PITTSBURGH WATER AND SEWER AUTHORITY COMPREHENSIVE DISTRIBUTION SYSTEM FLUORIDE TRACER STUDY

by

Colleen Rae Daley

B.S., University of Pittsburgh, 2005

Submitted to the Graduate Faculty of

School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2007

UNIVERSITY OF PITTSBURGH

SCHOOL OF ENGINEERING

This thesis was presented

by

Colleen Rae Daley

It was defended on

June 5, 2007

and approved by

Dr. Leonard Casson, Associate Professor, Civil and Environmental Engineering

Dr. Daniel Budny, Associate Professor, Civil and Environmental Engineering

Dr. Stanley States, Water Laboratory Manager, Pittsburgh Water and Sewer Authority

Thesis Advisor: Leonard Casson, Associate Professor, Civil and Environmental Engineering

PITTSBURGH WATER AND SEWER AUTHORITY COMPREHENSIVE DISTRIBUTION SYSTEM FLUORIDE TRACER STUDY

Colleen Rae Daley, M.S.

University of Pittsburgh, 2007

The Stage 2 Disinfectants and Disinfection Byproduct Rule (Stage 2 DBPR) builds on the Stage 1 Disinfectant and Disinfection Byproduct Rule (Stage 1 DBPR) and strengthens public health protection for utility customers by tightening compliance monitoring requirements for disinfection byproduct (DBP) formation, including total trihalomethanes (TTHM) and haloacetic acids (HAA5), in finished drinking water. All community water systems and non-community water systems which add a disinfectant to their finished water, excluding ultraviolet light, are required to comply [EPA, 2006]. Many of these drinking water systems will not be able to comply with the Stage 2 DBPR unless changes are made to their treatment or distribution system to improve water quality. One way to asses the degradation of water in distribution systems and identify operational improvements is through a tracer study.

Pittsburgh Water and Sewer Authority (PWSA) completed a fluoride tracer study from October to December, 2006. The tracer study data were used to assess the aging of water from the PWSA clearwell to selected sampling points in the distribution system. The results were also used to evaluate the mixing of the primary reservoirs, to calibrate the hydraulic model, and to identify potential operational improvements to increase water quality and balance of the distribution system prior to completing the Initial Distribution System Evaluation (IDSE) for the Stage 2 DBPR.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS XV

INTRODUCTION 1

1.0 BACKGROUND 3

1.1 PITTSBURGH WATER AND SEWER AUTHORITY 3

1.1.1 Capacity and Demands of Distribution System 3

1.1.2 Pumpage 5

1.1.3 Pressure Zones 7

1.1.4 Finished Water Storage 9

1.1.5 Treatment Operations and Water Quality 13

1.1.6 PWSA Hydraulic Model 16

1.2 PREVIOUS TRACER STUDIES 17

1.2.1 Distribution System Tracer Case Studies 19

1.2.1.1 Avon Lake, Ohio 19

1.2.1.2 Raleigh, North Carolina 20

1.2.1.3 Durham, North Carolina 20

1.2.1.4 Phoenix, Arizona 21

1.2.1.5 Denver, Colorado 23

1.2.1.6 Fort Collins, Colorado 25

1.2.2 Properties of Tracers 28

1.2.3 Conducting a Tracer Study ... 29
1.2.3.1 Types of Reactors ... 29
1.2.3.2 Pulse Input Tracer Test ... 30
1.2.3.3 Step Input Tracer Test ... 31
1.2.4 Transport Time Scales and Formulations ... 32
1.3 WATER QUALITY IN THE DISTRIBUTION SYSTEM ... 38
1.3.1 Water Age and Disinfection Byproduct Formation ... 39
1.3.2 Causes of Excessive Water Age ... 40
1.3.3 Disinfection Byproduct Formation ... 41
1.3.4 Disinfectant/Disinfection Byproduct Regulations ... 44
1.3.5 Chlorine vs. Chloramines Disinfectant ... 45
1.4 FINISHED WATER STORAGE FACILITIES ... 46
1.4.1 Reservoir Mixing ... 47
1.4.2 Potential Risks ... 49
1.4.2.1 Sediment ... 49
1.4.2.2 Physical Contamination. ... 50
1.4.2.3 Uncovered Reservoirs. ... 51
1.4.2.4 Floating Covers ... 51
1.4.3 Indication of Water Quality Problems ... 51
2.0 MATERIALS AND METHODS ... 53
2.1 PERMITTING ... 54
2.2 FLUORIDE SAMPLING ... 55
2.2.1 Selection of Sample Locations ... 55
2.2.2 Field Equipment and Set-up ... 62

2.2.2.1 Autosamplers ... 64

2.2.2.2 Hydrants ... 69

2.2.3 Sample Collection ... 71

2.2.3.1 Fluoride Samples ... 71

2.2.3.2 Disinfection Byproduct Samples ... 78

2.2.4 Sampling Crews and Routes ... 78

2.2.5 Laboratory Analysis ... 79

2.2.6 Tracer Study Execution ... 79

3.0 RESULTS AND DISCUSSION ... 82

3.1 DETERMINATION OF AVERAGE WATER AGE ... 82

3.1.1 Average Water Ages in the PWSA Distribution System ... 85

3.1.2 TTHM Formation in the PWSA Distribution System ... 90

3.2 EFFECTS OF FINISHED WATER STORAGE FACILITIES ... 95

3.2.1 Highland No. 1 Reservoir ... 96

3.2.1.1 Highland No. 1 Sediment Accumulation ... 96

3.2.1.2 Mean Residence Time in Highland No. 1 Reservoir ... 100

3.2.1.3 Highland No. 1 Mixing ... 103

3.2.1.4 Highland No. 1 Reservoir Security ... 108

3.2.2 Highland No. 2 Reservoir ... 109

3.2.2.1 Highland No. 2 Mean Residence Time ... 109

3.2.2.2 Highland No. 2 Mixing ... 114

3.2.3 Lanpher Reservoir ... 117

3.2.3.1 Lanpher Reservoir Mean Residence Time ... 117

3.2.3.2 Lanpher Reservoir Mixing ... 125

3.2.4 Herron Hill Reservoir 130

3.2.5 Effects of Highland No. 2 and Lanpher Reservoir Supersystem Separation 133

4.0 SUMMARY AND CONCLUSIONS 140

5.0 RECOMMENDATIONS FOR FUTURE STUDIES 146

APPENDIX A 149

APPENDIX B 180

APPENDIX C 183

APPENDIX D 185

APPENDIX E 189

APPENDIX F 191

BIBLIOGRAPHY 193

ABBREVIATIONS 197

LIST OF TABLES

Table 1. Water quality problems associated with increased water age.. 39

Table 2. Summary of water quality problems associated with finished water storage facilities .. 49

