final load coming from adjacent subbasins and the NR subbasin itself. The sequence of the equations is from upstream to downstream. The list below shows the subbasins and the mass balance equations for each subbasin.
- NR0 point receives no load from adjacent subbasins into it but only has the load from NR0 itself. Therefore, NR0’s load goes into NR9.

- NR9 point receives load from the following subbasins: NR0, TD1, HC1, LY1, BR1, GC1, and NR9SB. BR1 and TD1 subbasins receive load from adjacent subbasins. BR1 receives load from BR2 and BR1SB. TD1 receives load from LK1 and TD1SB.

  \[ L(\text{BR1}) = L(\text{BR1SB}) + L(\text{BR2}) \]
  \[ L(\text{TD1}) = L(\text{TD1SB}) + L(\text{LK1}) \]

  \[ L(\text{NR9}) = L(\text{NR0}) + L(\text{TD1}) + L(\text{HC1}) + L(\text{LY1}) + L(\text{BR1}) + L(\text{GC1}) + L(\text{NR9SB}) \]

- NR8 point receives load from the following subbasins: NR9, LB1, CA1, and NR8SB. CA1 receives load from CA1SB and CA2.

  \[ L(\text{CA1}) = L(\text{CA2}) + L(\text{CA1SB}) \]

  \[ L(\text{NR8}) = L(\text{NR9}) + L(\text{CA1}) + L(\text{LB1}) + L(\text{NR8SB}) \]

- NR7 point receives load from the following subbasins, NR8, EC1, and NR7SB.

  \[ L(\text{NR7}) = L(\text{NR8}) + L(\text{EC1}) + L(\text{NR7SB}) \]

- NR6 point receives load from the following subbasins, RB1, CL1, NT3, NR7, and NR6SB. CL1 point receives load from DC1, DCT, CL2, and CL1SB. CL2 receives load from CL3, BS1, and CL2SB. CL3 receives load from CL4 and CL3SB.

  \[ L(\text{CL3}) = L(\text{CL4}) + L(\text{CL3SB}) \]

  \[ L(\text{CL2}) = L(\text{CL3}) + L(\text{BS1}) + L(\text{CL2SB}) \]

  \[ L(\text{CL1}) = L(\text{CL2}) + L(\text{DCT}) + L(\text{DC1}) + L(\text{CL1SB}) \]

  \[ L(\text{NR6}) = L(\text{NR7}) + L(\text{CL1}) + L(\text{RB1}) + L(\text{NT3}) + L(\text{NR6SB}) \]
- NR5 point receives load from the following subbasins: NR6, SPC, NT2, CE1, and NR5SB. CE1 point receives load from CE2 and CE1SB. CE2 point receives load from CE3, BY1, and CE2SB. CE3 point receives load from CE4, LC1, BY2, and CE3SB.

\[
\begin{align*}
L(CE3) &= L(CE4) + L(LC1) + L(BY2) + L(CE3SB) \\
L(CE2) &= L(CE3) + L(BY1) + L(CE2SB) \\
L(CE1) &= L(CE2) + L(CE1SB) \\
L(NR5) &= L(NR6) + L(SPC) + L(NT2) + L(CE1) + L(NR5SB)
\end{align*}
\]

- NR4 point receives load from the following subbasins: NR5, FC1, and NR4SB

\[
L(NR4) = L(NR5) + L(FC1) + L(NR4SB)
\]

- NR3 point receives load from the NR4 and NR3SB subbasins.

\[
L(NR3) = L(NR4) + L(NR3SB)
\]

- NR2 point receives load from the following subbasins: NR3, BO1, BE1, GB1, TC1, NT1, and NR2SB. BO1 receives load from BO2 and BO1SB.

\[
\begin{align*}
L(BO1) &= L(BO2) + L(BO1SB) \\
L(NR2) &= L(NR3) + L(BO1) + L(BE1) + L(GB1) + L(TC1) + L(NT1) + L(NR2SB)
\end{align*}
\]

- NR1 point receives load from the following subbasins: NR2, CP1, and NR1SB.

\[
L(NR1) = L(NR2) + L(CP1) + L(NR1SB)
\]

The *E. coli* values, as mentioned previously, are for the points downstream of every subbasin. This initial measured concentration by the GSA is an accumulation of the subbasins above and the subbasin itself. Therefore, the *E. coli* concentration from each subbasin, noted with SB in its name, do not have a concentration. Using the mass balance
equations, the *E.coli* concentrations are determined, and the original count of microorganisms is calculated during the backward iteration. These values are used in the forward iteration from that point forward.

6.4.2 Binion Creek

Similar to the North River basin, Binion Creek basin is divided into many subbasins. The main channel is indicated by BC and tributaries are indicated by BT. Each BC segment is considered a phase in the mass balance equations. The sequence of the equations is from upstream to downstream. The list below shows the subbasins and the mass balance equations for each subbasin.

- BC3 point has no load coming from adjacent subbasins into it; it only has the load from BC3 subbasin itself. Therefore, BC3’s load flows into BC2.

- BC2 point receives load from BC3 and from BC2 subbasin.

  \[ L(BC2) = L(BC3) + L(BC2SB) \]

- BT6, BT5, BT2 and BT1 subbasins have no load coming from adjacent subbasin into them. The only load is from the subbasins themselves.

- BT4 point receives load from BT6 and from BT4 subbasin itself.

  \[ L(BT4) = L(BT6) + L(BT4SB) \]

- BT3 point receives load from BT4 and BT5 and from BT3 subbasin itself.

  \[ L(BT3) = L(BT4) + L(BT5) + L(BT3SB) \]

- BC1 point receives load from BT3, BT2, BT1 and from BC1 subbasin itself.

  \[ L(BC1) = L(BT3) + L(BT2) + L(BT1) + L(BC1SB) \]
6.5 Summary

The various components of the *E.coli* model were discussed. The concentration calculating phase has uncertainty in its parameters. This uncertainty is generated due to limited data. This limited data increases the error in the obtained results. Therefore, further data should be collected in order to reduce this uncertainty.

Once the mass balance and bacteria fate equations were entered and coded into the Excel spread sheets, entering the data and retrieving the results began. The data entry, as organized above, started from the top of the basin and worked towards the bottom to the Lake, which is similar to flow. The results and its analysis are discussed in the next chapter.
CHAPTER VII

*E.COLI* MODEL RESULTS AND ANALYSIS

7.1 Introduction

The *E.coli* model and the mass balance equations were presented in the previous chapter. In this chapter, the results and use of the model are discussed. Examples of calculating \( N_0 \), the initial count of microorganism at time 0, and running a mass balance using the model are explained. After showing and discussing the results of the model for both North River and Binion Creek, the levels needed by the controls in order to result in *E.coli* levels below 200 cfu/100mL in Lake Tuscaloosa are discussed.

7.2 Calculation Examples

7.2.1 Example of Calculating \( N_0 \)

The GSA collected samples in the watershed on April 26, 2005. This is the only data available for *E.coli* for the different subbasins in the watershed. An example of calculating the initial bacterial level (\( N_0 \)) in subbasin GC1 is explained in this section. The GC1 subbasin is located at the top of the North River basin. Its land use is categorized as forest and has an area of 5268 acres. The measured value for *E.coli* at GC1 during the 1.06 inch rain event was 73 cfu/100mL. The flow from this subbasin was 7.5 cfs. The partitioning coefficient (\( K_d \)) was assumed to be 30 mL/g, as obtained from the
literature for similar areas described by Pachepsky et al. (2006). The release rate parameter $K_2$ value was assumed to be 2 cm$^{-1}$ (also from Pachepsky et al. 2006). The die-off rate constant ($\mu$) value was assumed to be 0.95 (Pachepsky et al. 2006). After running the equations, the $N_0$ value for the GC1 subbasin was determined to be 357 cfu/g. The model parameter values used to calculate $N_0$ are shown in Table 7.1. The $N_0$ calculated values for the rest of the subbasins in North River are presented in Table 7.2, while calculated values for Binion Creek subbasins appear in Table 7.3.

| Table 7.1 Model Parameters Used to Calculate the $N_0$ Value for Subbasin GC1 |
|-----------------------------|---|---|---|---|---|
| **C water** | 73 | cfu/100mL | $k_2$ | 2 | /cm |
| **C water** | 0.73 | cfu/mL | $D_M$ | 21.9 | cfu/g |
| **Q subbasin** | 7.5 | Cfs | $M_s$ | 138.2 | cfu/g |
| **Area** | 2.29E+08 | sq ft | $N$ | 138.2 | cfu/g |
| **DQ** | 0.086 | Cm | $M$ | 0.95 | /day |
| **Kd** | 30 | mL/g | $T$ | 1 | Day |
| **S** | 21.9 | cfu/g | $N_0$ | 357 | cfu/g |
Table 7.2 Initial E. coli Concentrations ($N_0$) in North River Subbasins

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>$C$ in water cfu/100mL</th>
<th>$N_0$ cfu/g</th>
<th>Subbasin</th>
<th>$C$ in water cfu/100mL</th>
<th>$N_0$ cfu/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR0</td>
<td>56</td>
<td>238</td>
<td>NR6SB</td>
<td>980</td>
<td>128</td>
</tr>
<tr>
<td>BR2</td>
<td>206</td>
<td>847</td>
<td>CE4</td>
<td>1553</td>
<td>4187</td>
</tr>
<tr>
<td>LK1</td>
<td>184</td>
<td>592</td>
<td>LC1</td>
<td>308</td>
<td>1172</td>
</tr>
<tr>
<td>GC1</td>
<td>73</td>
<td>357</td>
<td>BY2</td>
<td>613</td>
<td>1131</td>
</tr>
<tr>
<td>BR1SB</td>
<td>30</td>
<td>339</td>
<td>BY1</td>
<td>4140</td>
<td>4961</td>
</tr>
<tr>
<td>HC1</td>
<td>72</td>
<td>546</td>
<td>NT2</td>
<td>980</td>
<td>2393</td>
</tr>
<tr>
<td>LY1</td>
<td>866</td>
<td>3391</td>
<td>SPC</td>
<td>2660</td>
<td>8686</td>
</tr>
<tr>
<td>TD1SB</td>
<td>296</td>
<td>835</td>
<td>CE3SB</td>
<td>199</td>
<td>712</td>
</tr>
<tr>
<td>NR9SB</td>
<td>41</td>
<td>2794</td>
<td>CE2SB</td>
<td>670</td>
<td>4284</td>
</tr>
<tr>
<td>LB1</td>
<td>47</td>
<td>173</td>
<td>CE1SB</td>
<td>649</td>
<td>9554</td>
</tr>
<tr>
<td>CA2</td>
<td>866</td>
<td>848</td>
<td>NR5SB</td>
<td>1344</td>
<td>1733</td>
</tr>
<tr>
<td>CA1SB</td>
<td>58</td>
<td>672</td>
<td>FC1</td>
<td>1650</td>
<td>4196</td>
</tr>
<tr>
<td>NR8SB</td>
<td>1610</td>
<td>1092</td>
<td>NR4SB</td>
<td>214</td>
<td>1345</td>
</tr>
<tr>
<td>EC1</td>
<td>125</td>
<td>437</td>
<td>NR3SB</td>
<td>1305</td>
<td>5492</td>
</tr>
<tr>
<td>NR7SB</td>
<td>173</td>
<td>3820</td>
<td>TC2</td>
<td>144</td>
<td>543</td>
</tr>
<tr>
<td>CL4</td>
<td>214</td>
<td>868</td>
<td>TC1SB</td>
<td>8978</td>
<td>8072</td>
</tr>
<tr>
<td>CL3SB</td>
<td>465</td>
<td>1868</td>
<td>BO2</td>
<td>6630</td>
<td>13479</td>
</tr>
<tr>
<td>BS1</td>
<td>172</td>
<td>1152</td>
<td>BE1</td>
<td>308</td>
<td>2097</td>
</tr>
<tr>
<td>CL2SB</td>
<td>159</td>
<td>824</td>
<td>GB1</td>
<td>921</td>
<td>3742</td>
</tr>
<tr>
<td>DC1</td>
<td>122</td>
<td>560</td>
<td>NT1</td>
<td>12360</td>
<td>25287</td>
</tr>
<tr>
<td>DCT</td>
<td>548</td>
<td>1934</td>
<td>BO1SB</td>
<td>308</td>
<td>1273</td>
</tr>
<tr>
<td>NT3</td>
<td>866</td>
<td>2653</td>
<td>NR2SB</td>
<td>165</td>
<td>2136</td>
</tr>
<tr>
<td>RB1</td>
<td>461</td>
<td>1600</td>
<td>CP1</td>
<td>411</td>
<td>1529</td>
</tr>
<tr>
<td>CL1SB</td>
<td>74</td>
<td>6404</td>
<td>NR1SB</td>
<td>1178</td>
<td>8816</td>
</tr>
</tbody>
</table>

Table 7.3 Initial E. coli Concentrations ($N_0$) in Binion Creek Subbasins

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>$C$ in water cfu/100mL</th>
<th>$N_0$ cfu/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC3</td>
<td>1119</td>
<td>1490</td>
</tr>
<tr>
<td>BT5</td>
<td>2420</td>
<td>2268</td>
</tr>
<tr>
<td>BT6</td>
<td>1733</td>
<td>2079</td>
</tr>
<tr>
<td>BT2</td>
<td>3050</td>
<td>3191</td>
</tr>
<tr>
<td>BC2SB</td>
<td>223</td>
<td>272</td>
</tr>
<tr>
<td>BT4SB</td>
<td>6313</td>
<td>6688</td>
</tr>
<tr>
<td>BT3SB</td>
<td>727</td>
<td>883</td>
</tr>
<tr>
<td>BC1SB</td>
<td>687</td>
<td>930</td>
</tr>
</tbody>
</table>

7.2.2 Example Mass Balance Calculation

This mass balance example shows how the E. coli levels were determined downstream of the NR8 subbasin before entering the NR7 subbasin during the 1.05 inch
rain event. NR8 receives bacteria from NR9, LB1, CA1, and NR8SB. CA1 receives bacteria from CA1SB and CA2. The mass balance equation is as follows, and the calculations are summarized in Table 8.4.

\[
L(NR8) = L(NR9) + L(CA1) + L(LB1) + L(NR8SB)
\]

The resulting bacterial level at CA1 is calculated using the following equation:

\[
L(CA1) = L(CA2) + L(CA1SB)
\]

\[
(32.1 \text{ cfs})(C \text{ cfu/100mL})(283.3) = (25.6 \text{ cfs})(219 \text{ cfu/100mL})(283.3) + (6.5 \text{ cfs})(7 \text{ cfu/100mL})(283.3),
\]

The 283.3 value cancels throughout the equation,

Calculating for C at CA1 = 176 cfu/100mL.

The bacterial level at NR8 is calculated as follows:

\[
(152.2 \text{ cfs})(C \text{ cfu/100mL}) = (109.3 \text{ cfs})(51 \text{ cfu/100mL}) + (32.1 \text{ cfs})(176 \text{ cfu/100mL}) + (5.1 \text{ cfs})(4 \text{ cfu/100mL}) + (5.7 \text{ cfs})(430 \text{ cfu/100mL}),
\]

Calculating for C at NR8 = 90 cfu/100mL.

This NR8 bacterial level and flow are taken to the next location to find the bacterial level at NR7.

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Contributing subbasins</th>
<th>Contributing subbasins</th>
<th>C in water (cfu/100mL)</th>
<th>Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA1SB</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA2</td>
<td>219</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA1SB</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA2</td>
<td>176</td>
<td></td>
<td>32.1</td>
</tr>
<tr>
<td>LB1</td>
<td></td>
<td></td>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td>NR8SB</td>
<td></td>
<td>430</td>
<td></td>
<td>5.7</td>
</tr>
<tr>
<td>NR8</td>
<td></td>
<td>90</td>
<td></td>
<td>152.2</td>
</tr>
</tbody>
</table>
7.3 North River *E.coli* Model Results Analysis

The results from running the *E.coli* model for the North River basin were compared with the observed *E.coli* readings. The readings, as mentioned previously, are for the year 2005. The observed readings were taken from the downstream site at the mouth of the basin. This site is the only one that has historical *E.coli* readings. The observed and calculated data, along with the calculated flows, are shown in Table 7.5.

Table 7.5 Observed and Calculated *E.coli* Data for North River Basin Downstream

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (in)</th>
<th>Flow (cfs)</th>
<th>Observed <em>E.coli</em> (cfu/100mL)</th>
<th>Calculated <em>E.coli</em> (cfu/100mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/14/2005</td>
<td>1.07</td>
<td>1105</td>
<td>276</td>
<td>381</td>
</tr>
<tr>
<td>2/9/2005</td>
<td>1.05</td>
<td>821</td>
<td>105</td>
<td>346</td>
</tr>
<tr>
<td>3/8/2005</td>
<td>1.66</td>
<td>508</td>
<td>112</td>
<td>360</td>
</tr>
<tr>
<td>4/7/2005</td>
<td>2.72</td>
<td>7670</td>
<td>2040</td>
<td>1749</td>
</tr>
<tr>
<td>4/12/2005</td>
<td>0.86</td>
<td>438</td>
<td>73</td>
<td>192</td>
</tr>
<tr>
<td>4/26/2005</td>
<td>1.06</td>
<td>198</td>
<td>135</td>
<td>147</td>
</tr>
<tr>
<td>5/15/2005</td>
<td>0.7</td>
<td>32</td>
<td>11</td>
<td>25</td>
</tr>
<tr>
<td>7/11/2005</td>
<td>3.2</td>
<td>2385</td>
<td>1120</td>
<td>1630</td>
</tr>
<tr>
<td>8/11/2005</td>
<td>1.3</td>
<td>113</td>
<td>33</td>
<td>91</td>
</tr>
</tbody>
</table>

The precipitation was plotted against the observed *E.coli* values on Figure 7.1. The plot shows a strong positive correlation between the precipitation and *E.coli*, where the larger rains are associated with higher *E.coli* values. The plot in Figure 7.2 shows the correlation between the observed and calculated *E.coli* values. The R² value for the plot is 0.92. In the one way ANOVA test, the p-value is 0.37 (>0.05), indicating that more data would be needed to be confident at the 95% level that the sets of data are different.

In order to verify the use of the model, residual analyses are conducted. The residual analyses use four plots. The first plot is the probability plot of the residuals (Figure 7.3). The p-value for this plot is 0.401 (>0.05), indicating that the residuals are normally distributed. The second plot is precipitation versus the residuals (Figure 7.4).
The plot shows an even band in the middle and two outlier values. The third plot is the residuals versus time (Figure 7.5). Similar to the previous plot, there is an even band in the middle and two outlier values. The fourth plot is the residuals versus the calculated values (Figure 7.6). This plot shows that the calculated values are as expected to be produced by the model and that the residuals are all small compared to the calculated values.

Analysis was conducted to estimate the number of samples (points) needed to achieve an $\alpha$ of 0.05 at a power of 0.8 and a difference of 25% with a coefficient of variation of 0.8. The results indicated that 150 points would be needed using these goals. Fewer data were available for these initial analyses, however.

Figure 7.1 *E.coli* plot against precipitation.
Figure 7.2 Observed versus calculated *E.coli* values in North River Basin.

Figure 7.3 Normal probability plot of residuals.
Figure 7.4 Residuals versus precipitation.

Figure 7.5 Residuals versus time.
Figure 7.6 Residuals versus calculated values.

The calculated flow is plotted against the observed and calculated E.coli values in Figure 7.7. In both plots, the $R^2$ value is above 0.90, and they have almost parallel trend lines.

Figure 7.7 Flow versus observed E.coli values.
The observed and modeled *E.coli* values have been plotted on a time series in Figure 7.8. This plot shows that the modeled *E.coli* values follow the observed values reasonably closely.

Figure 7.8 Observed and calculated *E.coli* time series.

### 7.4 Binion Creek *E.coli* Model Results Analysis

The results from running the *E.coli* model (calculated *E.coli* values) for Binion Creek basin are compared to the observed *E.coli* values. The measured values, as mentioned previously, are for the year 2005. The observed values are taken from the downstream site at the mouth of the Binion Creek watershed. This is the only site that has historical *E.coli* readings. The observed and calculated data, along with the calculated flow values, are shown in Table 7.6.
Table 7.6 Observed and Calculated *E.coli* Data for Binion Creek Basin Downstream

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (in)</th>
<th>Flow (cfs)</th>
<th>Observed <em>E.coli</em> (cfu/100mL)</th>
<th>Calculated <em>E.coli</em> (cfu/100mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/14/2005</td>
<td>1.07</td>
<td>263</td>
<td>165</td>
<td>131</td>
</tr>
<tr>
<td>2/9/2005</td>
<td>1.05</td>
<td>258</td>
<td>98</td>
<td>118</td>
</tr>
<tr>
<td>3/8/2005</td>
<td>1.66</td>
<td>245</td>
<td>461</td>
<td>406</td>
</tr>
<tr>
<td>4/7/2005</td>
<td>2.72</td>
<td>1070</td>
<td>816</td>
<td>623</td>
</tr>
<tr>
<td>4/12/2005</td>
<td>0.86</td>
<td>212</td>
<td>122</td>
<td>200</td>
</tr>
<tr>
<td>4/26/2005</td>
<td>1.06</td>
<td>156</td>
<td>377</td>
<td>377</td>
</tr>
<tr>
<td>5/15/2005</td>
<td>0.7</td>
<td>103</td>
<td>122</td>
<td>141</td>
</tr>
<tr>
<td>7/11/2005</td>
<td>3.2</td>
<td>579</td>
<td>108</td>
<td>125</td>
</tr>
<tr>
<td>8/11/2005</td>
<td>1.3</td>
<td>171</td>
<td>1120</td>
<td>162</td>
</tr>
</tbody>
</table>

The precipitation was plotted against the observed *E.coli* values in Figure 7.9. The plot shows a strong positive correlation between the precipitation and *E.coli*, where the higher the precipitation is, the higher the *E.coli* values are. The plot in Figure 7.10 shows the correlation between the observed and calculated *E.coli* values. The $R^2$ value for the plot is 0.63. This shows a correlation between both values but it is not as high as the one for North River (0.92). Similar to North River, the p-value is 0.169 (>0.05), indicating that more data would be needed to be confident at the 95% level that the sets of the data are different.

In order to verify the use of the model, residual analysis is conducted. There are four plots in the residual analysis. The first plot is the probability plot of the residuals (Figure 7.11). The p-value for this plot is <0.05, including that the residuals are not normally distributed as desired. If the one outlier is removed then the p-value 0.086 (>0.05) is not significant and the residuals are normally distributed. The second plot is precipitation versus the residuals (Figure 7.12). The plot shows an even band at the lower area and one outlier value. The third plot is the residuals versus time (Figure 7.13). Similar to the previous plot, there is an even band at the lower area and one outlier value.
The fourth plot is the residuals versus the calculated values (Figure 7.14). This plot shows that the calculated values are as expected to be produced by the model and that the residuals are all small compared to the calculated values.

Analysis was conducted to estimate the number of samples (points) needed to achieve an $\alpha$ of 0.05 at a power of 0.8 and a difference of 25% with a coefficient of variation of 1.4. The results indicated that 400 points would be required to achieve these error levels. However, this preliminary analysis used the fewer data that was available.

![Figure 7.9 E.coli plot against precipitation.](image-url)
Figure 7.10 Observed versus calculated \( E. coli \) values in North River Basin.

Figure 7.11 Normal probability plot of residuals.
Figure 7.12 Residuals versus precipitation.

Figure 7.13 Residuals versus time.
Figure 7.14 Residuals versus calculated values.

The calculated flow is plotted against the observed and calculated *E.coli* values in Figure 7.15. The plots show that the calculated flow has a high correlation with an $R^2$ value around 0.71.

Figure 7.15 Flow versus observed *E.coli* values.
The observed and calculated *E.coli* values have been plotted on a time series (Figure 7.16). This plot shows that the calculated *E.coli* values follow a close trend with the observed ones. The last value in the series shows a high deviation with the observed, and this is one reason for the variation in the previous plots.

![Figure 7.16 Observed and calculated *E.coli* time series.](image)

### 7.5 Investigation of Potential Sources and Need of Controls

#### 7.5.1 Introduction

The verified *E.coli* models for both North River and Binion Creek were used to investigate the impact of controlling the potential sources of bacteria on the water quality in the lake. The model was also used to identify the maximum allowable loads of *E.coli* that can be discharged from these sources in order to meet the water quality objectives in the lake.

In this investigation, the potential sources of *E.coli* responsible for the contamination of the lake are tested in terms of their potential impact on the downstream water quality. This investigation used the *E.coli* model in conjunction with the watershed
hydraulic model. The potential sources considered were agricultural activities (feedlot operations and chicken farms), urban infrastructures (wastewater treatment plants, on-site septic systems), and stormwater systems. The locations containing these activities may need to implement controls on their properties to reduce their negative impact on the water quality in the lake. A control is any system to be implemented at the source of pollution. This is to prevent the transport of the bacteria to the nearest water body. A discussion about the different controls is discussed in Chapter VIII.

7.5.2 Impact of Wastewater Treatment Plant (WWTP)

The WWTP in North River basin services the City of Berry (subbasin CE2). This city is located in the middle of the basin, close to Cedar Creek. Some policy makers and journalists have claimed that this WWTP discharged wastewater into the creek without proper treatment, adversely affecting the E.coli counts in the northern parts of the lake. According to information provided by ADEM through the Freedom of Information Act, the plant had no reported overflows or exceedences above the allowable levels.

The E.coli model developed for the North River basin was used to indicate the magnitude of the problem of hypothetical sewage discharge due to overflow from the plant on the water quality in Lake Tuscaloosa. Multiple precipitation events were used when conducting the analysis. This analysis, based on the model and using the best available data describing the watershed, showed minimal impact of the WWTP on the E.coli counts downstream. Even if a massive discharge event of untreated wastewater occurs, producing E.coli counts higher than have ever been recorded, the bacterial levels downstream would not reach the city’s limit. The plot in Figure 7.17 shows the
relationship between increasing levels of discharges from the plant and the levels downstream at Lake Tuscaloosa. The rain event used in this example was the 1.06 inches.

![Graph showing E.coli counts downstream at Lake Tuscaloosa](image)

Figure 7.17 Impact of WWTP subbasin on *E.coli* counts downstream at a 1.06 inch rain event.

This analysis showed that the WWTP has a negligible impact on the water quality in the lake. Recently, in early 2008, the City of Berry started implementing modifications and changes to its WWTP. The current plant is a single cell hydrograph controlled release (HCR) lagoon facility. The new proposed plant consists of an aerated single cell primary lagoon, a series of eight constructed wetlands treatment cells, a final effluent polishing pond, and an ultraviolet disinfection basin followed by cascade aeration prior to discharging the effluent into Cedar Creek.

### 7.5.3 Impact of On-site Septic Systems

The expected primary source of the *E.coli* problem in Lake Tuscaloosa near the City of Tuscaloosa was the on-site septic systems located around the lake. This was due
to their proximity to the lake. In order to protect the lake from pollution, the City passed ordinances to regulate the on-site septic systems. These ordinances require all the residents around the lake to register their on-site septic systems and to service the tanks and the related equipment (pumps) every three years. Currently, the on-site septic systems are generally operating properly, with minimal inappropriate discharges. The City’s ordinances are intended to ensure that they remain in a good condition and do not become significant pollutant source in the future.

The analysis in Chapter IV indicated that the northern part of the lake is the main contributor of *E. coli* in Lake Tuscaloosa. The largest number of houses serviced by on-site septic systems is located in the southern part, which has, according to the analysis, minimal impact on the lake’s water quality.

The City of Berry is the only city located in North River basin and north of Binion Creek that is serviced by a sewer network. There are a few scattered houses and farm houses which are miles apart that use on-site septic systems in these basins. Therefore, on-site septic systems around Lake Tuscaloosa do not contribute to the *E. coli* problem in the lake.

7.5.4 Investigating Stormwater Systems

In investigating the contribution of stormwater systems to the *E. coli* problem in the lake, it was found that these systems are not contributing to the problem. The main urban drainage areas are located in the southern part of the watershed. These areas, as indicated previously, are not a source for the current *E. coli* problem. This does not mean
there are not urban creeks that may affect the problem, but this is not the case in this study.

7.5.5 Investigating Agricultural Activities

Agricultural activities are another potential source of \textit{E.coli} in the watershed. These activities include chicken farms and feedlot operations. In order to study the impact of these activities on the \textit{E.coli} problem in the lake, the developed \textit{E.coli} model was used. The subbasins that have such activities are the ones under consideration. These subbasins are mainly located in the northern parts of the lake in North River and Binion Creek basins.

These agricultural activities contribute to the \textit{E.coli} problem through the animal’s manure. This manure, if improperly managed, can be a major \textit{E.coli} source. In order to manage the manure properly, agricultural controls need to be implemented. The different types of controls are discussed in Chapter VIII. In this discussion, the focus is to identify the levels of \textit{E.coli} that are permissible to be discharged into the nearby waterway without exceeding the allowable limit (200 cfu/100mL).

Different scenarios were tested to figure out these permissible discharges. In these scenarios, the \textit{E.coli} concentrations were replaced by various concentration values. These values were the regression analysis constant, 460 (discussed in Chapter IV); the minimum, average, and maximum readings in the basin during a given precipitation event; and the limit set by the city (200 cfu/100mL). The values were tested, and the ones that produced \textit{E.coli} levels below the city’s limit in the watershed waterways and in the lake were the city’s limit and minimum readings. In the watershed for North River basin
and Binion Creek basin, the city’s limit is the only value that reduced the \( E. coli \) concentration below the 200 limit.

Thirteen scenarios for implementing controls on chicken farms and feedlot operations (pastures) in the two basins were evaluated to measure the impact of their implementation on the water quality downstream. In these scenarios, it was assumed that the chicken houses were similar in size and magnitude. These scenarios are presented in a matrix format in Table 7.7. In the matrix, the letter P is for pasture and the CF is for chicken farm. The (%) number is the percent of that land use where controls were implemented.

Table 7.7 Matrix of Implementing Controls on Chicken Farms and Pastures Scenarios

<table>
<thead>
<tr>
<th>Land use</th>
<th>P (0%)</th>
<th>P (25%)</th>
<th>P (50%)</th>
<th>P (75%)</th>
<th>P (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF (0%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
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<tr>
<td>CF (25%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF (50%)</td>
<td></td>
<td></td>
<td>6</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>CF (75%)</td>
<td></td>
<td></td>
<td>8</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>CF (100%)</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

As an example, in scenario number (7), 50% of the chicken farms in the basin and 75% of pastures in the basin implemented controls to reduce the manure discharge into the nearby waterways.

7.5.6 Results and Analysis

7.5.6.1 North River

Implementing controls on all the sources of pollution in the basin and substituting their \( E. coli \) concentrations with the values discussed above shows that only using the 200 and minimum concentration values can achieve \( E. coli \) concentrations below 200.
cfu/100mL downstream in the streams, creeks, and the lake. This scenario is presented in Figure 7.18.

![Figure 7.18](image)

Figure 7.18 *E. coli* concentration downstream after implementing controls on all sources of pollution in the basin using the 200 and the minimum values.

The scenario for implementing controls on 50% of the chicken farms and all the pastures (scenario 5) and the scenario for implementing controls on only the pastures (scenario 2) are presented in Figure 7.19 for the 200 cfu/100mL. These scenarios are presented in Figure 7.20 for the minimum concentration value. These two plots show that only by implementing controls on both pastures and chicken farms can the water quality downstream be below the limit.
Figure 7.19 Using the 200 cfu/100mL value to replace the *E.coli* concentration for the scenarios of controlling only the pastures and controlling 50% of chicken farms and all the pastures.

Figure 7.20 Using the minimum value from each precipitation run to replace the *E.coli* concentration for the scenarios of controlling only the pastures and controlling 50% of chicken farms and all the pastures.

The scenario in Figure 7.21 presents controls implemented for only all chicken farms (scenario 3), only all pastures (scenario 2), and all pastures and chicken farms (scenario 1) using the 200 cfu/100mL level. Figure 7.22 is similar to the previous figure,
but the used values are the minimum value from each precipitation event. These two plots show similar results as the previous ones, where only by implementing controls on all the chicken farms and pastures will the water quality downstream be under the limit.

Figure 7.21 Using the 200 cfu/100mL value to replace the *E.coli* concentration for the scenarios of controlling all the pastures and for controlling all the chicken farms.

Figure 7.22 Using the minimum value from each precipitation run to replace the *E.coli* concentration for the scenarios of controlling all the pastures and for controlling all the chicken farms.
7.5.6.2 Binion Creek

Similar to North River, the only scenarios that result in achieving *E.coli* concentrations below the 200 cfu/100mL limit are implementing controls on all the chicken farms and pastures in the basin. Figure 7.23 compares the implementation, non-implementation, and partial implementation of controls in the basin.

![Figure 7.23 Using the 200 cfu/100mL value to replace the *E.coli* concentration for the scenarios of controlling the pastures and for controlling the chicken farms.](image)

7.5.7 Probability Plots for Different Scenarios Using Logistic Regression

The *E.coli* concentrations in both North River and Binion Creek are represented statistically using logistic regression. Logistic regression is a model used to predict the probability of the occurrence of an event. In this analysis, it is used to calculate the probability of the *E.coli* concentration above the 200 cfu/100mL limit for a given flow. The probability plot for no controls, controls only for chicken farms, controls for only pastures, controls for both chicken farms and pastures, and controls for only 50% of the chicken farms and pastures is presented in Figure 7.24.
Figure 7.24 Probability plot for implementation of different control scenarios in both North River and Binion Creek basins.

This figure indicates that a subbasin in either North River or Binion Creek basins has a probability of exceeding an *E. coli* count >200 in the rivers and streams of at least 0.40 (a 40% chance of exceeding the standard during any runoff event), with this probability increasing as the flow increases, especially without implementing any controls on the sources of pollution in the agricultural areas.

### 7.5.8 Percentage of Time Exceeding the Limit

The probability plot in Figure 7.24 was used to calculate the percentage of time the *E. coli* concentrations would likely exceed the limit during a typical period of rains in the adjacent rivers and streams. The probability is measured for the different controls on the plot for the same flow. The examined rain period was for the 1975 and 1976 rain events. These were chosen based on earlier evaluations of all rains from 1955 to 1986; it was found that these years had rains that were the closest to the long-term average conditions (on monthly and yearly total depth and event count basis) (Pitt and Clark
The probability for every flow event for this period exceeding the *E.coli* limit was determined and a histogram was prepared, as shown in Figure 7.25. This histogram shows that if no controls are implemented, 60% of the rain events would result in the *E.coli* levels above the limit in the rivers, streams, and the lake. If controls were implemented, then the percentage of rains exceeding the limit would be reduced to as low as 10%.

![Figure 7.25 Percentage of rains the *E.coli* levels in the lake would exceed the 200 cfu/100mL limit.](image)

### 7.6 Summary

The discussion in this chapter addresses two main aspects of the research: 1) the results and analysis of the *E.coli* model for both North River and Binion Creek (the results show that the derived model results in calculated values close to the observed values), and 2) the need to implement controls on all the agricultural activities. Every activity, whether it is a chicken farm or a feedlot operation, needs to have controls implemented to enhance the downstream water quality. The maximum discharges from these activities should be less than 200 cfu/100mL.
The WWTP in the City of Berry has a negligible impact on the downstream water quality. The main focus for reducing the *E.coli* levels in the Lake should be directed towards reducing bacteria discharges associated with the agricultural activities in the watershed. Additional monitoring throughout the watershed, especially examining other potential sources, will result in greater precision associated with the modeling activities and decision analysis process.
CHAPTER VIII

CHOOSING CONTROLS USING DECISION ANALYSIS

8.1 Introduction

Chapter III discussed the development and implementation of the EDAF. The EDAF enabled the generation of data and information that set the foundation for the analysis conducted in Chapters IV through VII. The results from these data analyses indicate that agricultural activities in North River and Binion Creek basins are the main reason behind the high levels of *E. coli* in the lake.

EDAF uses decision analysis, considering multiple and conflicting objectives in selecting the alternatives. The alternatives in this project are controls to be implemented on sites with agricultural activities.

8.2 Potential Alternatives to Control *E. coli* in Lake Tuscaloosa Watershed

8.2.1 Introduction

This section discusses the potential alternatives that can be used to control the *E. coli* problem in the Lake Tuscaloosa watershed. The main source of *E. coli* in the watershed appears to potentially be agricultural activities such as chicken farms and feedlot operations. Seventeen alternatives were initially studied. These alternatives went through an initial review phase in an attempt to narrow the range of options. This was based on comparing initial modeling results and then focusing on those that had the
greatest potential for significant benefits. The final list was reduced to seven alternatives: two alternatives control animal access to the close waterbodies, while the other five alternatives are for manure management. All of these alternatives are discussed in the coming sections.

8.2.2 Animal Access Control Alternatives to Nearby Waterbodies

In the North River basin, as seen in the pictures in Chapter IV, animals have direct access to nearby creeks and rivers. Therefore, one control alternative is to restrict animals from accessing these waterbodies. The descriptions of the control alternatives presented in the following paragraphs have been summarized from the National Management Measures to Control Nonpoint Pollution from Agriculture document published by the US EPA (US EPA 2003).

The first control alternative examined is prescribed grazing, where animals are managed and controlled within the pasture in order to keep them away from the waterbodies through fencing. The second alternative is to use buffer zones, such as a riparian forest buffer consisting of trees with brush and shrubs along the waterbody, to hinder the accessibility of the waterbodies to the animals.

In order to have a successful implementation of these alternatives, remote drinking units need to be installed at different locations within the pasture. The animals will have the alternative of staying within the boundaries of the pasture and not moving to the nearby waterbody.
8.2.3 Manure Management Alternatives

Agricultural activities in the Lake Tuscaloosa watershed may lack manure management operations. This may lead to the majority of the *E. coli* problems in the watershed. Five manure management alternatives were examined during this research: incineration, approved burial sites, waste storage structure, waste utilization (composting), and filter strip. The information about these alternatives was obtained from the EDAF. The information was categorized under each facet of the framework. The framework gave an additional layer of detail to the specifications of the alternatives. It gave information about economic, ecological and environmental, public health, education and training, regulatory, infrastructure, social and cultural, and resources facets for these alternatives.