Table 3. Fluoride sampling location identification names and descriptions................................ 58

Table 4. Standard settings for autosamplers. 66

Table 5. Adjusted concentrations used to determine the amount of time for 10, 20, 50, 80, and 90 percent of tracer to pass through the sampling point.. 84

Table 6. Average water age estimates (T_{50} values) from fluoride tracer response curves........... 86

Table 7. Highland No. 1 Reservoir depth. 97

Table 8. Highland No. 1 Reservoir theoretical hydraulic detention times................................. 102

Table 9. Highland No. 2 Reservoir theoretical detention time estimation................................. 111

Table 10. Average flow rate pumped to Highland No. 2 Reservoir during Phase II................. 113

Table 11. Lanpher Reservoir capacity and theoretical detention time estimates....................... 120

Table 12. Lanpher Reservoir comparison of the balance between the two cells 130

Table 13. PWSA average water ages and corresponding TTHM concentrations...................... 180

LIST OF FIGURES

Figure 1. Highland No. 1 and No. 2 Reservoir influent and effluent locations 6

Figure 2. PWSA water storage facility and pump station locations. 7

Figure 3. Normalized pulse output for ideal CSTR, CSTR in series, and PFR 31

Figure 4. Normalized step-output for an ideal CSTR, CSTRs in series, and PFR 32

Figure 5. Difference between water age and residence time 33

Figure 6. Step-up tracer response curve of concentration versus time (A) and F-curve or normalize concentration versus time (B) 35

Figure 7. Area above the F-curve determines the MRT 36

Figure 8. Step-Down tracer response curve in response to ideal step-down tracer feed 38

Figure 9. Fluoride sampling locations. 57

Figure 10. Highland No. 2 Reservoir hatch sampling sites and ID names. 61

Figure 11. Lanpher Reservoir hatch sampling sites and ID names... 62

Figure 12. Safety apparel for collecting floating cover hatch samples....................................... 64

Figure 13. Autosampler digital display interface.. 66

Figure 14. Highland No. 2 autosampler (A07) - Collecting samples from wetwell.................... 68

Figure 15. Site A01 - Sampling the effluent channel from the East Lanpher Reservoir Cell. 68

Figure 16. Herron Hill Pump Sta. (A10) - Autosampler connection to pressure main................ 69

Figure 17. Hydrant continuous monitoring equipment setup 70

Figure 18. Autosampler sample bottle collection 72

Figure 19. Labeled sample bottles in collection box. 73

Figure 20. Hydrant continuous sampler. 74

Figure 21. Collecting data from hydrant continuous fluoride analyzer. 74

Figure 22. Highland No. 1 Reservoir - Collecting sample and recording GPS location. 76

Figure 23. Lanpher Reservoir, dropping sampler down through hatch. 77

Figure 24. Collecting sample from cover of Lanpher Reservoir. 77

Figure 25. Average water age timeline, Phase I and II comparison. 92

Figure 26. Sampling site T_{50} estimations vs. TTHM concentrations. 94

Figure 27. Sampling site with T_{50} values estimations < 280 hours vs. TTHM concentrations. 95

Figure 28. Highland No. 1 depth meter. 97

Figure 29. Sediment accumulation in the southeast corner of the east Highland No. 1 Basin. 98

Figure 30. Locations of extensive sediment accumulation in Highland No. 1 Reservoir. 99

Figure 31. MRT of Highland No. 1 Reservoir Phase I. 101

Figure 32. Highland No. 1 Phase II response curve. 104

Figure 33. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 10/24/2006. 105

Figure 34. Location of abandoned outlets in Highland No. 1 Reservoir. 107

Figure 35. Highland No. 2 Reservoir pumping rates, depths, and fluoride concentrations. 110

Figure 36. Highland No. 2 Reservoir response curves. 112

Figure 37. Highland No. 2 influent and effluent response curves and T_{50} values. 114

Figure 38. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 11/15/06. 115

Figure 39. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 11/20/06. 117

Figure 40. Lanpher Reservoir depth, fluoride response curves, and rate of pumping to the reservoir. 119

Figure 41. Lanpher Reservoir Phase II - T_{50} approximation. 122

Figure 42. Lanpher Reservoir Phase I - T_{50} approximations. 124

Figure 43. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/17/2006........... 127

Figure 44. Lanpher Reservoir effluent channel and floating cover grab sample fluoride concentrations.. 128

Figure 45. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 10/27/2006........... 129

Figure 46. Lanpher Reservoir Phase I average hatch sample results from the west and east basins compared to the effluent channel data... 130

Figure 47. Herron Hill Reservoir influent and effluent response curves (Phase I & Phase II). . 132

Figure 48. Lanpher and Highland No. 2 Reservoirs daily pumping rates and water levels. 135

Figure 49. Lanpher Reservoir Phase I data comparison to hatch grab samples, Highland No. 2 Reservoir, Millvale, and Howard Pump Station 136

Figure 50. Lanpher Reservoir Phase II - Comparison of grab sample concentrations in the reservoir and concentrations after the reservoir. 138

Figure 51. Site W01 - Clearwell tracer response curves.. 149

Figure 52. Site A01 - Lanpher Reservoir east effluent tracer response curves.......................... 150

Figure 53. Site A02 - Lanpher Reservoir west effluent tracer response curves. 150

Figure 54. Site A03 - Lanpher Reservoir influent fluoride tracer response curves. 151

Figure 55. Site A04 - Bruecken Pump Station (Highland No. 1 Reservoir influent) tracer response curves. 151

Figure 56. Site A05 - Bruecken Pump Station (Highland No. 2 Reservoir influent) tracer response curves. 152

Figure 57. Site A06 - Highland No. 1 Reservoir tracer response curves.................................. 152

Figure 58. Site A07 - Highland No. 2 Reservoir effluent tracer response curves. 153

Figure 59. Site A09 - Mission Pump Station Tracer Response Curves 153

Figure 60. Site A10 - Herron Hill Reservoir influent tracer response curves............................ 154

Figure 61. Site A08 - Howard Pump Station tracer response curves.. 154

Figure 62. Site A11 - Herron Hill Reservoir effluent tracer response curves............................ 155