Each one of these alternatives is discussed separately in the section below. The source for this information is from the *Measures to Control Nonpoint Pollution from Agriculture* document published by the US EPA (US EPA 2003), unless mentioned otherwise in the text. These alternatives’ characteristics are summarized in Table 8.1.

8.2.3.1 Incineration

Incineration is the process of burning animal manure waste at high temperatures in a special facility. This alternative, in terms of reducing *E. coli*, has the capability of getting rid of 100% of the pathogens. The impact on the environment from incineration is that it reduces pollutants entering the water. Additionally, it reduces the CO₂ produced into the air by 2434 CO₂ equivalent/year. A negative of this alternative is that the
nutrients in the manure are lost and they cannot be used in agriculture activities; also, there are air quality issues in terms of particulate matter emissions.

The incineration process needs to be conducted at an incineration facility. The operators for this facility need proper training in operating and controlling the input, output, and process for the incineration. Additionally, the manure needs to be transported from the sites to the incineration plant. The maximum suggested distance for hauling is around 10 miles. The manure incineration is exempted from air quality emissions under the Other Solid Waste Incineration (OSWI) (US EPA 2007). The cost to incinerate the manure is around $10/ton of waste for the farmer. The incineration plant can generate revenue by selling electricity back to the grid for around 4.5-7.5 cents/ kWh, where each ton of manure generates 35 kWh.

8.2.3.2 Approved Burial Sites

Approved burial sites are onsite or offsite landfills for the manure. This alternative has the capability to reduce around 100% of the E.coli bacteria. The impact on the environment from burial sites is that it reduces pollutants going into the surface waters. The nutrients in the manure are lost and they cannot be used in agricultural activities. It may also be a potential groundwater pollutant if the burial site was not designed and constructed properly.

The burial sites, whether onsite or offsite, need special preparation to receive and contain the manure. These sites need to be operated and managed properly. If they are not, then the problem is transferred from one place to another. If the sites are located offsite, the hauling distance restriction applies.
The burial sites need to be located in areas far away from residential areas and not upwind. The sites should be on impermeable soils, far above the water table, and not located in the 100-year flood zone. The cost to bury the manure is around $10.80/ton of manure. This cost is paid by the farmer to the burial site.

8.2.3.3 Waste Storage Structures

A waste storage structure is a fabricated structure that temporarily stores the animal waste. This alternative has the capability to reduce E.coli pathogens by 90%. The impact on the environment from storing it reduces nutrients around 60% for nitrogen, 65% for phosphorus, and 70% for sediment. This alternative needs a special structure to store the manure. The structure needs to have impermeable flooring, and this can be achieved by placing concrete slabs or synthetic layers. The initial and operating costs are low, around $3/ton of manure. There is a loss value from not using the waste, especially the nutrients.

8.2.3.4 Composting

Composting is a type of waste utilization where the manure is treated by being naturally heated before redistributing it on fields. The compost improves the soil condition and positively affects the quality of the field products. Composting is capable of reducing 100% of the E.coli bacteria. The benefit of composting to the environment is that it adds some of the nutrients back to the environment. Composting reduces phosphorus by 90%, nitrogen by 80%, and sediments by 60%. Waterbodies close to the
fields that apply composting need to be protected from the runoff. Additionally, composting reduces the amount of CO\textsubscript{2} released into the air by 8291 CO\textsubscript{2} equivalent/year.

The manure can be composted at an onsite or offsite facilities. If composted at an offsite facility, the maximum hauling distance is around 10 miles. The composted manure can only be applied to actively growing crops and on lands with filter strips and buffer zones. It cannot be applied during a rainy period or when wind is blowing towards neighbors. The cost of the facility to compost the manure is around $8.5/ton, but it can be resold for $30-35/ton. This revenue can be an advantage for the land owners.

\textit{8.2.3.5 Filter Strips}

Filter strips are vegetated areas that are intended to reduce pollutants during sheet flow (flow over land where there are no defined channels) before flowing into the closest waterbody. Filter strips are capable of reducing around 55\% of \textit{E.coli} in the runoff, but this number is variable and depends on the site conditions. Filter strips can reduce nitrogen around 70\% (Dillaha et al. 1989; Lee et al. 2000), phosphorus by 80\%, and sediments by 60\%.

These filter strips, if not constructed or maintained properly, may become breeding grounds for mosquitoes. Filter strips should be constructed on slopes between 2\% to 6\%. Additionally, the soil should have high clay content. The cost to construct and maintain these filters is around $37.5/ton of manure.
Table 8.1 Summary of the Characteristics of Manure Management Alternatives

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
<th>Public Health</th>
<th>Economic</th>
<th>Environment &amp; Ecology</th>
<th>Education &amp; Training</th>
<th>Ancillary Infrastructure</th>
<th>Regulatory</th>
<th>Social &amp; Cultural</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Incineration</td>
<td>Burning animal waste at high temperatures</td>
<td>100% reduction in E.coli</td>
<td>Cost: $10/ton of manure</td>
<td>Pollutants do not enter the water.</td>
<td>Incinerator operation</td>
<td>Must transport waste to public incinerator</td>
<td>Most likely exempt from OSWI regulations Hauling should be within 10 mile radius</td>
<td>Smoke and smell free</td>
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<tr>
<td></td>
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<td>7.5 cents per kWh</td>
<td>Reduces the CO₂ emissions by 2434 CO₂ equivalent per year</td>
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<tr>
<td>2 Approved Burial Sites</td>
<td>On site or off site landfill.</td>
<td>100% reduction in E.coli</td>
<td>Cost: $10.8/ton of manure</td>
<td>May affect water quality and nitrate concentration in the area.</td>
<td>Operation of burial site</td>
<td>Transportation to off site landfill. Prepare the site to receive such waste</td>
<td>Do not use on sites with permeable soils, fractured bedrock or a high seasonal water table, or in a 100-year flood plain. Hauling should be within 10 mile radius</td>
<td>Not close to residential areas due to odors</td>
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<tr>
<td>3 Waste Storage Structure</td>
<td>A fabricated structure for temporary storage of animal wastes</td>
<td>90% reduction in E.coli</td>
<td>Cost: $3/ton of manure</td>
<td>Reduction: 60% Phosphorus, 65% Nitrogen, 70% Sediment</td>
<td>Operation and maintenance of burial site</td>
<td>May require earth compaction, imported clay, synthetic impermeable layers, or concrete</td>
<td>200 ft from natural water courses and lakes, 100 ft from milking parlor, 100 ft from drainage ditches</td>
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<tr>
<td>4 Waste Utilization/ Composting</td>
<td>Using animal wastes on land in an environmentally acceptable manner while maintaining or improving soil and plant resources after being composted</td>
<td>100% reduction if treated properly</td>
<td>Cost: $8.5/ton of manure</td>
<td>Adding nutrients from natural resources to agriculture practices. Nearby water resources need to be protected. Reduction: 90% Phosphorus, 80% Nitrogen, 60% Sediment Reduces CO₂ emissions by 8291 CO₂ equivalent per year</td>
<td>If use onsite composting facility training is needed for operation and maintenance</td>
<td>To have proper composting and hauling facilities</td>
<td>Cannot be applied in rain, only applied on actively growing crops, not on weekends, not when wind is blowing towards neighbors, only on land with filter strips, buffer zones, etc.</td>
<td>If properly composted, the manure has no bad odor</td>
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<tr>
<td>5 Filter Strip</td>
<td>Vegetated areas that are intended to treat sheet flow from an adjacent area.</td>
<td>55% reduction in E.coli</td>
<td>Cost: $37.5/ton of manure</td>
<td>Reduction: 85% Phosphorus, NA% Nitrogen, 60% Sediment If not constructed properly, it becomes a breeding ground for mosquitos.</td>
<td>Only use on slopes between 2 and 6%. Soil should have a high clay content. Requires mowing and sediment removal, as well as annual inspections.</td>
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</tr>
</tbody>
</table>
8.3 A Step-by-Step Approach for Selecting Controls

In this section, the procedure for comparing and selecting the controls according to multiobjective decision making is discussed using hypothetical, but reasonable, data based on the previously described modeling analyses and interviews of the stakeholders. The procedure in this discussion follows the paper written by Pitt and Voorhees (2007), which is based on Keeney and Raiffa (1976). The theory was discussed in Chapter II.

The objectives were developed using the EDAF, and these objectives are listed in Chapter III. Many objectives are developed from the stakeholder interviews. In this discussion, only a few objectives are considered: minimizing the threats to public health, minimizing the discharge of pollutants into the water, and minimizing the cost on the stakeholders.

The utility curves are based on the data and information provided and should not be affected by external personal factors. The tradeoffs, on the other hand, are affected by these personal factors, needs, and concerns. The tradeoffs for the different stakeholders are hypothetical and are for the purpose of illustrating the process for choosing controls to reduce *E. coli* concentration.

In this research, the example is hypothetical in terms of developing the tradeoffs. The utility curves are usually developed by experts in the field. The developed curves can be used for similar projects. The tradeoffs are developed by all stakeholders taking part in the project. These tradeoffs are project-dependent. This example is to illustrate the step-by-step procedure. Even though the tradeoffs are hypothetical, they are reasonable assumptions of what is expected from the stakeholders.
This decision analysis method can incorporate uncertainty in the analysis by using Monte Carlo and developing probability plots for the different variables. In this example, the values were all based on weight of evidence, and the level of uncertainty here does not have an impact on the results. Additionally, from the previously conducted analysis on the flow model and the \textit{E.coli} models, the number of data points was not high enough for the uncertainty analysis but was sufficient to show the joint correlation between the different parameters.

The first step in the decision analysis process is to identify the control alternatives and their characteristics, as presented in Table 8.1. The second step is to present the resultant values for each objective associated with each alternative after running the models for the watershed. This is presented in Table 8.2. The negative sign in the air pollution column indicates reductions in emissions compared to current practices, and the negative in the cost column indicates income associated with the practice.

Table 8.2 Values of the Objectives for Manure Management Alternatives

<table>
<thead>
<tr>
<th>Facets</th>
<th>Public Health(^1)</th>
<th>Environment</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>\textit{E.coli}</td>
<td>P</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Alternatives</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Incineration</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2 Burial Sites</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3 Waste Storage</td>
<td>90</td>
<td>60</td>
<td>65</td>
</tr>
<tr>
<td>4 Composting</td>
<td>100</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>5 Filter Strip</td>
<td>55</td>
<td>85</td>
<td>70</td>
</tr>
</tbody>
</table>

\(^1\) These are reductions in the percentages of rain events that exceed the \textit{E.coli} objectives in the lake, based on the watershed modeling.

The Table 8.2 values are summarized according to each facet and related objectives in terms of the units of measure and the range of operational values presented as best and worst outcomes. This information is presented in Table 8.3.
Table 8.3 Alternatives’ Facets and Their Objectives, Units of Measure and Ranges

<table>
<thead>
<tr>
<th>Facet</th>
<th>Measure</th>
<th>Units</th>
<th>Best</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Health</td>
<td>E.coli</td>
<td>%</td>
<td>100</td>
<td>55</td>
</tr>
<tr>
<td>Environment and Ecology</td>
<td>Phosphorus (P)</td>
<td>%</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Nitrogen (N)</td>
<td>%</td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Sediment</td>
<td>%</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Air Pollution</td>
<td>CO₂ eq/yr</td>
<td></td>
<td>-8291</td>
<td>0</td>
</tr>
<tr>
<td>Economic</td>
<td>Cost</td>
<td>$/ton</td>
<td>-24</td>
<td>37.5</td>
</tr>
</tbody>
</table>

The third step is developing utility curves for each objective. The utility curves represent the approach of the decision makers towards risk. The main concerns in developing the utility curves are identifying the upper, lower, and middle points of the curve. Afterwards, the shape of the curve is determined through the knowledge of the objective. The best utility is assigned a 1.0 (the least cost), while the worst utility is assigned a 0.0 (the highest cost).

For example, the utility curve for reducing the E.coli objective has the 55% and below values set to zero and the 100% value set to 1. The middle point of the curve was set to be the actual middle point between 100 and 55 (77.5). The 50-50 middle point was not set due to uncertainty in the outcome. The curve was set to be linear or Risk Neutral. The same procedure was conducted for the rest of the objectives. Their utility curves are shown in Figures 8.1 through 8.6. It is important to note that in the air pollution and in the cost utility curves, there are negative values indicating reductions and revenue, respectively.
Figure 8.1 Reducing *E.coli* utility curve.

Figure 8.2 Reducing phosphorus (P) utility curve.
Figure 8.3 Reducing nitrogen (N) utility curve.

Figure 8.4 Reducing sediment utility curve.
The fourth step is to establish the tradeoffs between the objectives for each group of stakeholders. This step needed the direct input of the stakeholders. Various hypothetical tradeoff scenarios have been developed for stakeholders in this project. The stakeholders were the public, the environmental group, and farmers. The stakeholders rank the objectives from the most to the least important. The first group to start with is
the public that uses the lake for recreation purposes. The public’s ranked objectives are
presented in Table 8.4. The public was mainly interested in only the \textit{E.coli} and cost
objectives.

Table 8.4 Public Objectives Ranking

<table>
<thead>
<tr>
<th>Objective</th>
<th>Rank</th>
<th>Tradeoff Constant (k_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{E.coli}</td>
<td>1</td>
<td>k1</td>
</tr>
<tr>
<td>Cost</td>
<td>2</td>
<td>k2</td>
</tr>
<tr>
<td>N</td>
<td>3</td>
<td>k3</td>
</tr>
<tr>
<td>Air pollution</td>
<td>4</td>
<td>k4</td>
</tr>
<tr>
<td>Sediment</td>
<td>5</td>
<td>k5</td>
</tr>
<tr>
<td>P</td>
<td>6</td>
<td>k6</td>
</tr>
</tbody>
</table>

After ranking the objectives, the tradeoffs between them (the sum of the tradeoffs
must equal 1.0) are determined by paring the objectives (worst, best) and comparing with
(?, worst). The (?) or unknown value for that objective was established when the
stakeholder reached a point of indifference (\equiv) between the two pairs of values. The
common comparison parameter between the objectives in the tradeoffs was the cost ($).
The first tradeoff was between the \textit{E.coli} and cost. The compared values were (55\%, -
$24) \equiv (?)$, $37.5$. The (?) value was assumed to be 80\%. The results from the rest of the
runs are summarized below.

Public Health, Cost: (55\%, -$24) \equiv (80\%, $37.5)

Cost, N: ($37.5, 100\%) \equiv ($37.5, 65\%)

Cost, Sediment: ($37.5, 100\%) \equiv ($37.5, 60\%)

Cost, Air pollution: ($37.5, -8291) \equiv ($37.5, 0)

Cost, P: ($37.5, 100\%) \equiv ($37.5, 60\%)
This information was used to establish the multiobjective utility function. The function was discussed in Chapter III and the equation is presented below.

\[ u(x_1, x_2, x_3, x_4, x_n) = \sum_{i=1}^{n} k_i v_i(x_i) \]

The tradeoff constant \((k_i)\) is calculated based on the individual objective utility functions and the indifference points for the pairs of objectives.

\[ \frac{k1}{k2} = u(80\%) = 0.6 \]

\[ \frac{k3}{k2} = u(37.5) = 0.0 \]

\[ \frac{k4}{k2} = u(37.5) = 0.0 \]

\[ \frac{k5}{k2} = u(37.5) = 0.0 \]

\[ \frac{k6}{k2} = u(37.5) = 0.0 \]

\[ \frac{k2}{k2} = 1.0 \]

Using the multiobjective equation and solving for \(k2\):

\[ \sum_{i=1}^{5} ki = (1.0 + 1.67 + 0 + 0 + 0)k2 = 1. \]

\(k2 = 0.37\) for the cost. This value is substituted in the above equations for the different \(k_s\).

The \(k1 = 0.63\) for the \(E.coli\). The rest of the \(k_s\) are 0. This is because the public had indifferent values for the environment and ecology objectives equal to the worst.

The fifth step is to assign the utility values for each objective for every control alternative examined. These values are presented in Table 8.5.
Table 8.5 Utility Values for the Related Objectives for Every Control Alternative

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Objectives</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E. coli</td>
<td>Cost</td>
<td>P</td>
<td>N</td>
<td>Sediment</td>
<td>Air pollution</td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>1.00</td>
<td>0.48</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Burial Sites</td>
<td>1.00</td>
<td>0.47</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Waste Storage</td>
<td>0.77</td>
<td>0.55</td>
<td>0.00</td>
<td>0.00</td>
<td>0.25</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Composting</td>
<td>1.00</td>
<td>1.00</td>
<td>0.75</td>
<td>0.49</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Filter Strip</td>
<td>0.00</td>
<td>0.40</td>
<td>0.55</td>
<td>0.15</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

The sixth step is to calculate the utility for every alternative. This is conducted by using the multiobjective utility function equation. The utility value for the objective for an alternative is multiplied by the relative k value for that objective. For example, the incineration alternative utility value is calculated as follows.

Utility = (1)(0.63) + (0.48)(0.37) + (1)(0) + (1)(0) + (1)(0) + (0.3)(0)

= 0.81

These alternatives’ utility values are presented in Table 8.6.

Table 8.6 Utility for Each Alternative

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composting</td>
<td>1.00</td>
</tr>
<tr>
<td>Incineration</td>
<td>0.81</td>
</tr>
<tr>
<td>Burial Sites</td>
<td>0.80</td>
</tr>
<tr>
<td>Waste Storage</td>
<td>0.69</td>
</tr>
<tr>
<td>Filter Strip</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Finally, hypothetically the most preferred alternative is the one with the highest utility. In this example the composting alternative had the highest utility value, followed by incineration and burial sites that were basically tied. Waste storage and filter strips had the least desirability.

The second group to have tradeoff analysis is the environmental watchdog group. This group has its main concerns as the environment and protecting the water
quality and the ecological system. The environmental group’s ranked objectives are presented in Table 8.7

<table>
<thead>
<tr>
<th>Objective</th>
<th>Rank</th>
<th>Tradeoff Constant ($k_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1</td>
<td>$k_1$</td>
</tr>
<tr>
<td>P</td>
<td>2</td>
<td>$k_2$</td>
</tr>
<tr>
<td>Sediment</td>
<td>3</td>
<td>$k_3$</td>
</tr>
<tr>
<td>E.coli</td>
<td>4</td>
<td>$k_4$</td>
</tr>
<tr>
<td>Air pollution</td>
<td>5</td>
<td>$k_5$</td>
</tr>
<tr>
<td>Cost</td>
<td>6</td>
<td>$k_6$</td>
</tr>
</tbody>
</table>

The tradeoff parings between the objectives is presented below, and the common comparison parameter between the objectives in the tradeoffs was the cost ($).

N, cost: (65%, -$24) ≡ (95%, $37.5)

Cost, P: ($37.5, 100%) ≡ ($5, 60%)

Cost, sediment: ($37.5, 100%) ≡ ($5, 60%)

Cost, E.coli: ($37.5, 100%) ≡ ($10, 55%)

Cost, air pollution: ($37.5, -8291) ≡ ($5, 0)

The calculated $k$ values for the objectives are presented in Table 30.