Figure 63. Site P01 - 27 Perryview Avenue tracer response curves... 155

Figure 64. Site P02 - 3133 Brunot Avenue tracer response curves. 156

Figure 65. Site P03 - 1114 Colfax Street tracer response curves.. 156

Figure 66. Site P04 - 6433 Forward Avenue tracer response curves.. 157

Figure 67. Site P05 - 5838 Darlington Road tracer response curves.. 157

Figure 68. Site H01 - Hydrant 1(401 Well Street) tracer response curves. 158

Figure 69. Site H02 - Hydrant 2 (1713 Brighton Road) tracer response curves........................ 158

Figure 70. Site H03 - Hydrant 3 (Termon Avenue) tracer response curves. 159

Figure 71. Site H04 - Hydrant 4 (4260 Evergreen Road) tracer response curves. 159

Figure 72. Site H05 - Hydrant 5 (Perrysville & Ivory Avenue) tracer response curves............ 160

Figure 73. Site H06 - Hydrant 6 (Penn Ave., between 39th & 40th St.) tracer response curves.160

Figure 74. Site H07 - Hydrant 7 (Lincoln Avenue & Joshua Street) tracer response curves..... 161

Figure 75. Site H08 - Hydrant 8 (Love Street, first hydrant on left off Whipple Street) tracer response curves. 161

Figure 76. Site H09 - Hydrant 9 (Bigelow & Tesla Street) tracer response curves................... 162

Figure 77. Site H10 - Hydrant 10 (Chartiers & Lorenz Street) tracer response curves............. 162

Figure 78. Site H11 - Hydrant 11 (Mon Warf Parking Lot) tracer response curves.................. 163

Figure 79. Site M01 - 114 Grant Avenue, Grant's Bar (Millvale) tracer response curves. 163

Figure 80. Site M02 - 1201 North Avenue, Hardees (Millvale) tracer response curves. 164

Figure 81. Millvale Sites M01, M02, M03 - Phase I tracer response curves comparison.......... 164

Figure 82. Millvale Sites M01, M02, M03 - Phase II tracer response curve comparison.......... 165

Figure 83. Site M03 - 232 North Avenue, P&G Diner (Millvale) tracer response curves......... 165

Figure 84. Site R01 - 4000 Mt Troy Road, cemetery (Reserve) tracer response curves. 166

Figure 85. Site R02 - 116 Biscayne Terrace, fire station (Reserve) tracer response curves....... 166

Figure 86. Site R03 - 33 Lonsdale Street, fire station (Reserve) tracer response curves............ 167

Figure 87. Site R04 - 2000 Mount Troy Road, bank (Reserve) tracer response curves. 167

Figure 88. Reserve Sites R01 through R05 - Phase I tracer response curves comparison. 168

Figure 89. Reserve Sites R01 through R05 - Phase II tracer response curves comparison. 168

Figure 90. Site R05 - 3367 Spring Garden Road (Reserve) tracer response curves. 169

Figure 91. Site F01 - Feed @ Rockwood Valve Station (Fox Chapel) tracer response curves.. 169

Figure 92. Site F02 - 1003 Fox Chapel Road (Fox Chapel) tracer response curves.................. 170

Figure 93. Site F03 - 280 Kappa Drive (Fox Chapel) tracer response curves. 170

Figure 94. Site F04 - Hampton Twp. Interconnect (Fox Chapel) tracer response curves. 171

Figure 95. Site F05 - Blawnox Boro Interconnect (Fox Chapel) tracer response curves. 171

Figure 96. Site F06 - 928 Field Club Road (Fox Chapel) tracer response curves. 172

Figure 97. Site F07 - 341 Kittanning Pike (Fox Chapel) tracer response curves. 172

Figure 98. Site F08 - 503 Guys Run Road (Fox Chapel) tracer response curves. 173

Figure 99. Site F09 - 3563 Harts Run Road (Fox Chapel) tracer response curves.................... 173

Figure 100. Site F10 - 502 Guyasuta Road (Fox Chapel) tracer response curves. 174

Figure 101. Site C01 - Baker Hall (CMU) tracer response curves. 174

Figure 102. Site C02 - Hunt Library (CMU) tracer response curves... 175

Figure 103. Site C03 - Porter Hall (CMU) tracer response curves. 175

Figure 104. Site C04 - Purnell Hall (CMU) tracer response curves. 176

Figure 105. Site C05 - Robert's Hall (CMU) tracer response curves. 176

Figure 106. Site C06 - Tepper School (CMU) tracer response curves. 177

Figure 107. Site C07 - University Center (CMU) tracer response curves. 177

Figure 108. Site C08 - Warner Hall (CMU) tracer response curves.. 178

Figure 109. Site C09 - Wean Hall (CMU) tracer response curves. 178

Figure 110. CMU Sites C01 through C09 - Phase I tracer response curve comparison............ 179

Figure 111. CMU Sites C01 through C09 - Phase II tracer response curve comparison. 179

Figure 112. Phase I and Phase II TTHM versus total chlorine residual 183

Figure 113. Phase I - TTHM & total chlorine residual versus time 184

Figure 114. Phase II - TTHM & total chlorine residual versus time 184

Figure 115. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 10/19/2006........ 185

Figure 116. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 10/27/2006........ 186

Figure 117. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/14/2006........ 186

Figure 118. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/17/2006........ 187

Figure 119. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/20/2006........ 187

Figure 120. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/22/2006........ 188

Figure 121. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/27/2006........ 188

Figure 122. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 10/26/06. 189

Figure 123. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 11/27/06. 190

Figure 124. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/14/2006......... 191

Figure 125. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/21/2006......... 192

Figure 126. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/28/2006......... 192

ACKNOWLEDGEMENTS

As a child growing up, I was always fascinated with water and loved to play in water. Ironically, my graduate research involved millions of gallons of water.

Many thanks to Dr. Leonard Casson and Dr. Dan Budny of the University of Pittsburgh and Dr. Stanley States of Pittsburgh Water and Sewer Authority (PWSA) for serving on my committee and their advice and critique. My thanks also go to Dr. Jeanne VanBriesen of Carnegie Mellon University for her helpful insight on the analysis of the study.

It is a pleasure to thank Dr. Casson and Dr. States for getting me involved with exciting and challenging drinking water distribution system fluoride tracer study. Dr. Casson, my advisor and professor, supported and guided me through this research project and during my career at Pitt. Dr. States was instrumental in defining, promoting, and completing this effort.