<table>
<thead>
<tr>
<th>$k_i$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$</td>
<td>0.27</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.13</td>
</tr>
<tr>
<td>$k_3$</td>
<td>0.13</td>
</tr>
<tr>
<td>$k_4$</td>
<td>0.11</td>
</tr>
<tr>
<td>$k_5$</td>
<td>0.13</td>
</tr>
<tr>
<td>$k_6$</td>
<td>0.23</td>
</tr>
</tbody>
</table>

After doing the calculations for the utility values for the different alternatives, the results are presented in Table 8.9.
Table 8.9 Utility for Each Alternative for Citizen Environmental Groups

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incineration</td>
<td>0.77</td>
</tr>
<tr>
<td>Burial Sites</td>
<td>0.73</td>
</tr>
<tr>
<td>Composting</td>
<td>0.70</td>
</tr>
<tr>
<td>Waste Storage</td>
<td>0.24</td>
</tr>
<tr>
<td>Filter Strip</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Hypothetically, the highest three utility values was first the incineration alternative followed by the burial sites and then composting. Waste storage and filter strips had the least desirability.

The third group is the farmers. This group has its main concern as implementing the control and staying in business. The farmers hypothetically ranked the objectives as presented in Table 8.10.

Table 8.10 Farmers Objectives Ranking

<table>
<thead>
<tr>
<th>Objective</th>
<th>Rank</th>
<th>Tradeoff Constant (k_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>1</td>
<td>k1</td>
</tr>
<tr>
<td>P. E.coli</td>
<td>2</td>
<td>k2</td>
</tr>
<tr>
<td>N</td>
<td>3</td>
<td>k3</td>
</tr>
<tr>
<td>Air pollution</td>
<td>4</td>
<td>k4</td>
</tr>
<tr>
<td>Sediment</td>
<td>5</td>
<td>k5</td>
</tr>
<tr>
<td>P</td>
<td>6</td>
<td>k6</td>
</tr>
</tbody>
</table>

The tradeoffs paring between the objectives is presented below, and the common comparison parameter between the objectives in the tradeoffs was the cost ($).

Public health, cost: (55%, -$24) ≡ (80%, $37.5)

Cost, N: ($37.5, 100%) ≡ ($3, 65%)

Cost, sediment: ($37.5, 100%) ≡ ($6.75, 60%)

Cost, air pollution: ($37.5, -8291) ≡ ($3, 0)
Cost, $P: (\$37.5, 100\%) \equiv (\$6.75, 60\%)

The calculated $k$ values for the objectives are presented in Table 8.11.

Table 8.11 The Calculated $k$ Values for Farmers

<table>
<thead>
<tr>
<th>$K_i$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$</td>
<td>0.27</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.16</td>
</tr>
<tr>
<td>$k_3$</td>
<td>0.15</td>
</tr>
<tr>
<td>$k_4$</td>
<td>0.15</td>
</tr>
<tr>
<td>$k_5$</td>
<td>0.14</td>
</tr>
<tr>
<td>$k_6$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

After doing the calculations for the utility values for the different alternatives, the results are presented in Table 8.12.

Table 8.12 Utility for Each Alternative for Farmers

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incineration</td>
<td>0.76</td>
</tr>
<tr>
<td>Burial Sites</td>
<td>0.72</td>
</tr>
<tr>
<td>Waste Storage</td>
<td>0.31</td>
</tr>
<tr>
<td>Composting</td>
<td>0.76</td>
</tr>
<tr>
<td>Filter Strip</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The highest utility value was for the incineration followed by composting and then the burial sites. The waste storage and the filter strip had the least desirability.

In the last three examples, the incineration, composting, and burial sites alternatives had the highest utility values. These are the alternatives that need to be considered by the stakeholders to achieve the objectives.

8.4 Summary

This chapter discussed the selection of alternatives using the EDAF and multiobjective decision analysis. The set of control alternatives under consideration were
chosen for agricultural activities. The analysis of the alternative controls to reduce the
impacts of discharges on the *E.coli* levels in the lake also examined a variety of other
worthwhile objectives, such as CO₂ emissions, nutrient discharges, and costs. There are
several control alternatives that could benefit many of the stakeholders. For example,
selecting manure composting as a control would not only reduce *E.coli* and other
pollutants, but could also become a source of possible revenue for the farmers.

The development of utility curves and tradeoff analyses was also discussed. Even
though they were based on hypothetical scenarios, they assisted in developing an
understanding of dealing with multiple stakeholders. It also gave an indication of what
may or may not be accomplished by these controls.
CHAPTER IX

CONCLUSIONS, DISCUSSION,
RECOMMENDATIONS, AND FUTURE RESEARCH

9.1 Introduction

The successful completion of this research has incorporated many disciplines such as engineering hydraulics and hydrology, fate and transport of pollutants, decision making and analysis, management information systems, geographic information systems, statistics, and systems modeling. All of these combined disciplines have assisted in developing and implementing the framework used in this research for an important water quality problem in West Alabama, the *E.coli* contamination in Lake Tuscaloosa.

The following discussion presents the closing summary of this research dissertation. The conclusions for this dissertation are discussed in relation to its goal, hypothesis, and related objectives. The discussions include the modifications on the EDAF and flow and *E.coli* models throughout this research. The recommendations are presented for decision makers to prepare a comprehensive watershed management plan. Finally, suggestions for future research work are presented.
9.2 Conclusions

9.2.1 Dissertation Goal and Related Objectives

The goal of the dissertation was to explore the use of an Environmental Decision Analysis Framework to inform and extend the evaluation of management practices to protect Lake Tuscaloosa. In accordance with this goal, the framework helped in identifying the stakeholders in the project and their role in it. These stakeholders provided data and information about the problem in addition to identifying their needs and concerns according to the facets of the methodology. The analysis of the data and information helped in identifying sources of *E. coli* in the watershed. It directed attention to new sources of nonpoint pollution, such as agricultural activities.

9.2.1.1 Goal Objective #1

The first goal objective of this study was stated as follows: enhance environmental management methods to better address the issues that cause projects to fail. This objective was addressed in both Chapters II and III. In Chapter II, the background for this objective was discussed. The background identified the reasons behind the failure of water, wastewater, or stormwater projects. These reasons for failure, such as the unavailability of supporting infrastructure, social and cultural issues, and inadequate or non-existing policies, became reasons for projects’ success when included in the early stages of the analysis. This ensures they are incorporated into the decision-making process. This inclusion was described in the EDAF in Chapter III. The framework organized these different reasons and identified their integration at the various stages of the project.
These reasons for success were also verified with the stakeholders during interviews. All the stakeholders agreed that including these reasons assisted them in considering other factors that were not previously included in the decision making.

9.2.1.2 Goal Objective #2

The second goal objective was stated as follows: calculate the potential benefit of implementing control practices on the Lake Tuscaloosa *E.coli* counts. This objective was covered in Chapters VII and VIII. In Chapter VII, the effect of implementing controls on the *E.coli counts* downstream was studied and analyzed. The results showed that implementing controls on the identified sources of pollution reduced the *E.coli counts* below the city’s limit. The various control alternatives were identified and discussed in Chapter VIII. These potential controls were chosen according to their capability to significantly impact the *E.coli* levels in the lake and in the watershed at large.

9.2.1.3 Goal Objective #3

The third goal objective was stated as follows: develop utility curves relating the possible range of outcomes for each control practice alternative and determine the utility value associated with each option. The theory behind the utility curves was discussed in Chapter II. The development of the utility curves for the various control alternatives was discussed in Chapter VIII. Chapter VIII also discussed the characteristics of these alternatives and their range of outcomes relating to the framework’s facets. This collected information assisted in developing the utility curves.
9.2.2 Dissertation Hypothesis and Related Objectives

The dissertation hypothesis stated: an appropriate environmental decision analysis framework, based on multiobjective decision analysis theory, can be an effective analytical/management tool, even on projects characterized by limited or incomplete data. This tool can also address a variety of stakeholders’ conflicting objectives. Moreover, the framework can be used on projects that are politically volatile, as each step is well documented and stakeholder input is used at various critical steps in the process, allowing for robust outcome(s).

The hypothesis was tested throughout the various stages of this research. The detailed tests and results are demonstrated in the related hypothesis objectives and are discussed below. The hypothesis used decision analysis theory to correlate the objectives of the stakeholders and the alternatives that were identified from the developed models. The utility curves and trade-offs were used to calculate the utility values using multiobjective utility function.

The null hypothesis stated that the EDAF will not provide additional insight and will not identify potential solutions any more useful than what the current studies have shown. The results obtained from this research reject the null hypothesis. The framework was able to provide additional insight and information about the E.coli problem in Lake Tuscaloosa. It also identified potential solutions that targeted the sources of pollution that the current studies could not discover.

The current studies were targeting effluents from on-site septic systems and wastewater treatment plants. The data analysis along with the watershed flow and E.coli modeling indicated that agricultural activities are likely responsible for the high E.coli
levels found in the northern parts of the Lake. Additionally, the poor sanitary infrastructure systems that leads to occasional SSOs, along with agricultural activities in Carroll’s Creek basin are likely responsible for the high *E.coli* levels in that particular area.

**9.2.2.1 Hypothesis Objective #1**

The first hypothesis objective stated that: use of the Environmental Data Analysis Framework (EDAF) to organizes the collected data in a useful scheme that addresses the conflicting objectives of the different stakeholders and ranks the most likely successful management alternatives.

This objective was discussed in Chapters III and VIII. Chapter III includes discussion about the framework and its implementation on the *E.coli* problem. The method of conducting the interviews and managing the information was illustrated. In Chapter VIII, the framework was used to organize information about the different alternatives. This organization of information assisted in the decision analysis process in ranking and choosing the management alternatives most likely to be successful.

**9.2.2.2 Hypothesis Objective #2**

The second hypothesis objective stated that: the framework can be implemented on a project characterized by limited/incomplete data that has high public interest (the *E.coli* problem in Lake Tuscaloosa). This objective had four sub-objectives. These sub-objectives are discussed further below.
This objective was discussed in many chapters throughout this dissertation. The *E.coli* problem in the watershed is considered one of the highest priorities for the City of Tuscaloosa. The lake is the major drinking water source for the city and the region. It is also considered a focal point for commercial, industrial, and residential developers and the general public for recreational activities. The lake is part of a watershed that is governed by multiple jurisdictions of cities and counties. This has reduced the quantity and quality of data obtained about the watershed and the *E.coli* problem over the years.

The framework was implemented on this important problem in order to assist in understanding its complexities and in choosing potential alternatives.

The results obtained from implementing the framework on the project were sound. Based on the stakeholder groups and multiple facets, the framework was capable of obtaining the information and objectives that were used for problem analysis and choosing alternatives.

The framework increased the number of stakeholder groups from a handful up to 16 groups. The number of facets included in the decision-making process increased from 4 to 8. The framework linked and prioritized the objectives according to the stakeholders’ needs. It also utilized utility curves to evaluate conflicting objectives.

Sub-objective #1

The 1st sub-objective was to analyze the available *E.coli* data for the watershed to identify locations, seasons, and flows associated with different *E.coli* levels in the waterbodies.
This objective was discussed in Chapter IV. The statistical tests used in analyzing the various types of data are the One-Way ANOVA, with an $\alpha$ value of 0.05, step wise and logistic regression analysis, and factorial design. Based on the analysis of the City’s and GSA’s data, there is a directly proportional correlation between precipitation and $E.\text{coli}$ levels, especially at the northern parts of the lake. The One-Way ANOVA test gave a p-value <0.05 on a 95% confidence interval, which meant that the values were significant.

The seasonal $E.\text{coli}$ analysis of the City’s data, using a factorial design, showed that during cold weather the $E.\text{coli}$ counts were above the limit. After comparing the $E.\text{coli}$ levels with rain data, it was determined that the main reason for these differences is that the majority of the City’s samples collected during cold weather were on or directly after rain events. Therefore, this increased the chances of having high $E.\text{coli}$ counts. On the other hand, during warm weather, the majority of the samples were collected during dry periods and not after rain events. Hence, the collection methods of the samples had an effect on the counts.

The analysis of the GSA data, alone, and its incorporation into the City’s data, (even though it was not significant), showed that the warm season had higher $E.\text{coli}$ counts than the cold season. Generally, once there is a precipitation event over the watershed, the $E.\text{coli}$ counts increase. It is mainly an on or off phenomenon. If there is a precipitation event, then there are high $E.\text{coli}$ counts, and the opposite is true unless there is a specific incident that causes the discharge of pathogens into the water. Therefore, more data needs to be collected and analyzed to study the impact of season on the $E.\text{coli}$ counts.
The location analysis, using a factorial design, of both the City’s data alone as well as the GSA and City’s data combined, was used to determine the areas that contribute to the high *E. coli* levels in the lake. This indicated that the upper areas of the watershed are the main sources of *E. coli*.

The regression modeling of the data, used to identify the land uses that are contributing to the high levels of *E. coli*, indicated that agricultural land use is the main contributor of *E. coli* discharges. The p-value of the agricultural practices, feedlot operations and chicken farm houses, was <0.05 with a 95% confidence interval. This indicated that the values were significant.

Sub-objective #2

The 2nd sub-objective was to identify the likely activities that contribute to high *E. coli* levels in the watershed.

This objective was discussed in Chapters IV and VII. The analysis and modeling results from these chapters have identified the activities contributing to the *E. coli* problem in the watershed. The analysis indicated that nonpoint sources are responsible for the *E. coli* problem in the lake and in the watershed at large. The main nonpoint sources are agricultural activities in the watershed, such as chicken farms and feedlot operations. These activities do not have proper management measures in place to deal with manure on their sites. Another source, which mainly depends on the infrastructure condition in the area, is the SSOs in the Carroll’s Creek basin. There were reports of wastewater infrastructure failure close to the residential areas that caused the sanitary wastewater to flow into the nearby creek.
Additionally, there was no evidence in the data and information provided that there was contribution from other sources around the lake (on-site septic systems) or up in the watershed (wastewater treatment plant). Therefore, continuous monitoring of the water quality around the lake and in the watershed is important to sustain the water quality in the lake.

Sub-objective #3

The 3rd sub-objective was to develop a calibrated hydrology/hydraulic model for the watershed to quantify variations in seasonal flows from different parts of the watershed and to determine travel times from these different areas to the Lake.

This objective was discussed in Chapter V and Appendix D, with the development of the hydraulic model in Appendix D and the results and their analysis in Chapter V. The results from the calibrated flow model during the period of study showed that the calculated results are reasonably close to the observed readings at the point of reference. The One-Way ANOVA test for the calculated values for North River and Binion Creek had a p-value <0.05. This indicated that, with a 95% confidence level, the values were significant.

Although these calculated and observed values were similar at the locations having historical data, this does not imply that the calculated values at other subbasins in the watershed are as close to the observed values at those points of reference. This is mainly due to the uncertainty in the parameters and the unavailability of historical flow readings throughout the basins. Since only a few locations with historical observations
were available to verify the model, it is recommended that additional data be collected at other locations, to increase confidence in the modeling results.

Sub-objective #4

The 4th sub-objective was to develop and calibrate a fate and transport model for the *E. coli* bacteria in the watershed for these potential source locations.

This objective was discussed in Chapters VI and VII. In Chapter VI, the development of the model was discussed, and in Chapter VII, the analysis and the results were discussed. The calibrated *E. coli* model for the period of study showed that the calculated results were reasonably close to the observed readings downstream and were also close to the GSA’s readings at the mouth of the subbasins in the watershed. Even though the calculated and observed values were close, the One-Way ANOVA test for both North River and Binion Creek data had a p-value >0.05 (0.37 and 0.17 respectively) with a 95% confidence level. This indicates that more data needs to be collected at different locations, especially ones close to the contributing sources. This would increase the confidence of the modeling.

9.3 Improvements on Framework and Models throughout the Research

9.3.1 EDAF

The use of the framework began by identifying the different components necessary to choose robust and sustainable alternatives. Afterwards, these components were arranged according to the flow of information. For example, the list of stakeholders
originally only included a hand full of stakeholder categories. This was improved by using the alignment method that enhanced the list of stakeholders for this project.

Another example of framework improvement was the removal of the DEMONS$^2$. This abbreviation represents dependability, efficiency, maintainability, occupation, neglect, safety, and security. The components of this acronym expand on the objectives that were developed from the facets of the framework. After a couple of iterations and in order to make the framework workable and to reduce complexity, these parameters were excluded.

9.3.2 Flow and E.coli

Both the flow and *E.coli* models in this research went through multiple iterations and improvements to reduce the error in the results. This was conducted by calibrating the different parameters. The calibration was conducted, for example, by sensitivity analysis for the parameter, obtaining further information, and by using internal calibration from the software itself. The parameters, after calibration, were able to produce results that are close to the observed values.

9.4 Challenges

There were many challenges in this research, both for the framework and for the flow and *E.coli* models. Some of the challenges for the framework were identifying the stakeholders and being able to meet with them. The ability to obtain data and information from private and public sector agencies was essential to this study; however, many of the
requests for data had to go through multiple channels, and sometimes these attempts were not successful.

The development of the flow model was challenging in terms of identifying the values of the parameters to be incorporated in the model, such as land use and base flow. The incorporated data for the parameters were inserted using the best available knowledge of that parameter in the subbasin. The other parameters had to be modified according to the sensitivity of the results to these parameters. Still other parameters were fixed and could not be modified due to the unavailability of data. For example, there is only one precipitation gauge close to the watershed, and it is located at the Tuscaloosa airport, which is located outside the watershed. Additionally, there is only one flow gauge for the entire North River basin, which represents more than 50% of the size of the watershed.

Similar to the flow model, the development of the bacteria fate and transport model used in this dissertation was challenging due to limited data and information about the watershed and its inherent variability. There was uncertainty in the parameters, such as the coefficients of the land use and in the decay rate of \textit{E.coli}. There is also the uncertainty that was transferred with flow. In the model, the uncertain values were modified according to the sensitivity of the values downstream.

\textbf{9.5 Recommendations to Develop a Comprehensive Watershed Management Plan for the Lake Tuscaloosa Watershed}\n
Throughout this research, the data availability and limitations for the Lake Tuscaloosa watershed hindered the analyses. In terms of water quality, some locations in
the watershed had continuous historical data, mainly around the lake, and other locations did not. This is attributable to the city’s jurisdiction and its inability to work in the entire watershed. In terms of flow data and precipitation gauges, the watershed at large lacked this important data. This research has covered a wide spectrum of issues associated with the watershed in terms of water quality and quantity. Recommendations for the city that may help in protecting the watershed at large and the lake are discussed in this section.

9.5.1 On-site Septic Systems

The City of Tuscaloosa issued an ordinance to register all the on-site septic systems in its jurisdiction. According to the available data, it was found in this research that the on-site septic systems were currently not a significant contributing source to the \( E. coli \) problem in the lake. In order to sustain the integrity and safe operation of these septic systems, they should be monitored and maintained periodically. It is important for these systems to continue to operate under the current safe conditions, because if a widespread failure occurs, a significant negative impact on the lake’s water quality may occur.

9.5.2 Monitoring and Rehabilitating the Infrastructure

Infrastructure deterioration of wastewater collection systems is a contributor to the \( E. coli \) problem, especially at Carroll’s Creek (discussed in Chapter IV). The infrastructure at these areas needs continuous monitoring and evaluation to implement changes that reduce discharges and impact on the water quality downstream. If the infrastructure demonstrates that it needs replacement or rehabilitation, then such
improvements should be a priority for the decision makers because of the high pollution risk downstream.