I want to express my gratitude to PWSA for the opportunity to take part in the PWSA fluoride tracer study. I appreciated the following PWSA employees for their hard work and assistance during the study: Gina Cyprych, Kristen Doyle, Kelly Hays, Shawnelle Jackson, Mark Stoner, and Chris Westbrook. Their dedication to this study made it possible and a success. My thanks also go to Tom Gigliotti at PWSA for his advice and support during this study.

Thank you to my loving and supportive parents, Bob and Sandra Daley, who have always believed in me and have encouraged me to reach for the stars. I followed brother's footsteps to Pitt and I want to thank him, Pat Daley, for being there for me. I want to thank Nick Elliott for his love, support, and patience. I am also grateful for my colleagues in graduate school Ana Maria Benavides, Xihua Chen, and Troy Williams who have become dear friends.

INTRODUCTION

The Pittsburgh Water and Sewer Authority (PWSA) is a public drinking water utility serving a very hilly distribution system with 15 pressure zones. The PWSA distribution system is complex containing 1,200 miles of distribution mains, four finished water reservoirs (several holding >100 million gallons of water), 10 finished water storage tanks, 11 pumping stations, and seven chlorine booster stations. Because the utility has only one water source, one drinking water treatment plant, and no substantial backup finished water supply available from neighboring utilities, PWSA must rely on several days of stored water for emergencies.

The large volume of stored finished drinking water in the system makes it difficult to control disinfection byproduct (DBP) concentrations at the far reaches of the distribution system. PWSA conducted two fluoride tracer studies, for the entire water system, including three consecutive systems, in an effort to obtain accurate information on water age in the distribution system and ultimately to calibrate the utility's recently upgraded hydraulic model. During the first study, the addition of fluoride to the finished water leaving the plant was discontinued for a three week period and the decreasing concentrations of fluoride were measured at 58 locations throughout the distribution system. The second tracer study was conducted with resumption of fluoridation at the treatment plant and measurement of increasing fluoride levels at the same locations in the distribution system.

The data from the two tracer studies provided valuable information concerning the age of water in various parts of the distribution system, flow of water through the city, circulation of water within finished water reservoirs, and mean residence time (MRT) in the primary reservoirs. Preliminary results from the first tracer study revealed imbalances in the distribution and storage system that were addressed prior to the second test. These imbalances included substantial differences in detention time between paired cells of a 133 million gallon finished water reservoir, and an extensive mixing of finished water between two major pressure zones. The Phase II results showed improved balance of water utilization between the two pressure zones and improved balance of water ages between the two reservoir basins after closing the river-crossings and adjusting the effluent gates of the two reservoir cells. The data obtained from the tracer study was also used to calibrate the PWSA hydraulic model, but the data alone were found to be very useful in analyzing the PWSA distribution system, identifying problematic areas, and determining potential operational adjustments to aid in compliance with regulations such as the Stage 2 Disinfectants and Disinfection Byproduct Rule (Stage 2 DBPR).

1.0 BACKGROUND

1.1 PITTSBURGH WATER AND SEWER AUTHORITY

The Aspinwall Water Treatment Plant is located on the north bank of the Allegheny River. The plant intakes draw water from the Allegheny River for treatment. The goal of PWSA is to provide high quality water to customers with sufficient pressure at minimal cost.

1.1.1 Capacity and Demands of Distribution System

The PWSA distribution system is robust with sufficient pump, storage, and pipe network capacity to meet current and future population, fire flow, and emergency demands. The distribution system has 10 pump stations within the 15 pressure zones. The elevation changes and large service area provide for great variability within the system and the vast service area with multiple storage facilities creates for long detention times in the system.

System demand is a function of water usage patterns and temporal and diurnal variations. The PWSA system has variations in water demands depending on industrial and commercial usage, seasons, weather, and community practices. The Allegheny River provides a continuous source of water to meet these demands, therefore, water scarcity is not a concern for Pittsburgh.

The PWSA treatment system includes two treatment facilities, the Aspinwall Water Treatment Plant (AWTP), which uses conventional coagulation/sedimentation/filtration treatment and the Highland No. 1 Membrane Filtration Plant (membrane plant). The AWTP is located in Pittsburgh near Aspinwall, PA on the north shore of the Allegheny River. This treatment plant is the primary drinking water treatment facility for the Pittsburgh storage and distribution system, producing approximately 70 million gallons per day (MGD) on average and servicing over 250,000 customers. Depending on demand, AWTP may treat up to 100 MGD (design and permitted capacity). The membrane plant is located in Highland Park, a neighborhood within the city of Pittsburgh. It treats the effluent from the Highland No. 1 uncovered finished water storage reservoir. The membrane plant has the capacity to treat 20 MGD.

Pittsburgh's drinking water system was significantly impacted in the 1980s by the collapse of the United States steel industry. Like many other cities in the northeast United States, Pittsburgh was booming during the industrial revolution. However, today Pittsburgh does not have the manufacturing plants and industry that once created large water demands. Instead, Pittsburgh is focused on remediating these industrial properties into residential and commercial areas. The future of Pittsburgh lies in healthcare, technology, education, and health services [Flaherty, 2002]. In addition to the economy change, Pittsburgh's population has been and is projected to continue declining. Now the PWSA stored volume of water is large compared to the daily demand. Although it should be noted that the distribution system is aging and encounters many breaks, especially during the winter months. The PWSA stored water is imperative to maintain service to customers due to system reliability problems.

1.1.2 Pumpage

Once water is filtered through the AWTP dual media filters, the water flows by gravity to the clearwell where it is chlorinated and fluoridated. The water leaves the clearwell through a common wetwell where water is then drawn to one of two high service pump stations, Aspinwall or Bruecken Pump Station. Aspinwall Pump Station is located directly east of the clearwell. Water flows east to west through the clearwell, therefore, Aspinwall Pump Station draws water back through an 84-inch pipe that runs along the bottom of the clearwell. Bruecken Pump Station is south of the clearwell, drawing water across the Allegheny River through two 72-inch suction mains.

In Figure 1 Bruecken Pump Station (B) takes water from the clearwell (C) and lifts it to the Highland No. 1 and Highland No. 2 Reservoirs (1 & 2, respectively) influents (yellow balloons). Water exits the reservoirs at the locations marked by the blue balloons. The water, which exits Highland No. 2 Reservoir, goes directly into the distribution system. The Highland No. 1 Reservoir water is treated by the membrane plant (M) before being discharging to the distribution system. The Aspinwall Pump Station pumps water directly to Fox Chapel and to Lanpher Reservoir. After water is lifted to one of the three primary reservoirs, water is pumped and/or gravity fed throughout the system, going from one storage facility to another to get water to all of the pressure zones. Eight outlying pump stations are used to transfer water to higher pressure zones in the system, including Herron Hill, New Highland, Lincoln, Herron Hill Tank, Saline, Mission, Howard, and Fox Chapel Pump Stations. Millvale Borough, one of three consecutive systems, which purchases water from PWSA, also has a pumping station that is currently not in service. The interconnection and pumping station operated by Millvale Borough is located on the 60-inch main leading from Lanpher Reservoir. A schematic of how the water is pumped to the different storage facilities from the AWTP is display in Figure 2.

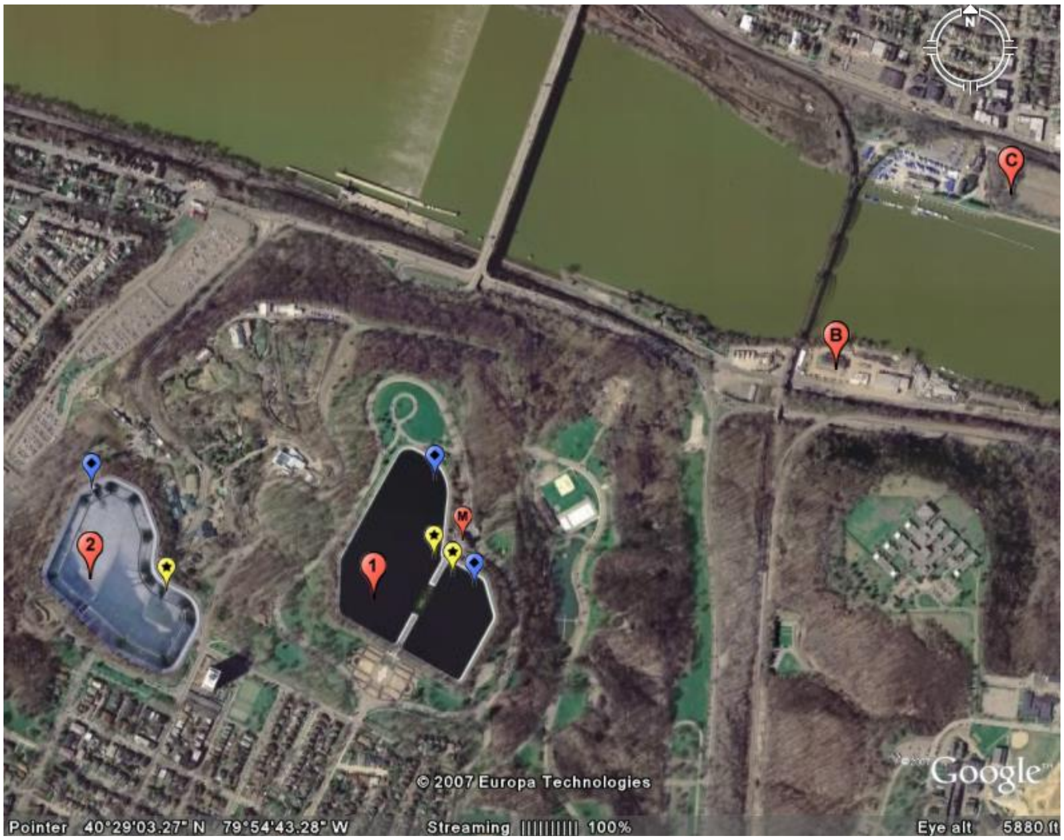

Figure 1. Highland No. 1 and No. 2 Reservoir influent and effluent locations; (C) = Clearwell Outlet, (B) = Bruecken Pump Station, (1) = Highland No. 1 Reservoir, (2) = Highland No. 2 Reservoir, (M) = Membrane Plant, Yellow Balloons = Reservoir Influents, Blue Balloons = Reservoir Outlets. The distance between (C) and (B) ≈ 0.29 miles. The distance between the closest boarders of (1) and (2) ≈ 0.17 miles

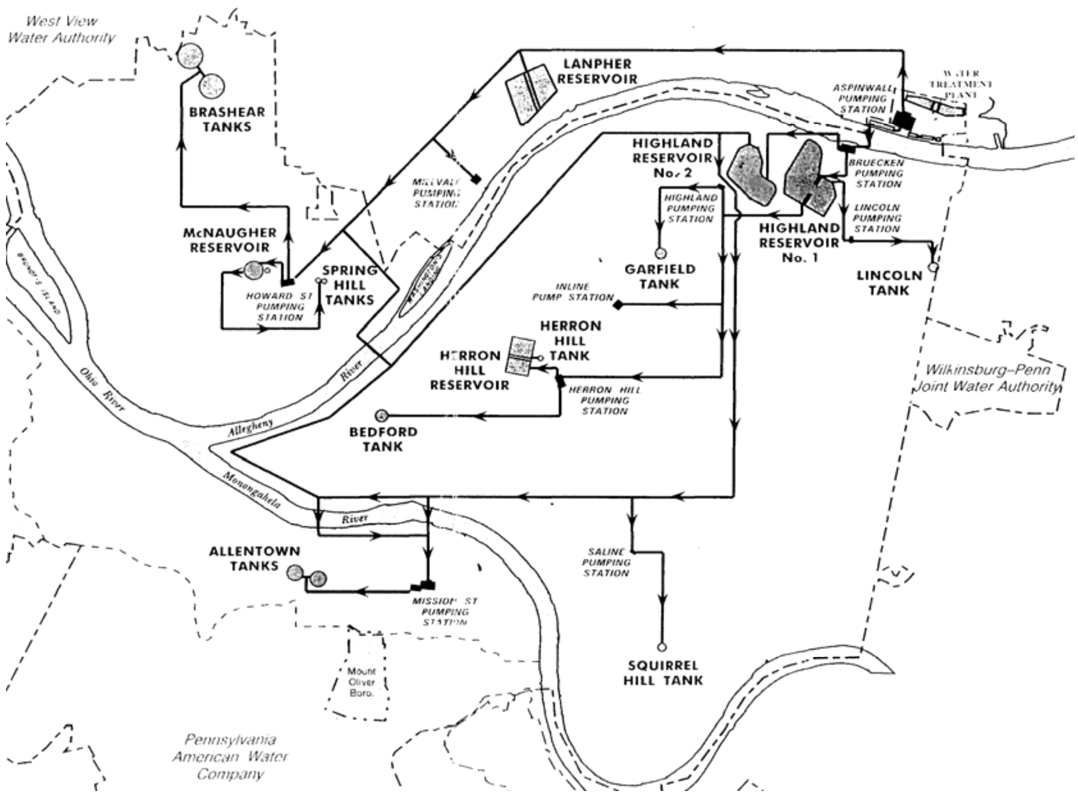

Figure 2. PWSA water storage facility and pump station locations.