9.5.3 Flow and Precipitation Gauges

The Lake Tuscaloosa watershed study was limited by the lack of information about flow and precipitation. There should be rain gauges distributed throughout the watershed. The location of these gauges should be at the northern, middle, southern, eastern, and western parts of the watershed. There should be flow gauges distributed at key locations in the watershed.

The entire North River basin is covered by one flow gauge. Since there are many creeks and streams flowing into it, there should be a flow gauge at every major connection to the main stem of the river. These gauges should be placed evenly throughout the watershed at one third and two thirds the distance from the existing gauge to the upper part of the watershed.

At Carroll’s Creek, there should be another flow gauge in the middle of the basin, in addition to the existing one downstream. Additionally, Dry Creek basin does not have a flow gauge, and there should be one located downstream.

These suggested precipitation and flow gauge locations are presented in Figure 9.1. The current flow gauges are presented in red. The suggested flow gauges are presented in green. The suggested location of rain gauges are presented in brown.
9.5.4 Water Quality Monitoring and Sampling

A comprehensive water quality monitoring program should be developed for the entire watershed. The Lake Tuscaloosa Watershed is relatively large (425 sq miles). Therefore, this program should start by combining efforts between the various organizations, government entities, and the community at large to look after the water quality throughout the watershed.

Continuous monitoring, especially at the hot spots identified in this research, is important. It was identified in this research that pollution levels, especially *E.coli*, are higher after precipitation events. Therefore, the collection of samples should target these events in addition to the scheduled sample collection program. The community should be
involved as part of the sampling program, once they receive the proper training and education. They can report observations in the water and on land to the authorities. There are many communities where the locals are trained to use field kits to sample and examine the water quality on a regular basis and report these results to the authorities.

An important component in the monitoring program is the sampling methods. These methods should be performed properly because they impact the quality of the results. These methods and guidelines for proper sampling, for any water quality parameter, are thoroughly described in the *Stormwater Effects Handbook* by Burton and Pitt (2001).

### 9.5.5 Develop Education and Training Program

During the interviews with the stakeholders using the EDAF, the education and training facet was one of the top facets that the stakeholders agreed on the importance of. The stakeholders agreed that investing in educating the public, policy makers, farmers, etc., about the importance of the lake and methods to prevent pollution has a higher significant impact than adding and enforcing new regulations.

This education and training program should be developed to target different ages, levels of education, and cultural backgrounds. This program should use different media channels such as radio, television, internet, city hall meetings, and billboards. These information sources should be updated regularly.
9.6 Future Research Studies

This research was an example of the need of interdisciplinary studies to explore, understand, analyze, and develop robust and sustainable alternatives for water, wastewater, and stormwater infrastructure systems. This research created opportunities for research in three major areas. The first area was enhancing the framework. The second area was the modeling of the flow and *E.coli* in the watershed. Finally, the third area was implementing controls in the watershed at sources of pollution. Each one of these areas is further discussed below.

The EDAF, unlike many decision analysis frameworks, is widely applicable to many types of decision making processes. Its flexibility allows for use in a wide variety of projects. The EDAF assists not only in the pre-planning stage, but also throughout the life cycle of the project to ensure the objectives of the project are met. Therefore, it supports choosing robust and sustainable solutions. The framework’s use will reduce the project’s total cost and time, because it is effective despite limited or unavailable data.

9.6.1 Extension and Testing of EDAF

In this research, the EDAF background, components, and structure were developed. The framework was used in the initial phases of the research project, and it showed its success in terms of collecting and managing the data and information. The framework needs to be extended and tested further to become a robust tool.

The next steps to extend the framework are to take the results that were obtained from this project, mainly the objectives, and prepare a survey for stakeholders which can
be administered face-to-face or through the mail. This way, a wider spectrum of stakeholders is included in the enhancement of this tool.

9.6.2 Flow and *E. coli* Modeling

The watershed is spread over a large area of land that is starting to experience an increased rate of development. For example, in North River basin there are more than forty subbasins. This entire watershed has only one gauge downstream at the mouth of the basin, but there should be continuous flow and precipitation gauges spread over the watershed in order to establish a substantial database for the hydraulics and hydrology in the watershed. Additionally, further on-land investigation of the land uses and creek and stream visits are required to develop a deeper understanding of the watershed and its uses.

In terms of *E. coli* modeling, additional water quality samples need to be taken at different locations in the watershed. This will help in reducing the areas that are responsible for the discharge of pollutants into nearby waterbodies. Additionally, it will establish a solid database about the water quality in the watershed. This will assist in developing water quality models, in terms of fate and transport of the bacteria, that will have less uncertainty. This process is also correlated with the next section, implementing controls.

9.6.3 Implementing Controls in Watershed

Implementing controls at the sources of pollution in the watershed can make long strides in improving water quality. The US EPA, in cooperation with the local
environmental agencies, has programs to implement controls and study their impact on water quality at the sources of pollution. Section 319 allows communities to apply for federal grants to implement best management practices (BMPs) to protect and improve water quality. A subbasin can be a pilot study for these controls, as comprehensive analysis for that subbasin and the discharges from it can be implemented. Researchers in hydrology, hydraulics, geotechnics, control technologies, water quality, ecology, and many other fields can take part in the project. This pilot study can then be implemented at other locations within the watershed.

9.7 Presentations to Stakeholders

9.7.1 City of Tuscaloosa

Part of these research results were presented (March 2008) to the Engineers for the City of Tuscaloosa and the city’s consultants. They all agreed that this research and its results will assist them in managing the \textit{E.coli} problem in the lake. It helped them to identify the sources of pollution. It also identified a need to establish a watershed committee that looks after the entire watershed. The framework components and results have added a new dimension to the understanding of problems and decision making. According to Pat O’Neil, it also \textit{“helped bridge to an information-based decision system”}.

9.7.2 Lower Black Warrior Basin Committee

The lower Black Warrior Basin committee is a joint committee from various professional disciplines that looks after the soundness and integrity of the Black Warrior
watershed. The Lake Tuscaloosa watershed is part of the Black Warrior system and is located in the lower region. Many members of this committee were interviewed as part of this research. They were the stakeholders that provided input and data about the *E.coli* problem in Lake Tuscaloosa. A presentation on May 21st was conducted for the committee about the problem and the outcomes that were obtained from this research. The committee affirmed that this research was a good starting point. The research was long waited for in order to start taking actions in the watershed to reduce *E.coli* and other pollutants of concern. Additionally, some members from the GSA noted that this research will help them in their work in the watershed.

### 9.8 Research Contribution

This research made the following major contributions:

- Developed and demonstrated an integrated holistic pre-planning approach for determining the attributes to include in the planning phase of a complex project having limited data;

- Identified the significant lower and/or upper bounds that are acceptable for that facet within confines of environmental engineering specifically, looking at *E.coli*; and

- Assisted the City of Tuscaloosa in developing a sustainable and robust plan to control the *E.coli* bacteria problem in the watershed.
REFERENCES


Cho, C. *Development of the Project Definition Rating Index (PDRI) for Building Projects*. Austin, TX: University of Texas Press, 2000.


Utley, G. 2007. Conversation about reasons for *E.coli*. Tuscaloosa, AL.


APPENDIX A

AERIAL PHOTOS AND LAND USES FOR
NORTH RIVER AND BINION CREEK BASINS

A.1 Introduction

This appendix shows the aerial photo and land use(s) for each subbasin in North River and Binion Creek basins. These two basins combined represent around 70% of the Lake Tuscaloosa watershed. The aerial photos for this discussion were taken from Google Earth in 2007. North River is the first basin in the discussion, followed by discussion of Binion Creek. The red lines are subbasin boundaries, the blue lines indicate rivers, and yellow circles indicate the location of the stations.

A.2 North River Basin

A.2.1 NR0

NR0 subbasin is the furthest basin north on the river. It is the starting point of North River. The point NR0 is the bottom of the subbasin, where the $E.coli$ reading was measured. The area of this subbasin is 2342 acres and its land use is forest. This is shown in the aerial photo in Figure A.1.
A.2.2 LK1 – Lick Creek

Lick Creek is located in the northern part of North River basin. This creek flows into Tanyard Creek. It has a subbasin area of 482 acres with a main land use of forest. This is shown in the aerial photo in Figure A.2.

Figure A.2 LK1 subbasin aerial photo.
A.2.3 TD1 – Tanyard Creek

Tanyard Creek is located in the northern part of North River basin. It has an area of 1917 acres; the majority of it (1888 acres) is forest and the rest (29 acres) is pasture. The aerial photo of the subbasin is shown in Figure A.3. Tanyard Creek receives flow from Lick Creek and flows into North River in subbasin NR9.

Figure A.3 TD1 subbasin aerial photo.

A.2.4 HC1 – Hendon Creek

Hendon Creek is located below Tanyard Creek. The area of this subbasin is 1008 acres of forest. The aerial photo of the subbasin is shown in Figure A.4. The creek flows directly into North River in the NR9 subbasin of the river.
A.2.5 LY1 – Lowery Creek

Lowery Creek is located below Hendon Creek. The area of this subbasin is 822 acres of forest. The aerial photo of the subbasin is shown in Figure A.5. The creek flows directly into North River in the NR9 subbasin of the river.

Figure A.5 LY1 subbasin aerial photo.
A.2.6 BR2 and BR1 – Beaver Creek

The Beaver Creek subbasin is divided into 2 parts, BR2 and BR1. BR2 is upstream of BR1. Beaver Creek is located below Lowery Creek. BR2 has an area of 1446 acres of forest land, and BR1 has an area of 1871 acres of forest land. The aerial photo of these two subbasins is shown in Figure A.6. Beaver Creek flows directly into North.

Figure A.6 BR2 and BR1 subbasins aerial photo.

A.2.7 GC1 – George Creek

The George Creek subbasin drains into the NR9 subbasin section of North River. It covers an area of 5268 acres of forest land. The aerial photo, Figure A.7, shows the GC1 subbasin.
Figure A.7 GC1 subbasin aerial photo.

**A.2.8 NR9**

NR9 is the second subbasin on North River main channel. It is located below NR0, and the TD1, LY1, HC1, BR1, and GC1 adjacent subbasins flow into it. The NR9 subbasin covers an area of 7399 acres of forest land. The aerial photo of the subbasin is shown in Figure A.8.

Figure A.8 NR9 subbasin aerial photo.
A.2.9 LB1 – Laney Branch

Laney Branch is located to the east of NR8 subbasin. This branch directly drains into North River. It covers an area of 563 acres of forest land. The aerial photo of the subbasin is shown in Figure A.9.

Figure A.9 LB1 subbasin aerial photo.

A.2.10 CA2 and CA1 – Cane Creek

The Cane Creek subbasin is located below LB1 and to the east of NR8. It is divided into 2 other subbasins, CA2 and CA1. CA2 is located upstream of CA1. The CA2 subbasin covers an area of 1129 acres, where 1118 acres are forest and the rest (11 acres) is pasture land. On the other hand, the CA1 subbasin covers an area of 2616 acres of forest land. Both are pictures in Figure A.10.
A.2.11 NR8

The NR8 subbasin is the third section of North River subbasins on the river’s main channel. It is located south of NR9 and has flow from adjacent subbasins LB1 and CA2 and 1 into it. This subbasin covers an area of 2319 acres of land, where the majority of the land 2203 acres is forest and the rest (116 acres) is pasture. The aerial photo of NR8 subbasin is also shown in Figure A.10.

A.2.12 EC1 – Ellis Creek

Ellis Creek is located north of the NR7 subbasin. This subbasin covers an area of 1541 acres of forest land. The aerial photo of this subbasin is shown in Figure A.11.
A.2.13 NR7

The NR7 subbasin is the fourth section of North River subbasins on the river’s main channel. This section receives flow only from the EC1 subbasin. NR7 covers an area of 3725 acres, where 3613 acres are forest and the rest (112) is pasture. The aerial photo of the subbasin is also shown in Figure A.11.

A.2.14 CL4 and CL3 – Clear Creek

The Clear Creek subbasin is dived into 4 subbasins (CL4, CL3, CL2, and CL1). Clear Creek is located north of the North River basin. It is adjacent to Bear Creek, but it flows into NR6 subbasin. The first two subbasins to be discussed are CL4 and CL3. CL4 is located upstream and flows into CL3. The CL4 subbasin covers an area of 512 acres, where 497 acres are forest and the rest (15) is pasture land. CL3 is located downstream of CL4. It covers an area of 3719 acres, where 3421 acres are forest and the rest (298) is pasture land. Both the CL4 and CL3 subbasins are shown in Figure A.12.
A.2.15 BS1 – Boles Creek

The Boles Creek subbasin is adjacent to CL3, and it flows into CL2 subbasin. CL2 covers an area of 1867 acres of forest land. The aerial photo of the subbasin is shown in Figure A.12.

A.2.16 CL2 – Clear Creek

Clear Creek CL2 station is located south of CL3. CL2 covers an area of 5378 acres, where 4840 acres are forest and the rest (538) is pasture land. The aerial photo of this subbasin is shown in Figure A.13.
A.2.17 DC1 – Dallas Creek

The Dallas Creek subbasin is adjacent to the CL2 subbasin. This creek flows into the CL1 subbasin. This creek covers an area of 6854 acres, where 5483 acres are forest and the rest (1371) is pasture land. The aerial photo of this subbasin is shown in Figure A.13.

A.2.18 DCT – Dallas Creek Tributary

The Dallas Creek Tributary subbasin is located below the DC1 subbasin. This creek flows into the CL1 subbasin. DCT subbasin covers an area of 2095 acres, where 2032 acres are forest land and the rest (63) is pasture land. The aerial photo of this subbasin is shown in Figure A.14.
A.2.19 CL1 – Clear Creek

The final Clear Creek subbasin, before connecting with the North River basin NR6, is CL1. CL1 receives flow from DC1, DCT, and CL2. CL1 covers an area of 1002 acres of forest land. The aerial photo of this subbasin is shown in Figure A.14.

A.2.20 NR6

NR6 is the fifth subbasin on North River main channel. This subbasin receives flow from NR7 and CL1. This subbasin covers an area of 1804 acres, where 902 acres are forest land and the rest (902) is pasture land. The aerial photo of this subbasin is shown in Figure A.14.
A.2.21 RB1 – Rocky Branch

Rocky Branch is located south of the NR6 subbasin. This branch flows into the North River NR5 subbasin. It covers an area of 908 acres of forest land. The aerial photo of this subbasin is shown in Figure A.14.

A.2.22 SPC – Sandy Point Creek

Sandy Point Creek subbasin is located south of DCT and RB1, where it flows into North River NR5 subbasin. This subbasin covers an area of 1804 acres, where one half is 902 acres of forest and the other half is pasture land. The aerial photo of this subbasin is shown in Figure A.14.

A.2.22 LC1 – Little Creek

Little Cedar Creek subbasin is located south of the Cane Creek subbasins. LC1 flows into the CE3 subbasin. This subbasin covers an area of 3069 acres, where 2916 acres are forest land and the rest (153) is pasture land. The aerial photo of this subbasin is shown in Figure A.15.
A.2.23 CE4 and CE3 – Cedar Creek

The Cedar Creek subbasin is divided into 4 subbasins, CE4, CE3, CE2, and CE1. The CE4 subbasin is located upstream of the creek. The first subbasin to be discussed is CE4. CE4 is located south of the LC1 subbasin. The subbasin covers an area of 2383 acres, where 2359 acres are forest land and the rest (24) is pasture land. The CE3 subbasin is located below CE4. This subbasin covers an area of 3158 acres, where 3095 acres are forest land and the rest (63) is a quarry. The aerial photo for both CE4 and CE3 is shown in Figure A.15.

A.2.24 CE2 and CE1 – Cedar Creek

The CE2 subbasin is located below CE3. This subbasin also receives flow from the City of Berry (BY1). The CE2 subbasin covers an area of 841 acres, where 757 acres are forest land and the rest (84) is pasture land. The CE1 subbasin is located below CE2. This
subbasin covers an area of 1340 acres, where 1005 acres are forest and the rest (335) is pasture land. Both are pictured in A.16.

Figure A.16 BY1, CE2, CE1, and NT2 subbasins aerial photo.

A.2.25 BY1 – City of Berry

City of Berry subbasin is presented as the BY1 subbasin. The flow from BY1 represents the generated runoff from the city. This subbasin covers an area of 493 acres, where 419 acres are residential, 49 acres are forest land, and 25 acres are pasture land. The aerial photo of this subbasin is shown in Figure A.16.

A.2.26 NT2 – North River Tributary

NT2 is one of the unnamed North River tributaries. It is located beside the CE1 and NR5 subbasins. This subbasin covers an area of 475 acres, where 380 acres are forest land and the rest (95) is pasture land. The aerial photo of NT2 is shown in Figure A.16.
A.2.27 TC2 – Tyro Creek

The Tyro Creek subbasin is located south of the Cedar Creek subbasins. It is divided into 2 subbasins, TC2 and TC1. The TC2 subbasin covers an area of 13761 acres of forest land. The aerial photo of TC2 is shown in Figure A.17.

Figure A.17 TC2 subbasin aerial photo.

A.2.28 TC1 – Tyro Creek

TC1 is the second subbasin in Tyro Creek. TC1 flows into the NR2 subbasin. It covers an area of 1595 acres of forest land. The aerial photo for this subbasin is shown in Figure A.18.
A.2.29 BE1 – Bear Creek

The Bear Creek subbasin is located south of the TC2 subbasin. BE1 flows into the NR2 subbasin. This subbasin covers an area of 9597 acres of forest land. The aerial photo of this subbasin is shown in Figure A.19.
A.2.30 NR5

The sixth subbasin on the North River main channel is NR5. The NR5 subbasin receives flow from the NR6, SPC, and CE1 subbasins. The subbasin covers an area of 8576 acres, where 6861 acres are forest land and the rest (1715) is pasture land. The aerial photo of this subbasin is shown in Figure A.20.

![NR5 subbasin aerial photo](image)

Figure A.20 NR5 subbasin aerial photo.

A.2.31 FC1 – Freeman Creek

The Freeman Creek subbasin is located south of the SPC subbasin. The FC1 subbasin flows into the North River main channel through the NR4 subbasin. It covers an area of 1296 acres, where 1257 acres are forest land and the rest (39) is pasture land. This subbasin contains 3 chicken farms. The aerial photo of FC1 is shown in Figure A.21.
A.2.32 NR4

The NR4 subbasin is the seventh subbasin on the North River main channel. NR4 receives flow from the NR5 and FC1 subbasins. This subbasin covers an area of 2116 acres, where 1058 acres are forest land and the rest (1058) is pasture land. There is one chicken farm in this subbasin. The aerial photo of this subbasin is also shown in Figure A.21.

A.2.33 NR3

The NR3 subbasin is the eighth subbasin on the North River main channel. The NR3 subbasin receives flow from NR4. It covers an area of 2427 acres, where 2184 acres are forest land and the rest (243) is pasture land. The aerial photo of this subbasin is shown in Figure A.22.
A.2.34 BO2 and BO1 – Boone Creek

The Boone Creek subbasin is divided into 2 subbasins, BO2 and BO1. These subbasins are located south of the FC1, NR4, and NR3 subbasins. The flow from this subbasin flows into the NR2 subbasin. BO2 covers an area of 2760 acres, where 2070 acres are forest land and the rest (690) is pasture land. The BO1 subbasin covers an area of 3380 acres, where 3042 acres are forest land and the rest (338) is pasture land. There is one chicken farm located in this subbasin. The aerial photo for both BO1 and 2 subbasins are shown in Figure A.23.