1.1.3 Pressure Zones

PWSA has a complicated distribution system including 15 pressure zones that are organized into the following supersystems:

- Highland No. 1 Supersystem
  - Highland No. 1 Reservoir
  - Inline Pump Station
  - Lincoln Tank
  - Garfield Tank
  - Herron Hill Reservoir
  - Herron Hill Tank
  - Bedford Tank
  - Pressure Regulated Areas

  - Bloomfield Regulator
  - Highland Park/Garfield Regulator
  - Zoo Regulator

- Highland No. 2 Supersystem
  - Highland No. 2 Reservoir
  - Squirrel Hill Tank
  - Allentown Tanks

- Lanpher Supersystem
  - Lanpher Reservoir
  - McNaugher Reservoir/Spring Hill Tanks
  - Brashear Tanks
  - Pressure Regulated Areas
    - McNaugher Regulator

The supersystems are based off the three primary reservoirs, Highland No. 1, Highland No. 2, and Lanpher Reservoir. The Highland No. 2 and Lanpher Reservoirs are at approximately the same surface elevation, which is almost 100 feet lower than the surface elevation in the Highland No. 1 Reservoir. Therefore, Highland No. 1 Supersystem services the high elevations and the Highland No. 2 and Lanpher Supersystems service the lower elevations. The Highland No. 2 (south of the Allegheny River) and Lanpher (north of the Allegheny River) Reservoir Supersystems were connected by three river-crossings until November 10, 2006 (located at 26th Street, North Franklin Street, and For Duquesne Bridge). Now, the distribution system is operated as three isolated systems.

1.1.4 Finished Water Storage

Pittsburgh has a complex reservoir and water tower gravity fed system. PWSA storage facilities include:

- Reservoirs (storage basins or below grade)
  - Lanpher Reservoirs (2 cells)
  - Highland No. 1 Reservoir (2 connected cells)
  - Highland No. 2 Reservoir (1 cell)
  - Herron Hill Reservoir (2 cells)
- On-Ground Tanks (storage tanks at grade)
  - Spring Hill Tanks (2)
  - Brashear Tanks (2)
  - Allentown Tanks (2)
  - Squirrel Hill Tank (1)
  - Bedford Tank (1)
  - Lincoln Tank (1)
- Elevated Storage Tanks (storage tanks above grade)
  - Herron Hill Tank
  - Garfield Tank
- AWTP Secondary Sedimentation Basins (3)

These storage facilities provide sufficient water and pressure to the Pittsburgh distribution system during high and low demand periods. They also provide emergency flow for fires, water main breaks, power outages, and AWTP shut down periods. If the intakes to AWTP need to be closed due to a river spill or plant maintenance, the storage facilities can be filled to the operating capacity to service the distribution system. At full capacity, the ability of the storage facilities to service the distribution system is limited by the 20 MGD membrane plant.

The membrane plant services the Highland No. 1 Supersystem, which has demands exceeding 20 MGD. Therefore, water is pumped directly to some of the Highland No. 1 Supersystem areas from the AWTP. The secondary sedimentation basins, which are part of the AWTP process train, provide an addition 123 MG of stored water within the plant. When the intakes are closed, these secondary storage tanks assure that there will be sufficient finished water to pump to the three primary reservoirs and directly to the Highland No. 1 Supersystem, since there is no substantial backup finished water supply available from neighboring utilities. With the 15 pressure zones in the system, the reservoirs and elevated towers are able provide a constant pressure, via gravity feed, to customers with minimal fluctuations during emergency situations such as power outages and water main breaks.

Flows patterns in the distribution system and levels in the reservoirs are continuously changing. The fluctuations are due to diurnal demands patterns and pumping protocols and create non-steady state hydrodynamic conditions through the distribution system. The majority of pumping occurs during nights and weekends when electricity rates are lower and demand is low. Since the volume of water pumped is greater than the volume of water in demand, net storage increases. By Monday morning, the storage facilities are typically filled to their designated maximum level. Then, during the week, the levels in the reservoirs tend to drop due to deceased pumping. Keeping the reservoirs full allows PWSA to provide water with sufficient pressure to the distribution system during emergencies (e.g. power outages, fires, waterline breaks). From an AWWA and Economic and Engineering Services, Inc. (EES) literature review of finished storage water facilities [2002] prepared for the USEPA, it was found that finished water storage facilities were historically operated at their maximum capacity, emphasizing hydraulic considerations. However, recent DBP regulations focus attention on water quality considerations. Maintaining full storage facilities provides more storage capacity than is needed for non-emergency demands, so water "sits" in the system while water quality degrades. Therefore, PWSA has lowered the maximum operating fill levels of some of the storage facilities in effort to better utilize the existing water storage and maintain water quality.

PWSA's storage facilities pose a security risk since they are nodes for intentional water contamination. The tank enclosures, reservoir covers, and membrane plant are protective barriers to guard against intentional water contamination. Until the mid 1990's, all of Pittsburgh's reservoirs were uncovered. Then the amendment to the Pennsylvania Department of Environmental Protection (PADEP) Chapter 109 (Safe Drinking Water) of the Title 25 Environmental Protection document required PWSA to replace or cover the reservoirs [PADEP, 2004]. Now all of them, except one, are covered with a floating cover.

Highland No. 1, Highland No. 2, and Lanpher Reservoirs are the three primary reservoirs with capacities of 117, 125, and 133 MG, respectively. Highland No. 1 Reservoir, located in Highland Park, consists of two basins that are connected by a shallow channel as shown in Figure 1. At one time, the reservoir consisted of two separate cells, however, the shared wall failed when taking water level down in one of the cells. This reservoir is the only Pittsburgh storage facility that remains uncovered. This reservoir is not baffled and there is one inlet and outlet in each cell. The geometry of Highland No. 1 is irregular, with the smaller, squarer basin to the east. During the week, Highland No. 1 Reservoir is visually inspected daily for contamination, vandalism, dead animals, operational readiness etc. The inspection protocol matches the AWWA and EES [2002]covered storage facility literature and research review which outline recommendations to complete daily or weekly physical inspections of storage facilities. The 100 percent of the effluent from both basins of the Highland No. 1 Reservoir is treated through the 20 MGD membrane plant.