Figure A.22 NR3 subbasin aerial photo.
A.2.35 NR2

The NR2 subbasin is the ninth subbasin on the North River main channel. The NR2 subbasin receives flow from the NR3, TC1, BE1, BO1, GB1, and NT1 subbasins. It covers an area of 7857 acres, where 6678 acres are forest land and the rest (1179) is pasture land. This subbasin also contains a chicken farm. The aerial photo of this subbasin is shown in Figure A.24.
A.2.36 GB1 – Gin Branch

The Gin Branch subbasin is located south of the BO1 subbasin. This subbasin flows into the NR2 subbasin on the North River main channel. The GB1 subbasin covers an area of 1370 acres, where 685 acres are forest land and the rest (685) is pasture land. The aerial photo of this subbasin is shown in Figure A.24.

A.2.37 NT1 – North River Tributary

NT1 is one of the unnamed North River tributaries. It is located south of the GB1 subbasin. NT1 flows into the North River through the NR2 subbasin. This subbasin covers an area of 1296 acres, where 648 acres are forest land and the rest (648) is pasture land. The aerial photo of NT1 is shown in Figure A.24.
A.2.38 CP1 – Cripple Creek

The Cripple Creek subbasin is located south of the BE1 subbasin. It flows into the North River main channel through the NR1 subbasin. This subbasin covers an area of 7812 acres, where 7421 acres of forest land and the rest (391) is pasture land. The aerial photo of CP1 subbasin is shown in Figure A.25.

![Figure A.25 CP1 subbasin aerial photo.](image)

A.2.39 NR1

NR1 subbasin is the tenth subbasin on North River main channel. NR1 subbasin receives flow from NR2 and CP1 subbasins. It is the last subbasin for North River before entering Tuscaloosa Lake. It covers an area of 11744 acres, where 8221 acres are forest land and the rest (3523) is pasture land. This subbasin also contains a chicken farm. The aerial photo of this subbasin appears in A.26.
A.3 Binion Creek Basin

A.3.1 BC3

The BC3 subbasin is the upstream basin in Binion Creek. It is the starting point of the creek. This creek flows into the BC2 subbasin. The area of this subbasin is 4707 acres, where 4613 acres are forest land and the rest (94) is pasture land. The aerial photo of this subbasin is shown in Figure A.27.
A.3.2 BC2

The BC2 subbasin is located south of BC3. This creek flows into the BC1 subbasin. The area of this subbasin is 2031 acres, where 2011 acres are forest land and the rest (20) is pasture land. The aerial photo of this subbasin is shown in Figure A.28.
A.3.3 BT2 – Binion Creek Tributary

BT2 is one of the tributary subbasins. This subbasin is located south of BC2 and flows into the BC1 subbasin. The area of this subbasin is 1083 acres, where 1072 acres are forest land and the rest (11) is pasture land. The aerial photo of this subbasin is shown in Figure A.29.

![Figure A.29 BT2 subbasin aerial photo.](image)

A.3.4 BT1 – Binion Creek Tributary

BT1 is one of the tributary subbasins. This subbasin is located south of BT2 and flows into the BC1 subbasin. The area of this subbasin is 4636 acres, where 4590 acres are forest land, 23 acres are residential, and the rest (23) is pasture land. The aerial photo of this subbasin is shown in Figure A.30.
A.3.5 BT6 – Binion Creek Tributary

BT6 is one of the tributary subbasins. This subbasin is located north of the creek’s basin. It flows into the BT4 subbasin. The area of this subbasin is 3591 acres, where 2963 acres are forest land and the rest (988) is pasture land. In this subbasin, there are 2 chicken farms. The aerial photo of this subbasin is shown in Figure A.31.
A.3.6 BT4 and BT5 – Binion Creek Tributary

BT4 is one of the tributary subbasins. This subbasin is located south of BT6. It flows into the BT3 subbasin. The area of this subbasin is 1101 acres, where 551 acres are forest land, 55 acres are residential, and the rest (495) is pasture land. The aerial photo of this subbasin is shown in Figure A.32. BT5 is one of the tributary subbasins. This subbasin is located beside BT6. It flows into BT3 subbasin. The area of this subbasin is 2062 acres, where 2052 acres are forest land and the rest (10) is pasture land. There is one chicken farm in this subbasin. The aerial photo of this subbasin is shown in Figure A.32.
A.3.7 BT3 – Binion Creek Tributary

BT3 is one of the tributary subbasins. This subbasin is located south of BT5 and BT4. It flows into the BC1 subbasin. The area of this subbasin is 1782 acres, where 1604 acres are forest land and the rest (178) is pasture land. The aerial photo of this subbasin is shown in Figure A.33.
A.3.8 BC1

The BC1 subbasin is downstream from the creek. This creek flows into 001 subbasin, where it then flows into Tuscaloosa Lake. This subbasin receives the flow from all other subbasins in the basin. The area of this subbasin is 3270 acres, where 3172 acres are forest land and the rest (98) is pasture land. There is one chicken farm in this subbasin. The aerial photo of this subbasin is shown in Figure A.34.

![BC1 subbasin aerial photo](image)

Figure A.34 BC1 subbasin aerial photo.

A.3.8 001

The 001 subbasin is the connecting subbasin between the creek and the lake. The area of this subbasin is 2208 acres, where 2153 acres are forest land, 11 acres are residential, and the rest (44) is pasture land. The aerial photo of this subbasin is shown in Figure A.35.
Figure A.35 001 subbasin aerial photo.
APPENDIX B

FLOW AND E.COLI PLOTS FOR NORTH RIVER
AND BINION CREEK BASINS

B.1 Introduction

This appendix shows modeled plots for the precipitation versus the flow and the flow versus *E.coli* for every subbasin in North River and Binion Creek basins. The plots show the $R^2$ value and the related equation for each plot. The fitted equations are power equations for both flow and *E.coli*.

B.2 North River

B.2.1 NR0

![Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR0).](image)

Figure B.1 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR0).
B.2.2 LK1 – Lick Creek

Figure B.2 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (LK1).

B.2.3 TD1 – Tanyard Creek

Figure B.3 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (TD1).

B.2.4 HC1 – Hendon Creek

Figure B.4 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (HC1).
B.2.5 LY1 – Lowery Creek

Figure B.5 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (LY1).

B.2.6 BR2 – Beaver Creek

Figure B.6 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BR2).

B.2.7 BR1 – Beaver Creek

Figure B.7 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BR1).
B.2.8 GC1 – George Creek

![Graph](image1)

Figure B.8 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (GC1).

B.2.9 NR9

![Graph](image2)

Figure B.9 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR9).

B.2.10 LB1 – Laney Branch

![Graph](image3)

Figure B10. Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (LB1).
B.2.11 CA2 – Cane Creek

Figure B.11 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (CA2).

B.2.12 CA1 – Cane Creek

Figure B.12 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (CA1).

B.2.13 NR8

Figure B.13 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (NR8).
B.2.14 EC1 – Ellis Creek

Figure B.14 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (EC1).

B.2.15 NR7

Figure B.15 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (NR7).

B.2.16 CL4 – Clear Creek

Figure B.16 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (CL4).
B.2.17 CL3 – Clear Creek

(a)  
\[ y = 9.76x^{2.41} \quad R^2 = 0.58 \]

(b)  
\[ y = 22.71x^{0.79} \quad R^2 = 0.84 \]

Figure B.17 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CL3).

B.2.18 BS1 – Boles Creek

(a)  
\[ y = 2.52x^{2.37} \quad R^2 = 0.55 \]

(b)  
\[ y = 24.15x^{0.89} \quad R^2 = 0.93 \]

Figure B.18 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BS1).

B.2.19 CL2 – Clear Creek

(a)  
\[ y = 21.19x^{2.55} \quad R^2 = 0.59 \]

(b)  
\[ y = 10.42x^{0.71} \quad R^2 = 0.77 \]

Figure B.19 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CL2).
B.2.20 DC1 – Dallas Creek

Figure B.20 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (DC1).

B.2.21 DCT – Dallas Creek Tributary

Figure B.21 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (DCT).

B.2.22 CL1 – Clear Creek

Figure B.22 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (CL1).
B.2.23 NR6

Figure B.23 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (NR6).

B.2.24 RB1 – Rocky Branch

Figure B.24 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (RB1).

B.2.25 SPC – Sandy Point Creek

Figure B.25 Plot (a) precipitation versus flow and plot (b) is flow versus E.coli (SPC).
B.2.26 LC1 – Little Creek

Figure B.26 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (LC1).

B.2.27 CE4 – Cedar Creek

Figure B.27 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (CE4).

B.2.28 CE3 – Cedar Creek

Figure B.28 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (CE3).
B.2.29 CE2– Cedar Creek

Figure B.29 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CE2).

B.2.30 CE1– Cedar Creek

Figure B.30 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (CE1).

B.2.31 BY1 – City of Berry

Figure B.31 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BY1).
B.2.32 NT2 – North River Tributary

Figure B.32 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (NT2).

B.2.33 TC2 – Tyro Creek

Figure B.33 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (TC2).

B.2.34 TC1 – Tyro Creek

Figure B.34 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (TC1).
B.2.35 BE1 – Bear Creek

Figure B.35 Plot (a) precipitation versus flow and plot (b) is flow versus \( E\. coli \) (BE1).

B.2.36 NR5

Figure B.36 Plot (a) precipitation versus flow and plot (b) is flow versus \( E\. coli \) (NR5).

B.2.37 FC1 – Freeman Creek

Figure B.37 Plot (a) precipitation versus flow and plot (b) is flow versus \( E\. coli \) (FC1).
B.2.38 NR4

Figure B.38 Plot (a) precipitation versus flow and plot (b) is flow versus \(E. coli\) (NR4).

B.2.39 NR3

Figure B.39 Plot (a) precipitation versus flow and plot (b) is flow versus \(E. coli\) (NR3).

B.2.40 BO2 – Boone Creek

Figure B.40 Plot (a) precipitation versus flow and plot (b) is flow versus \(E. coli\) (BO2).
B.2.41 BO1 – Boone Creek

Figure B.41 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BO1).

B.2.42 NR2

Figure B.42 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (NR2).

B.2.43 GB1 – Gin Branch

Figure B.43 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (GB1).
B.2.44 NT1 – North River Tributary

Figure B.44 Plot (a) precipitation versus flow and plot (b) is flow versus $E. coli$ (NT1).

B.2.45 CP1 – Cripple Creek

Figure B.45 Plot (a) precipitation versus flow and plot (b) is flow versus $E. coli$ (CP1).

B.2.46 NR1

Figure B.46 Plot (a) precipitation versus flow and plot (b) is flow versus $E. coli$ (NR1).
B.3 Binion Creek

B.3.1 BC3

Figure B.47 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BC3).

B.3.2 BC2

Figure B.48 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BC2).
B.3.3 BT2

![Graphs showing linear relationships between precipitation and flow, and flow and E. coli for BT2.](image)

Figure B.49 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (BT2).

B.3.4 BT1

![Graphs showing linear relationships between precipitation and flow, and flow and E. coli for BT1.](image)

Figure B.50 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (BT1).

B.3.5 BT6

![Graphs showing linear relationships between precipitation and flow, and flow and E. coli for BT6.](image)

Figure B.51 Plot (a) precipitation versus flow and plot (b) is flow versus *E. coli* (BT6).
B.3.6 BT4

Figure B.52 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BT4).

B.3.7 BT5

Figure B.53 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BT5).

B.3.8 BT3

Figure B.54 Plot (a) precipitation versus flow and plot (b) is flow versus *E.coli* (BT3).
B.3.9 BC1

Figure B.55 Plot (a) precipitation versus flow and plot (b) is flow versus \(E.\text{coli}\) (BC1).

B.3.10 001

Figure B.56 Plot (a) precipitation versus flow and plot (b) is flow versus \(E.\text{coli}\) (001).
APPENDIX C

STAKEHOLDER INTERVIEWS

C.1 Introduction

The results from conducting the interviews were discussed in Chapter III. This appendix is a contact report for the interviews that were conducted as part of implementing the EDAF on the *E.coli* problem in the watershed. This contact report includes the representatives from each group that were interviewed, the list of questions and answers, and the time they were interviewed.

C.2 Stakeholder Group Representatives

The list of stakeholders groups that are concerned about the *E.coli* problem in Lake Tuscaloosa watershed was listed in Table 3.3 in Chapter III. The list of the representatives from these groups that were interviewed is presented in Table C.1. The names and contact information of the representatives are not mentioned for privacy reasons. Only the roles of these representatives are declared. These interviews were conducted May through June, 2007.
Table C.1 Information about the Group Representatives that Were Interviewed

<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Representative Role</th>
<th>Interview Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Tuscaloosa</td>
<td>Superintendent</td>
<td>In person</td>
</tr>
<tr>
<td>Water and Wastewater Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>City of Tuscaloosa City Council</td>
<td>Councilman</td>
<td>In person</td>
</tr>
<tr>
<td>City of Northport water Treatment</td>
<td>Manager</td>
<td>In person</td>
</tr>
<tr>
<td>Geological Survey of Alabama (GSA)</td>
<td>Director/ Water Investigations</td>
<td>In person</td>
</tr>
<tr>
<td>Forest Management</td>
<td>Forest Management Specialist</td>
<td>In person</td>
</tr>
<tr>
<td>Local and National Engineers</td>
<td>Engineers</td>
<td>In person</td>
</tr>
<tr>
<td>Environmental and Ecological watchdogs</td>
<td>River Keeper, Facilitator</td>
<td>In person</td>
</tr>
<tr>
<td>Farmers (USDA/NRCS)</td>
<td>District Conservationist</td>
<td>In person</td>
</tr>
<tr>
<td>Public Health Department</td>
<td>Supervisor</td>
<td>In person</td>
</tr>
<tr>
<td>Alabama Department of Environmental Management (ADEM)</td>
<td>Inspector</td>
<td>Telephone</td>
</tr>
<tr>
<td>Residents around the lake and general public</td>
<td>Residents</td>
<td>In person/ Telephone</td>
</tr>
<tr>
<td>Commercial and residential developers</td>
<td>Realtor</td>
<td>In person</td>
</tr>
</tbody>
</table>

The structure of the interview was similar for each one of the stakeholders. At the beginning, the stakeholders had a brief introduction regarding the purpose of the project and why their input was important. The stakeholders were asked to provide objectives, if available, for each one of the facets presented in Table 3.2. Then they were asked if these facets assisted in providing more objectives and input. Afterwards, they were asked to give the highest two facets that were of concern to them. They were asked if they had data that would help in the research. Finally, they were asked to recommend other people who should be contacted relating to this problem. The questions were as follows:
- What are the objectives of concern (a facet) for relating to the *E.coli* problem in Lake Tuscaloosa?

- Did these facets assist in organizing your objectives?

- Did these facets assist in providing more objectives?

- What are the two highest facets of concern?

- Can you provide data that may help in this research?

- Can you identify other stakeholders or individuals that may have or provide further information and input about the problem?

The answers to the 1st and 4th questions relating to the objectives are presented in Table C.2 and C.3. All the stakeholders answered positively to the 2nd and 3rd questions. They affirmed that the facets helped them in providing more objectives and organizing them. The data provided by the stakeholders is presented in Table C.4. In relation to the 6th question, the majority of the stakeholders identified other individuals to contact, and sometimes these identified individuals had already been contacted. For example, the GSA director identified the superintendent at the City of Tuscaloosa. The supervisor at the Public Health Department identified the District Conservationist, and the district conservationist identified the inspector at ADEM.
<table>
<thead>
<tr>
<th>Stakeholders Group Representatives</th>
<th>Facets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superintendent</td>
<td><strong>Public Health</strong></td>
</tr>
<tr>
<td></td>
<td>- Maintain high water quality in the lake</td>
</tr>
<tr>
<td></td>
<td>- Minimize threat to public</td>
</tr>
<tr>
<td></td>
<td>- Allocate funds to reduce threat</td>
</tr>
<tr>
<td></td>
<td>- Allocate funds to keep water clean</td>
</tr>
<tr>
<td></td>
<td>- Maintain the chemical and biological status</td>
</tr>
<tr>
<td></td>
<td>- Control zoning in the area</td>
</tr>
<tr>
<td></td>
<td>- Educate people about the lake and the watershed</td>
</tr>
<tr>
<td></td>
<td>- Operate and maintain the current sewer network</td>
</tr>
<tr>
<td></td>
<td>- Increase the city’s zoning control</td>
</tr>
<tr>
<td></td>
<td>- Increase the city’s regulatory power</td>
</tr>
<tr>
<td></td>
<td>- Have more manpower and equipment</td>
</tr>
<tr>
<td></td>
<td>- Encourage social use of the lake</td>
</tr>
<tr>
<td></td>
<td>- Restrict direct sanitary connections to the lake</td>
</tr>
<tr>
<td>Councilman</td>
<td><strong>Financial &amp; Economic</strong></td>
</tr>
<tr>
<td></td>
<td>- Ensure people have no health threat while using the lake</td>
</tr>
<tr>
<td></td>
<td>- Maintain the area as a focal point for investors and developers</td>
</tr>
<tr>
<td></td>
<td>- Maintain a proper environment system</td>
</tr>
<tr>
<td></td>
<td>- Formulate ordinances to protect environment</td>
</tr>
<tr>
<td></td>
<td>- Educate to prevent future pollution</td>
</tr>
<tr>
<td></td>
<td>- Inform the public about the importance of sustaining the lake’s water quality</td>
</tr>
<tr>
<td></td>
<td>- Operate and maintain water systems properly</td>
</tr>
<tr>
<td></td>
<td>- Have more government entities work together</td>
</tr>
<tr>
<td></td>
<td>- The less regulations, the better</td>
</tr>
<tr>
<td></td>
<td>- Allocate external sources to help in the protection efforts</td>
</tr>
<tr>
<td></td>
<td>- Try to approach the people and explain the different ordinances</td>
</tr>
<tr>
<td>Forest Management Specialist</td>
<td><strong>Environmental &amp; Ecology</strong></td>
</tr>
<tr>
<td></td>
<td>- Have clean water all year round</td>
</tr>
<tr>
<td></td>
<td>- Have a bigger budget to operate efficiently</td>
</tr>
<tr>
<td></td>
<td>- Protect the eco-system from changes due to pollution</td>
</tr>
<tr>
<td></td>
<td>- Educate the field workers about septic tanks and their related issues</td>
</tr>
<tr>
<td></td>
<td>- Educate landowners in the basin to improve their land uses</td>
</tr>
<tr>
<td></td>
<td>- Educate more than regulate</td>
</tr>
<tr>
<td></td>
<td>- Implement more water quality tests in the watershed</td>
</tr>
<tr>
<td></td>
<td>- Have more qualified personnel</td>
</tr>
<tr>
<td></td>
<td>- Have a special group to contact and reach out to people from different backgrounds</td>
</tr>
</tbody>
</table>
Table C.2 (cont.)

<table>
<thead>
<tr>
<th>Stakeholders Group Representatives</th>
<th>Facets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Public Health</strong></td>
<td><strong>Financial &amp; Economic</strong></td>
</tr>
<tr>
<td>Supervisor</td>
<td>- Minimize threat to public health</td>
</tr>
<tr>
<td></td>
<td>- Educate the public about sewage collecting systems</td>
</tr>
<tr>
<td></td>
<td>- Educate the public about the legal liabilities for collection systems</td>
</tr>
<tr>
<td>District Conservationist</td>
<td>- Protect water quality</td>
</tr>
<tr>
<td></td>
<td>- Protect the ecology and the environment</td>
</tr>
<tr>
<td></td>
<td>- Educate and train people to protect the natural resources</td>
</tr>
<tr>
<td>Engineers</td>
<td>- Public feel safe to use, swim, fish and have free contact with the water with low to minimal hazard</td>
</tr>
<tr>
<td></td>
<td>- Bad PR about the lake would drive away investments and companies from Tuscaloosa</td>
</tr>
<tr>
<td></td>
<td>- Have a balanced ecosystem to encourage people to go and fish</td>
</tr>
<tr>
<td></td>
<td>- Educate landowners about septic tanks and their related issues</td>
</tr>
<tr>
<td></td>
<td>- Educate landowners in the basin to improve their land uses to protect the lake</td>
</tr>
<tr>
<td></td>
<td>- Provide sanitary sewer system</td>
</tr>
<tr>
<td></td>
<td>- Introduce BMPs to farms</td>
</tr>
<tr>
<td></td>
<td>- Educate and inform better than regulate</td>
</tr>
<tr>
<td></td>
<td>- Have advanced equipment to verify and protect the water quality in the lake and the watershed</td>
</tr>
<tr>
<td></td>
<td>- Teach the different people about the lake and its importance according to their interests</td>
</tr>
<tr>
<td>District Conservationist</td>
<td>- Improve regulations outcome through educating people</td>
</tr>
<tr>
<td></td>
<td>- Deal with different people to protect the natural resources</td>
</tr>
<tr>
<td>Supervisor</td>
<td>- Have stricter regulations to protect the public health and the lake</td>
</tr>
<tr>
<td></td>
<td>- Cultivate the ability to address the needs and concerns of different people</td>
</tr>
<tr>
<td>Engines</td>
<td>- Have advanced equipment to verify and protect the water quality in the lake and the watershed</td>
</tr>
<tr>
<td></td>
<td>- Teach the different people about the lake and its importance according to their interests</td>
</tr>
<tr>
<td>Stakeholders Group Representatives</td>
<td>Facets</td>
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<tr>
<td>-----------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Public Health</strong></td>
<td>- Maintain long-term investment</td>
</tr>
<tr>
<td></td>
<td>- Work with the city to receive tax breaks and incentives</td>
</tr>
<tr>
<td></td>
<td>- Have sewer systems</td>
</tr>
<tr>
<td></td>
<td>- Have ready infrastructure for development</td>
</tr>
<tr>
<td></td>
<td>- Ease zoning policies</td>
</tr>
<tr>
<td></td>
<td>- Ease investment policies</td>
</tr>
<tr>
<td></td>
<td>- Target people who will give you higher return on investment</td>
</tr>
<tr>
<td><strong>Financial &amp; Economic</strong></td>
<td>- Maintain funds to protect the watershed</td>
</tr>
<tr>
<td></td>
<td>- Allocate budget for a watershed management plan</td>
</tr>
<tr>
<td></td>
<td>- Protect watershed should be a high priority</td>
</tr>
<tr>
<td></td>
<td>- Maintain the lake as an important source for fishing, swimming, drinking, etc</td>
</tr>
<tr>
<td></td>
<td>- Bacteria from agriculture is detrimental to wildlife</td>
</tr>
<tr>
<td></td>
<td>- Develop watershed management plan</td>
</tr>
<tr>
<td></td>
<td>- Educate people in the watershed about its importance</td>
</tr>
<tr>
<td></td>
<td>- Educate kids and young people about this water resource and its importance</td>
</tr>
<tr>
<td></td>
<td>- Inform the public about the different problems in the watershed</td>
</tr>
<tr>
<td></td>
<td>- Water treatment costs get higher as the water gets more polluted</td>
</tr>
<tr>
<td></td>
<td>- Place proper practices at sources of pollution</td>
</tr>
<tr>
<td></td>
<td>- Stricter regulations to protect the lake</td>
</tr>
<tr>
<td></td>
<td>- Introduce BMPs for all agriculture lands</td>
</tr>
<tr>
<td></td>
<td>- Make the city’s website about the lake richer with information and update it regularly</td>
</tr>
<tr>
<td></td>
<td>- Include other potential sources of the problem not only septic tanks</td>
</tr>
<tr>
<td><strong>Social &amp; Cultural</strong></td>
<td>- Tendency of people to stop using the lake if pollution increases (This takes a long time to be regained)</td>
</tr>
<tr>
<td><strong>Regulatory</strong></td>
<td>- Easy zoning policies</td>
</tr>
<tr>
<td></td>
<td>- Ease investment policies</td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td>- Target people who will give you higher return on investment</td>
</tr>
<tr>
<td><strong>Environmental &amp; Ecology</strong></td>
<td>- Maintain the lake as an important source for fishing, swimming, drinking, etc</td>
</tr>
<tr>
<td></td>
<td>- Bacteria from agriculture is detrimental to wildlife</td>
</tr>
<tr>
<td><strong>Ancillary Infrastructure</strong></td>
<td>- Develop watershed management plan</td>
</tr>
<tr>
<td><strong>Education &amp; Training</strong></td>
<td>- Educate people in the watershed about its importance</td>
</tr>
<tr>
<td></td>
<td>- Educate kids and young people about this water resource and its importance</td>
</tr>
<tr>
<td><strong>Ancillary Infrastructure</strong></td>
<td>- Inform the public about the different problems in the watershed</td>
</tr>
<tr>
<td></td>
<td>- Water treatment costs get higher as the water gets more polluted</td>
</tr>
<tr>
<td></td>
<td>- Place proper practices at sources of pollution</td>
</tr>
<tr>
<td><strong>Ancillary Infrastructure</strong></td>
<td>- Stricter regulations to protect the lake</td>
</tr>
<tr>
<td></td>
<td>- Introduce BMPs for all agriculture lands</td>
</tr>
<tr>
<td><strong>Education &amp; Training</strong></td>
<td>- Make the city’s website about the lake richer with information and update it regularly</td>
</tr>
<tr>
<td><strong>Ancillary Infrastructure</strong></td>
<td>- Include other potential sources of the problem not only septic tanks</td>
</tr>
<tr>
<td><strong>Ancillary Infrastructure</strong></td>
<td>- Tendency of people to stop using the lake if pollution increases (This takes a long time to be regained)</td>
</tr>
</tbody>
</table>

Table C.2 (cont.)
Table C.3 Highest Two Facets Ranked by the Stakeholders’ Group Representatives

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Facet 1</th>
<th>Facet 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superintendent</td>
<td>Public Health</td>
<td>Education and Training</td>
</tr>
<tr>
<td>Councilman</td>
<td>Public Health</td>
<td>Regulatory</td>
</tr>
<tr>
<td>Forest Management Specialist</td>
<td>Public Health</td>
<td>Education and Training</td>
</tr>
<tr>
<td>Supervisor</td>
<td>Public Health</td>
<td>Education and Training</td>
</tr>
<tr>
<td>District Conservationist</td>
<td>Public Health</td>
<td>Education and Training</td>
</tr>
<tr>
<td>Engineers</td>
<td>Public Health</td>
<td>Education and Training</td>
</tr>
<tr>
<td>Realtor</td>
<td>Financial and Economic</td>
<td>Regulatory</td>
</tr>
<tr>
<td>River Keeper</td>
<td>Public Health</td>
<td>Environmental and Ecology</td>
</tr>
<tr>
<td>Resident</td>
<td>Public Health</td>
<td>Environmental and Ecology</td>
</tr>
</tbody>
</table>

Table C.4 Data Provided by the Stakeholders’ Group Representatives

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Provided Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superintendent</td>
<td>- Sampling data</td>
</tr>
<tr>
<td></td>
<td>- Maps</td>
</tr>
<tr>
<td></td>
<td>- Logistical information about lake</td>
</tr>
<tr>
<td></td>
<td>- Access to engineers</td>
</tr>
<tr>
<td>Councilman</td>
<td>- Insight about decision making in the City Council</td>
</tr>
<tr>
<td>Forest Management Specialist</td>
<td>- Watershed information</td>
</tr>
<tr>
<td></td>
<td>- Observations in the watershed</td>
</tr>
<tr>
<td>Supervisor</td>
<td>- Data</td>
</tr>
<tr>
<td></td>
<td>- SSOs events in watershed</td>
</tr>
<tr>
<td></td>
<td>- Potential problem areas</td>
</tr>
<tr>
<td>District Conservationist</td>
<td>- Information about watershed</td>
</tr>
<tr>
<td></td>
<td>- Technical data about agricultural activities</td>
</tr>
<tr>
<td>Engineers</td>
<td>- Decision making</td>
</tr>
<tr>
<td></td>
<td>- Information about watershed</td>
</tr>
<tr>
<td>Realtor</td>
<td>- Targeted areas for development</td>
</tr>
<tr>
<td>River Keeper</td>
<td>- Reports about watershed</td>
</tr>
<tr>
<td></td>
<td>- Aerial photos</td>
</tr>
<tr>
<td></td>
<td>- Information about watershed</td>
</tr>
<tr>
<td></td>
<td>- Observations in watershed</td>
</tr>
<tr>
<td>Resident</td>
<td>- Information about activities</td>
</tr>
<tr>
<td></td>
<td>- Information about watershed</td>
</tr>
<tr>
<td>Director</td>
<td>- Sampling information</td>
</tr>
<tr>
<td></td>
<td>- Available reports</td>
</tr>
<tr>
<td></td>
<td>- Available maps</td>
</tr>
<tr>
<td></td>
<td>- Watershed information</td>
</tr>
<tr>
<td>Inspector</td>
<td>- Information about agricultural activities in</td>
</tr>
<tr>
<td></td>
<td>watershed</td>
</tr>
<tr>
<td></td>
<td>- Role of regulatory agencies in protecting the</td>
</tr>
<tr>
<td></td>
<td>water quality</td>
</tr>
</tbody>
</table>
C.3 Discussion

These interviews provided an in-depth perspective about the stakeholders’ needs and concerns regarding the \textit{E.coli} problem in the Lake Tuscaloosa watershed. It also provided access to data about the watershed and the water quality. Additionally, it identified individuals who have information or have access to data. Finally, these interviews verified the use of the framework as a beneficial tool that can assist in the collection and organization of data and objectives.
APPENDIX D

FLOW MODEL

D.1 Introduction

Flow in the rivers and streams is an important factor for the transport of pollutants, especially \textit{E.coli}, from the different parts of the watershed to Lake Tuscaloosa. Flow is generated through precipitation, where runoff from different land uses in the watershed flows into the adjacent creeks, streams, and rivers until reaching its destination of Lake Tuscaloosa. Therefore, developing a flow model was an important first step in order to build an \textit{E.coli} fate and transport model, as discussed in Chapter VI.

The Lake Tuscaloosa watershed did not have an available watershed rainfall-runoff model for its’ different subbasins. Additionally, historical flow data is only available at three locations within the entire watershed at the lake’s northern section. One location is near the confluence of North River, where it connects with the lake. The second location is near the confluence of Binion Creek with the lake. The third location is in the center of the Turkey Creek drainage basin. These three recording stations are not sufficient to create a comprehensive understanding of the flow regime in the whole upper watershed area but were suitable for calibrating a watershed model for the whole basin and verifying assumptions made for each subbasin.

Developing a flow model for large areas having limited data is challenging. Information about the subbasins, especially land cover and soil information, was not
available, increasing the uncertainty in the model parameters and reducing the accuracy of the calculated results. There are many computer models that can assist in predicting, simulating and calibrating the flow from rain events. Two often-used software packages are WinTR-55 and HEC-HMS (NCDENR 2005).

**D.2 WinTR-55**

WinTR-55 stands for Windows Technical Release 55. It is software that analyses urban hydrology for small watersheds for single-event rainfall runoff. It was first issued in 1975 under TR-55 by the Soil Conservation Service (SCS) to simplify stormwater runoff calculations and associated runoff volume, peak discharge, hydrographs, and storage volumes. Throughout the years, several revisions and modifications were made to this software. Today, the software is operated under Windows and it has become an efficient tool for engineers and scientists (NRCS and ARS 2003).

WinTR-55 has many limitations in calculating and predicting runoff. For example, it has a limited number of subbasins (1 to 10) that can be simulated at a time, limited rainfall events, and the maximum area for the watershed is 25 mi\(^2\). Even with these limitations, WinTR-55 was used to calculate and prepare some data needed as input for the HEC-HMS, such as lag time.

**D.3 HEC-HMS**

The Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers developed the Hydrologic Modeling System (HMS), known as HEC-HMS. HEC-HMS is a modeling system designed to simulate the precipitation runoff in basins and subbasins
over a large area. The produced hydrographs can be used in studies of water-availability, drainage, flow forecasting, reservoir design, flood plain design, and regulation (Scharffenberg and Fleming 2006).

The first edition started with HEC-1 and went through different iterations and changes that included algorithms from other software such as HEC-1F, PRECIP, and HEC-IFH. Afterwards, HEC-2 was released with modifications for continuous simulation. The new HEC was developed to solve the problems found in previous releases and has an easier interface for the user (Scharffenberg and Fleming 2006).

HEC-HMS has the capability of performing extensive hydrologic simulations. Several parameters are entered into the software for the simulation. HEC-HMS has different modules built into it that can deal with different types of data available to the user. The software builds information about the watershed’s physical description, meteorology, flow control, GIS connection, and many more (Scharffenberg and Fleming 2006).

The limitations of HEC-HMS are attributed to the complexity of the system and the amount of information that needs to be analyzed. The simpler the system, the faster and more accurately results can be obtained. Additionally, the mathematical model uses deterministic values, where the boundary, initial conditions, and the parameters should be known exactly.

For more information about HEC-HMS and the way it works, the guidebook is comprehensive and full of examples and descriptions (Scharffenberg and Fleming 2006).
D.3.1 Developing Flow Model Using HEC-HMS

The first step in entering the data is to map the flow diagram of the basin under consideration. This is very important for the model because if any connection is wrong or missing, it will affect the output. In order to develop the flow diagram, pre-set symbols in HEC represent a component in the diagram. The bucket with a water drop symbolizes a subbasin, the bucket with an arrow pointing downwards symbolizes a junction, and the arrow connecting junctions together or subbasins with junctions is called a reach.

After mapping the watershed, information is entered into the database. Every subbasin, junction, and reach needs data in order to run the simulation. HEC-HMS uses many methods for simulation depending on user selections. In this project, the Soil Conservation Service (SCS) methods (TR-55) are used. The loss method is the SCS Curve Number (CN), and the transform method is the SCS unit hydrograph.

In order to follow a step-by-step data entry, HEC-HMS has the parameters that need to be entered for simulation built in; they can be found in the pull-down menu (Figure D.1).

![Figure D.1 Parameters option in the pull-down menu.](image)
The first parameter shown is the subbasin area. In this parameter, the area of each subbasin is entered. The units for the entered values and for the project in general can be customized as either SI or US customary units. These units can be changed under tools in the pull-down menu and by selecting project options. The area values for the subbasins are set in this project to mi\(^2\). An example of the area is shown in Figure D.2.

![Figure D.2 Subbasin area entry.](image)

The second values to be entered are the loss values. A loss value is a rate component that estimates how much rainfall would turn into excess runoff. In the loss window, Figure D.3, three values are entered: the initial abstraction, the curve number (CN), and the impervious, as a percent. The values entered depend on the soil type and the land use. The soil data was obtained from the Web Soil Survey (WSS) website (http://websoilsurvey.nrcs.usda.gov/app/), provided by the Natural Resources Conservation Service (NRCS 2007), part of the United States Department of Agriculture (USDA). This website is based on Geographic Information System (GIS), where the area under consideration is chosen and the soil data is retrieved. In general, the watershed has loam, sandy loam, or silt loam soil.

The land use is mainly forest, followed by agricultural activities and a few scattered residential areas. The land use information was obtained from aerial photos, as shown in Appendix A. The curve number was determined using this information and the
curve number table. Additionally, this information helped supplement the impervious values obtained from the literature (Cappiella and Brown 2001; Gunn et al. 2001; SCS 1986). For example, the impervious values associated with buildings and roads were between 0 and 5% for the forest areas, which cover the majority of the basins. For agricultural activities, the values were between 2 and 10%. The initial abstraction value (Ia) was calculated using this equation.

\[ I_a = 0.2 \, S \]  
\[ S = (1000/CN)^{-10}, \]  

where \( S \) is the potential maximum retention after runoff begins (in), \( I_a \) is the initial abstraction value (in), and \( CN \) is the curve number.

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Initial Abstraction (IN)</th>
<th>Curve Number</th>
<th>Impervious (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE1</td>
<td>0.94</td>
<td>68</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure D.3 Loss values entry.

The third parameter to be entered is the transform data. Transform data includes the lag time \( (t_l) \) (min). Lag time is defined as the time from the centroid of excess precipitation to the peak of the hydrograph. Lag time is calculated from the time of concentration \( (t_c) \) that is calculated using WinTR-55. According to SCS, lag time is calculated using the following equation.

\[ t_l = 0.6 \, t_c, \]  

where \( t_l \) is the lag time (min) and \( t_c \) is the time of concentration (min).
The fourth parameter to be entered is the base flow. The base flow is the flow during dry events. This flow needed to be calculated because there was no available information for the base flow for each subbasin. The flow area distribution method was used to estimate the flow in these subbasins (Viessman and Lewis 2003). In this method, the base flow at the reference point downstream is distributed on the subbasins according to their areas. An example for this calculation is presented in Section D.4 for North River. The base flow method used was constant monthly.

The first step in entering the data about the different subbasins is now complete. The second step is to enter the meteorological information about the basin. Similar to above, the SCS method was used for meteorology. The type of precipitation event is type III; this information is taken from WinTR-55 for Tuscaloosa County. The closest rain gauge during the duration of observed flows is a few miles away at the City of Tuscaloosa Municipal Airport. These rain events are recorded on daily bases. The precipitation value is entered according to the rain event into the model.

The third step is to enter the control for the simulation. This control defines the duration in which the simulation is run. The data for this part is the starting and ending dates, the starting and ending times, and the time interval.

The fourth step is to enter the available data about this basin in the time-series data. There are two available data sets: the first is the flow and the second is the precipitation. For flow, there is only one gauge in the entire basin that has data. This gauge is at the end of the basin, and it records the daily flow. This information is entered in the discharge gauges section. The precipitation data is obtained from the precipitation records at the Tuscaloosa Airport rain gauge.
Once all the information is entered, the model is ready for execution. The execution is performed under the compute pull-down menu. HEC-HMS tests the data for completion and errors in the data. After completing the execution, a table is produced for the flow values in each subbasin. A flow value is calculated for every precipitation event during the period under consideration.