Highland No. 2 Reservoir is one large basin with one inlet and outlet. This ‘L’ shape basin, also shown in Figure 1, was covered and baffled in 1998 with a flexible polypropylene floating cover. It is also in Highland Park, west of Highland No. 1 Reservoir. Water exits to the west of this basin through a chlorine house where it is boosted with sodium hypochlorite. Since the installation of the cover, the inside of the reservoir has not been inspected for structural integrity or possible debris accumulation, although, the cover is visually inspected daily by PWSA personnel.

Lanpher Reservoir is located in Shaler Township between Etna and Millvale, PA. The reservoir was originally one basin, but was divided into two for Class 1 reliability. Both cells are trapezoidal in shape. Water flows in through a common channel, down the center of the two cells, from the northwest to southeast. The division structure at the end of the channel splits the influent into two cells. Water flows into the cells through a baffling structure that spans approximately half of the tank width. There is one outlet in each cell. The two effluent channels and one influent channel can be accessed in the chlorine house. Residual chlorine is added to the effluent channel. The two effluent channels are then connected into the 60-inch service main where the effluents are mixed together. Like Highland No. 2 Reservoir, Lanpher reservoir was covered with a polypropylene cover in response to the Chapter 109 amendment to the Title 25 Environmental Protection document which required PWSA to replace or cover the reservoirs [PADEP, 2004]. Since the installation of the polypropylene covers, neither the Highland No. 2 nor the Lanpher Reservoir has been taken out of service for cleaning or inspection of structural integrity. The three primary reservoirs are visually inspected daily from the perimeter, but the AWWA and EES [2002] review of finished water storage facilities listed recommendations of cleaning covered facilities at least every three to five years and uncovered reservoirs annually or bi-annually to maintain water quality in the storage facilities.

1.1.5 Treatment Operations and Water Quality

PWSA operates a conventional 100 MGD drinking water treatment plant consisting of raw water screens, rapid mix, flocculation, flocculation, two-stage clarification, and filtration processes. PWSA recently started enhanced coagulation, which was stated by AWWA and EES [2002] in a literature review prepared for the USEPA on how the age of water effects quality in distribution systems, to be the best available technology specified in the DBPR for natural organic matter (DBP precursor) removal. This process improves the biochemical stability of the finished water and decreases water quality problems associated with aging water. This quality improvement is the result of reduced organic matter and suppressed biological and chemical reaction rates in the stable water [AWWA and EES, 2002].

Currently, PWSA monitors the distribution system daily for disinfectant residual. This test ensures that the general distribution water quality is acceptable, with a total chlorine residual goal of 0.5 mg/L at all taps. Typically, almost all the total chlorine residual is in the form of free chlorine. PWSA also runs weekly composite chemical analysis on the finished water to determine turbidity, temperature, pH, alkalinity, hardness, carbon dioxide, chloride, calcium, magnesium, fluoride, sulfate, specific conductance, total solids, dissolved solids, and suspended solids [PWSA, 2006]. In addition, total metals analysis is conducted on the influent and finished water to determine the removal efficiency of iron, manganese, sodium, zinc, silver, arsenic, beryllium, cadmium, chromium, copper, nickel, lead, antimony, selenium, and thallium [PWSA, 2006]. The Allegheny River is rich in manganese and iron, due in part, to acid mine drainage. PWSA uses the oxidation/sedimentation/filtration processes for the removal of iron and manganese, and other metals to decrease the levels released into the distribution system.

The operations center for the AWTP and pump stations is located in the operations building at the Aspinwall Plant. Built in 1969, the operations building provides office, laboratory, conference, mechanical, and storage space for administrative and operations usage. In the future, the membrane plant control center, which is currently located in the membrane plant, will also be based out of the AWTP. The majority of the AWTP equipment and distribution system is monitored continuously by a PWSA employee on computers and panels that relay the plant and distribution system status information. The plant operators manually record reading from the system hourly. These values include pump rates, storage tank elevations, and other treatment plant information. Recording the values on paper allows the PWSA employee to the review the operations status signals and check for system alarms. The recorded data also provides valuable historical records on how the system was operating during a certain period.

A variety of chemicals are used during the water treatment process including potassium permanganate, powdered activated carbon, coagulant aid polymer, ferric chloride, lime, caustic soda, and soda ash. Post filtration, the finished water receives hydrofluosilicic acid and sodium hypochlorite feeds.

Although there are background levels of fluoride in the source water, PWSA adds hydrofluosilicic acid as a 25 percent solution to finished water between the filters and the clearwell to raise the concentration. Fluoride is added to the water for dental health benefits.

The dosage pump runs continuously and is adjusted once daily based on sampling results. The goal is to achieve a fluoride concentration of approximately 1.0 mg/L throughout the distribution system.

Sodium hypochlorite is used as PWSA's primary and secondary disinfectant. The finished water receives a primary dose of sodium hypochlorite at the entrance to the clearwell. Continuous rechlorination systems, which are on/off controlled, provide secondary disinfection throughout the PWSA distribution system. There is chlorine feed at the membrane plant to water entering the distribution system from Highland No. 1 Reservoir and seven chlorine booster stations located at outlets of the following facilities:

- Lanpher Reservoir
- New Highland Pump Station (influent to Garfield Tank)
- Highland No. 2 Reservoir
- Herron Hill Reservoir
- Brashear Tanks
- McNaugher Reservoir
- Bedford Tank

There are plans to add additional booster chlorine stations to the outlets of the following facilities:

- Allentown Tanks
- Squirrel Hill Tank
- Lincoln Tank

The three additional chlorine booster stations will hopefully allow PWSA to better control chlorine residual and DBP formation through the distribution system. Currently, the Allentown and Squirrel Hill Tanks are fed from Highland No. 2 Reservoir and Lincoln Tank is fed from Highland No. 1 Reservoir. High concentrations of chlorine are added at the effluents of these two primary reservoirs to assure adequate disinfectant residual through the secondary storage facilities and to customer homes. The new booster stations will be paced by chlorine residual so lower concentrations of chlorine will need to be added at the primary reservoirs. However, the residual pacing still does not guarantee predictable residual levels [AWWA and EES, 2002]. Chlorine residual will still change depending on flow patterns and chlorine demand in the water after the booster station. Therefore, PWSA may still incur periodic over or under dosages of chlorine.