D.3.1.1 Flow Model Calibration

HEC-HMS has the ability to calibrate the produced flow model. This option in HEC-HMS is under optimization. After executing the model, the generated values might be greater or less than the actual value. Optimization is the process where parameters are chosen to be calibrated in order to produce values closer to the actual ones. These parameters have enough uncertainty in them that they need to be adjusted, and the optimization order tries to reduce this uncertainty as much as possible. Therefore, the calibration of these parameters is important for the model (Scharffenberg and Fleming 2006). There are additional uncertainty values that the model cannot adjust, such as the precipitation over the entire watershed. There should be more rain gauges in the watershed and on the boundaries to be able to better represent actual rainfall over the watershed.

HEC-HMS uses Monte Carlo simulation to do multiple iterations for the parameter under consideration to get as close as possible to the actual value. The outcome of the model after calibration may diverge from or converge with the actual value. In the case of divergence, the parameter under consideration should be changed, and another parameter should be chosen to be calibrated.
In order to calibrate a simulation in HEC-HMS, the first thing is to create a new optimization trial. To create the trial, in the pull-down menu under compute there is, “Create Optimization Trial”, shown in Figure D.4.

Figure D.4 Creating an optimization trial in HEC-HMS.

After creating the trial, it is edited in the side menu under compute, where the data and information for the optimization are entered, as shown in Figure D.5.

Figure D.5 Editing optimization trials.
There are two main items to fill with the data, objective function and parameters (Figure D.6). Under objective function, the method of analysis is chosen. There is a list of six options to choose from (Figure D.6). Each method shows the users, after execution, a value that is of interest to their analysis. These values are different ways of representing the error. They do not have an effect on the flow results. The smaller these numbers are, the better the model performs. For example, in the optimization trials for this project, sum of absolute residuals was chosen.

![Figure D.6 Methods to choose from in the objective function.](image)

The second value to enter is the location. The location of interest in the project is the site downstream, where the historical data is available. This point is the reference point for the optimization trials. The third value is the missing flow as a percentage. Usually, the reference point does not have missing data, but if there is, it can be specified in this location. In this project, the value of missing flow is zero. The rest of the items are related to date and time. These values match the values entered at the beginning in control in order to calibrate the calculated values with the calibrated ones.

After entering the information in the objective function, the information is entered for the parameter item. The parameter item consists mainly of an element and a
parameter. The element is the subbasin to be calibrated. The parameter consists of the parameter for calibrating the flow through the element. There are four methods to choose from: no action, curve number, initial abstraction, or SCS lag. These choices are shown in Figure D.7.

![Figure D.7 Parameters to choose from for calibration.](image)

The curve number option calibrates the curve number value entered in the subbasin information in the beginning. The curve number window has the curve number initial value, which is the one entered. It also has the range for the minimum and maximum value for calibration, shown in Figure D.8. There is also the option to lock the element if the user does not want to change the value for that subbasin.
The SCS lag option calibrates the lag time for the unit hydrograph. The value for lag time for the element is the one entered previously for the run. The optimization window consists also of the minimum and maximum lag time range for calibration (refer to Figure D.9).

The final option is the initial abstraction parameter, as shown in Figure D.10. This option calibrates the initial abstraction value $I_a$ that was entered in the curve number loss...
parameter. Similar to the previously discussed parameters, the initial abstraction has a minimum and maximum value.

![Initial abstraction parameter window](image)

Figure D.10 Initial abstraction parameter window.

The three parameters were tested to find out which one calibrates the simulation to get as close as possible to the actual value. Each one of these calibration parameters may converge, diverge, or have no effect on the simulated value. The initial abstraction parameter had a minimal or no effect on the values. The curve number and the SCS lag parameters were the ones successful in calibrating the simulation. The SCS lag parameter calibration trials were more successful than the curve number trials.

The following is an example that shows how HEC-HMS calibrated the values of the simulation for a flow. The run is for a rain event in January, where the precipitation was 1.03 inches. The actual flow on that day was 639 cfs. The simulated value for the flow was 784.7 cfs, as shown in Figure D.11. The flow was calibrated using the SCS lag parameter. After the calibration trial was run, the simulated flow value was 633.8 cfs, as shown in Figure D.12.
Figure D.11 Results of the simulation without calibration.

Figure D.12 Results of simulation with calibration.
This calibration shows that HEC-HMS, depending on the available data, can be close to the actual flow value. The comparison between the actual and the calibrated flows are further discussed in the following sections.

D.4 North River Flow Model

D.4.1 Introduction

North River basin is the main and largest source of water for Lake Tuscaloosa. The main flow into the River comes from this basin. North River basin has an area of 238 square miles (56% of the watershed area), as shown in Figure D.13. The basin is located in both Tuscaloosa and Fayette counties. It is divided into 45 subbasins. The thick blue line in the middle of the basin in Figure D.13 is North River. This basin is only monitored by one USGS flow station, USGS site # 02464000; the downstream point is marked in red on the map in Figure D.13. This station is the only reference point for the simulation, analysis, and calibration of flow for the entire basin.
This gauge station has flow data from 1938 until today. Initially the period of interest is from 1998 to 2007. This period was chosen because it covers the same period as the City of Tuscaloosa *E.coli* sampling period around the lake. The second period of interest is the flow in 2005 during the collection of samples by the GSA, and this year is the one that is used in the *E.coli* model. The reason is that there are no *E.coli* data that can be correlated with the precipitation and flow during that period for the whole basin, except in 2005. The GSA sampled in the basin during two periods.

The flow and precipitation time series plot from 1998 until 2007 at the USGS station is shown in Figure D.14. The time series plot for 2005 is in Figure D.15.
Figure D.14 Flow and precipitation time series for North River during 1998-2005.

Figure D.15 Flow and precipitation time series for North River during 2005.
D.4.2 Data Entry

The flow diagram for North River basin was divided into two figures, due to its large size. The first figure, Figure D.16, is from upstream until station NR5 (J17), and the second figure, Figure D.17, is from NR5 (J17) to downstream.

After mapping the subbasins, data for each subbasin was entered into the model. The area data was from appendix A. The initial abstraction and lag time are presented in Table D.1. The CN can be retrieved from the initial abstraction equation.

Figure D.16 North River basin from upstream to station NR5 (J17).
Figure D.17 North River basin from NR5 (J17) to downstream.
Table D.1 Initial Abstraction and Lag Time Values for North River Subbasins

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Initial Abstraction (in)</th>
<th>Lag time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE1</td>
<td>1.08</td>
<td>90.48</td>
</tr>
<tr>
<td>BO1</td>
<td>1.13</td>
<td>27.12</td>
</tr>
<tr>
<td>BO2</td>
<td>0.90</td>
<td>54.30</td>
</tr>
<tr>
<td>BR1</td>
<td>1.08</td>
<td>30.36</td>
</tr>
<tr>
<td>BR2</td>
<td>1.17</td>
<td>33.48</td>
</tr>
<tr>
<td>BS1</td>
<td>1.23</td>
<td>81.6</td>
</tr>
<tr>
<td>BY1</td>
<td>0.86</td>
<td>3.60</td>
</tr>
<tr>
<td>CA1</td>
<td>0.99</td>
<td>31.2</td>
</tr>
<tr>
<td>CA2</td>
<td>1.23</td>
<td>13.08</td>
</tr>
<tr>
<td>CE1</td>
<td>0.94</td>
<td>68.04</td>
</tr>
<tr>
<td>CE2</td>
<td>1.17</td>
<td>19.98</td>
</tr>
<tr>
<td>CE3</td>
<td>0.94</td>
<td>12.48</td>
</tr>
<tr>
<td>CE4</td>
<td>0.99</td>
<td>14.28</td>
</tr>
<tr>
<td>CL1</td>
<td>1.23</td>
<td>26.10</td>
</tr>
<tr>
<td>CL2</td>
<td>1.17</td>
<td>48.48</td>
</tr>
<tr>
<td>CL3</td>
<td>1.17</td>
<td>35.52</td>
</tr>
<tr>
<td>CL4</td>
<td>1.17</td>
<td>30.90</td>
</tr>
<tr>
<td>CP1</td>
<td>1.70</td>
<td>30.48</td>
</tr>
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<td>DC1</td>
<td>1.23</td>
<td>46.44</td>
</tr>
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<td>DCT</td>
<td>1.23</td>
<td>26.10</td>
</tr>
<tr>
<td>EC1</td>
<td>1.23</td>
<td>23.88</td>
</tr>
<tr>
<td>FC1</td>
<td>0.86</td>
<td>11.10</td>
</tr>
<tr>
<td>GB1</td>
<td>1.23</td>
<td>37.68</td>
</tr>
<tr>
<td>GC1</td>
<td>1.57</td>
<td>52.08</td>
</tr>
<tr>
<td>HC1</td>
<td>1.17</td>
<td>108.24</td>
</tr>
<tr>
<td>LB1</td>
<td>1.28</td>
<td>28.86</td>
</tr>
<tr>
<td>LC1</td>
<td>1.23</td>
<td>33.30</td>
</tr>
<tr>
<td>LK1</td>
<td>1.17</td>
<td>20.94</td>
</tr>
<tr>
<td>LY1</td>
<td>0.86</td>
<td>31.62</td>
</tr>
<tr>
<td>NR0</td>
<td>1.17</td>
<td>39.78</td>
</tr>
<tr>
<td>NR1</td>
<td>0.99</td>
<td>3.60</td>
</tr>
<tr>
<td>NR2</td>
<td>1.08</td>
<td>35.40</td>
</tr>
<tr>
<td>NR3</td>
<td>0.90</td>
<td>11.10</td>
</tr>
<tr>
<td>NR4</td>
<td>0.82</td>
<td>28.20</td>
</tr>
<tr>
<td>NR5</td>
<td>0.90</td>
<td>139.96</td>
</tr>
<tr>
<td>NR6</td>
<td>0.94</td>
<td>92.70</td>
</tr>
<tr>
<td>NR7</td>
<td>1.23</td>
<td>123.60</td>
</tr>
<tr>
<td>NR8</td>
<td>1.23</td>
<td>38.94</td>
</tr>
<tr>
<td>NR9</td>
<td>1.28</td>
<td>80.28</td>
</tr>
<tr>
<td>NT1</td>
<td>0.90</td>
<td>10.74</td>
</tr>
<tr>
<td>NT2</td>
<td>1.13</td>
<td>9.12</td>
</tr>
<tr>
<td>RB1</td>
<td>1.23</td>
<td>22.20</td>
</tr>
<tr>
<td>SPC</td>
<td>1.03</td>
<td>23.16</td>
</tr>
<tr>
<td>TC1</td>
<td>1.08</td>
<td>90.48</td>
</tr>
<tr>
<td>TC2</td>
<td>1.17</td>
<td>31.56</td>
</tr>
</tbody>
</table>
D.4.2.1 North River Base Flow

The base flow for the North River subbasins was based on distributing the flow measured at the downstream station (USGS station) over the subbasins according to their areas, in comparison to the total area of the basin. The average base flow for North River was approximately 45 cfs. The base flow was distributed over the subbasins, starting from downstream to upstream. For example, the average base flow through station NR1 is 45 cfs. This flow is the total flow coming from all the subbasins into this point, including the NR1 subbasin itself. The contribution of NR1 subbasin is calculated as follows.

\[ q = Q \left( \frac{a}{A} \right) \]

where \( q \) is flow from subbasin (cfs), \( Q \) is the total flow at point downstream (cfs), \( a \) is the subbasin area, and \( A \) is the total area.

Flow from NR1 = 45 cfs \( \times \frac{(18.35 \text{mi}^2)}{(238 \text{ mi}^2)} \)

= 3.47 cfs

The flow coming into NR1 subbasin is coming from NR2 and CP1. CP1 does not have subbasins above it. Therefore, the flow from CP1 subbasin is as follows.

Flow from CP1 = 45 cfs \( \times \frac{(12.21 \text{ mi}^2)}{(238 \text{ mi}^2)} \)

= 2.31 cfs

The remaining flow for the rest of the subbasins, which is for NR2, is the original flow (45 cfs) minus the flow from CP1 and NR1.

NR2 flow = 45 cfs \(-\) (3.47 cfs + 2.31 cfs)

= 39.22 cfs
This flow (39.22) was distributed over the rest of the subbasins, similar to the calculation above. A summary of the flow in every subbasin is shown in Table D.2. After all this data was entered into the model and executed, the results were retrieved and analyzed. The analysis is presented in Chapter V.
Table D.2 Base Flow in North River Subbasins

<table>
<thead>
<tr>
<th>River/Creek</th>
<th>Subbasin</th>
<th>Expected Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North River</td>
<td>NR1</td>
<td>3.47</td>
</tr>
<tr>
<td>Cripple Creek</td>
<td>CP1</td>
<td>2.31</td>
</tr>
<tr>
<td>North River</td>
<td>NR2</td>
<td>2.33</td>
</tr>
<tr>
<td>North River Tributaries</td>
<td>NT1</td>
<td>0.53</td>
</tr>
<tr>
<td>Gin Branch</td>
<td>GB1</td>
<td>0.45</td>
</tr>
<tr>
<td>Bear Creek</td>
<td>BE1</td>
<td>2.86</td>
</tr>
<tr>
<td>Tyro Creek</td>
<td>TC1</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>TC2</td>
<td>4.07</td>
</tr>
<tr>
<td>Boone Creek</td>
<td>BO1</td>
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</tr>
<tr>
<td></td>
<td>BO2</td>
<td>0.84</td>
</tr>
<tr>
<td>North River</td>
<td>NR3</td>
<td>0.74</td>
</tr>
<tr>
<td>North River</td>
<td>NR4</td>
<td>0.67</td>
</tr>
<tr>
<td>Freeman Creek</td>
<td>FC1</td>
<td>0.43</td>
</tr>
<tr>
<td>North River</td>
<td>NR5</td>
<td>2.54</td>
</tr>
<tr>
<td>North River Tributaries</td>
<td>NT2</td>
<td>0.15</td>
</tr>
<tr>
<td>Sandy Point Creek</td>
<td>SPC</td>
<td>1.14</td>
</tr>
<tr>
<td>Cedar Creek and Tributaries</td>
<td>CE1</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>CE2</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>CE3</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>CE4</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>LC1</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>BY1</td>
<td>0.19</td>
</tr>
<tr>
<td>Rocky Branch</td>
<td>RB1</td>
<td>0.27</td>
</tr>
<tr>
<td>North River</td>
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</tr>
<tr>
<td>Clear Creek</td>
<td>CL1</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>CL2</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>CL3</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>CL4</td>
<td>0.15</td>
</tr>
<tr>
<td>Deadwater Creek</td>
<td>DCT</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>DC1</td>
<td>2.04</td>
</tr>
<tr>
<td>North River</td>
<td>NR7</td>
<td>1.10</td>
</tr>
<tr>
<td>North River</td>
<td>EC1</td>
<td>0.46</td>
</tr>
<tr>
<td>North River</td>
<td>NR8</td>
<td>0.72</td>
</tr>
<tr>
<td>Laney Branch</td>
<td>LB1</td>
<td>0.17</td>
</tr>
<tr>
<td>Cane Creek</td>
<td>CA1</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>CA2</td>
<td>0.37</td>
</tr>
<tr>
<td>North River</td>
<td>NR9</td>
<td>2.19</td>
</tr>
<tr>
<td>George Creek</td>
<td>GC1</td>
<td>1.58</td>
</tr>
<tr>
<td>Lowery Branch</td>
<td>LY1</td>
<td>0.24</td>
</tr>
<tr>
<td>Hendon Creek</td>
<td>HC1</td>
<td>0.32</td>
</tr>
<tr>
<td>North River</td>
<td>NR0</td>
<td>0.69</td>
</tr>
<tr>
<td>Tanyard Creek</td>
<td>TD1</td>
<td>0.59</td>
</tr>
<tr>
<td>Lick Creek</td>
<td>LK1</td>
<td>0.23</td>
</tr>
<tr>
<td>Beaver Creek</td>
<td>BR1</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>BR2</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>45.00</strong></td>
</tr>
</tbody>
</table>
D.5 Binion Creek Flow Model

D.5.1 Introduction

The Binion Creek basin is the second largest basin in the watershed. This basin has an area of 40 square miles (10% of the watershed area, shown in Figure D.18). The majority of the basin is located in Tuscaloosa County. It is divided into nine subbasins. This basin is only monitored by one USGS flow station, USGS site # 02464360, the downstream point on the map in Figure D.18. This station is the only reference point for the simulation, analysis, and calibration of flow for this basin.

Similar to North River, the period of interest to model the flow is from 1998 to 2007. The second period of interest is the flow in 2005 during the collection of samples by the GSA, and this year is the one that is used in the E.coli model. The flow and precipitation time series plot from 1998 until 2007 at the USGS station is shown in Figure D.19. For the year 2005, the plot is presented in Figure D.20.
Figure D.18 Binion Creek basin in Lake Tuscaloosa watershed.

Figure D.19 Flow and precipitation from January 1998 until January 2007.
D.5.2 Data Entry

The flow diagram for Binion Creek basin is presented in Figure D.21. After mapping the subbasins, data for each subbasin was entered into the model. The area data was from appendix A. The initial abstraction and lag time are presented in Table D.3. The CN can be retrieved from the initial abstraction equation.
Table D.3 Initial Abstraction and Lag Time Values for Binion Creek Subbasins

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Initial Abstraction (in)</th>
<th>Lag time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1</td>
<td>1.19</td>
<td>180.5</td>
</tr>
<tr>
<td>BC2</td>
<td>1.17</td>
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<tr>
<td>BC3</td>
<td>1.23</td>
<td>95.4</td>
</tr>
<tr>
<td>BT1</td>
<td>0.92</td>
<td>116.6</td>
</tr>
<tr>
<td>BT2</td>
<td>1.05</td>
<td>46.7</td>
</tr>
<tr>
<td>BT3</td>
<td>1.13</td>
<td>79.4</td>
</tr>
<tr>
<td>BT4</td>
<td>1.25</td>
<td>52.6</td>
</tr>
<tr>
<td>BT5</td>
<td>1.08</td>
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</tr>
<tr>
<td>BT6</td>
<td>0.99</td>
<td>74.0</td>
</tr>
</tbody>
</table>

D.5.2.1 Binion Creek Base Flow

The base flow for the Binion Creek subbasins was based on distributing the flow measured at the downstream station (USGS station) over the subbasins according to their areas related to the total area of the basin. The average base flow for Binion Creek was approximately 30 cfs. The base flow was distributed over the subbasins, starting from...
downstream to upstream. A summary of the flow in every subbasin is shown in Table D.4.

Table D.4 Base Flow in Binion Creek Subbasins

<table>
<thead>
<tr>
<th>River/Creek</th>
<th>Subbasin</th>
<th>Expected Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tributary</td>
<td>BT6</td>
<td>4.82</td>
</tr>
<tr>
<td></td>
<td>BT5</td>
<td>2.52</td>
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<tr>
<td></td>
<td>BT4</td>
<td>1.34</td>
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<td></td>
<td>BT3</td>
<td>2.17</td>
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</tr>
<tr>
<td></td>
<td>BC1</td>
<td>30.00</td>
</tr>
</tbody>
</table>

After all this data was entered to the model and executed, the results were retrieved and analyzed. The analysis is shown in Chapter V.

**D.6 Summary**

The flow models for both North River and Binion Creek basins were built according to the best available data about them. It is important to collect more data about this watershed in order to reduce the uncertainty in the parameters. This reduction in uncertainty increases the accuracy of the results from the models.