1.1.6 PWSA Hydraulic Model

Mathematical modeling of distribution systems really started in the mid-1980's with the findings of Males et al. [1985] and Grayman and Clark et al. [AWWA and EES, 2002]. Males et al. [1985] developed an algorithm to solve water system mixing problems. These primitive models were steady-state time travel models which were further developed, as discussed by Grayman and Clark et al. [1988], into dynamic models to estimate water age variations. AWWA and EES [2002] stated that hydraulic models incorporate water quality models to predict parameters such as chlorine residual [Rossman, 1994] and DBP formation [Clark, Thurnau et al., 2001]. PipelineNet is a simulation tool that further integrates EPANET (a hydraulic and water quality models) with ArcGIS for vulnerability and consequence assessment of public water supplies [SAIC, 2005].

PWSA's first hydraulic model, developed in 1995, used the Stoner Associates Stoner Workstation Service. However, due to the changes in water demands and operating procedures since 1995 and the advancement in software, the model data input physical feature files were updated and converted to the SynerGEE Version 4.10 platform by Maslanik [2006], a professional engineer and senior technical consultant working for Chester Engineers. Stoner Associates is now under Advantica, Inc. and the most current version of the Stoner Workstation Service software is SynerGEE Version 4.10. The new software provides more capacity to run extended period simulations (EPS). The EPS allow the model to study the movement of fluids and estimate water age within the system by averaging model results from 24-hour periods. In order to make the updated PWSA model representative of current conditions, verification and calibration were required. In March of 2006, a comprehensive tracer study was proposed by PWSA as a method for validating and calibrating the updated model. This method was discussed by Grayman et al. [1998], who have completed extensive distribution system modeling work, to be a viable approach.

Model verification differs from calibration in that verification uses parameters outside of the calibration period. Verification is a check to see if the calibrated model works under different conditions and to determine if the model can be used for reliable and practical applications. A significant amount of time and money is needed to run a tracer study and calibrate and verify a model, especially for distribution systems like PWSA that are large and complex.

1.2 PREVIOUS TRACER STUDIES

Tracer studies have been used to gain understanding of flow paths and hydraulic behavior of drinking water distribution systems. The basic concept of a tracer test involves monitoring the change in concentration of a material with time. Previous tracer studies, including the two discussed by DiGiano et al. [2005], have found that the data collected during the tracer test may be used as a diagnostic tool to calculate water travel times (average water age) within the distribution system. In addition to water age estimations, reactor theory discussed by Lawler et al. [In Press], also described how tracer study response curves are used to analyze mixing pattern and better understand the multiple types of reactors that work together within a system to optimize operational practices and improve water quality.

Tracer studies are also used to calibrate and verify hydraulic and water quality models. Using tracer study data is standard industry practice to try to align the model more closely with the actual system by adjusting computer model parameters until the field collected data results coincide with to computer model simulation results [Maslanik, 2006]. The data which are collected during the study and the verified model can then be use to develop correlations between water quality parameters, such as chlorine residual and DBP formation, and water age [AWWA and EES, 2002]. The security of a drinking water distribution system is somewhat dependent on the understanding of the system. If a contaminant is introduced into the system, having a calibrated model to estimate the time to flush out the system is important to public health. The data can also be used to determine areas that will have the highest concentrations/lowest concentrations to prioritize response.

For systems that do not have a hydraulic model, or do not have the means to calibrate an existing model, conducting a tracer study is an alternative, less expensive method for estimating water age, a common parameter calculated by hydraulic models [DiGiano, Zhang et al., 2005]. However, when a tracer study is completed, it captures an image of how the system works at one point in time at the sampling points. Therefore, the tracer study may need to be repeated, depending on the system's operations, to account for water demand range between seasons [DiGiano, Zhang et al., 2005].

1.2.1 Distribution System Tracer Case Studies

Multiple tracer studies have been conducted on distribution systems through the United States. The following are descriptions of how some other cities implemented tracer studies and how the results were utilized.

1.2.1.1 Avon Lake, Ohio distribution system tracer study was reported on by Kennedy et al. [1991]. This study was used to compare the actual field response to their water quality model simulation results. Avon Lake has a relatively large distribution system with extensive looping. At the time of the study, June 12, 1990, the Avon Lake distribution system served 89,000 customers, with an average demand of 13 MGD. The Avon Lake model, AQUA, was non-skeletonized including pipes ranging from 6 to 30 inches. Modifications were being made in attempt to calibrate this model for 10 years prior to the tracer study.

The study use a step decrease tracer buy turning off the fluoride feed at their sole water treatment facility. Hourly samples were taken at five locations, for 50 hours. Sampling points were not available at the end of the clearwell exiting the plant. Therefore, two hydrants close to the plant were select to be representative of water entering the system. Three hydrants were also selected at key locations within the distribution system. All hydrants maintained a continuous flow of two gallons per minute (gpm). Kennedy et al. [1991] explained that the continuous purging from the hydrants was done to assure representative timed samples from the system. A limited number of sampling locations were used due to the closely space sampling time intervals.

The samples were stored is glass and plastic bottles at room temperature until analysis could be completed. Both the SPADNS colorimetric method and ion-selective electrode methods were used for analysis, two standard methods [APHA, 1998]. The response curves did not reach background fluoride concentrations within the 50-hour study period. This attenuation of fluoride was due to dispersion and mixing, because under plug flow conditions Kennedy et al. [1991] estimated that the decrease would take place in 15-hours.

To simulate the study with their model, Kennedy et al. [1991] used water usage data, pumping records, and flow balances. The demands in the model were then adjusted to better correlate the model and field T_{50} estimates. The model initial over estimated water age, suggesting that the pipe velocities were too slow.

1.2.1.2 Raleigh, North Carolina distribution system included four pressure zones and 250,000 customers. DiGiano et al. [2005] conducted a tracer study in Raleigh, North Carolina starting on September 21, 1998 when the fluoride feed to the distribution system was shut off. The fluoride remained off for five days and samples were taken at 20 sites. Of the 20 sites, only 12 sites provided complete response curves at the end of the sampling period.

This system has a hydraulic model, however, at the time of the study, the model calibration was outdated since 1993. Even so, the Raleigh distribution system model was still found to be good for a rough comparison for average water ages calculated via field data and model simulations. DiGiano et al. [2005] also used the model to generate F- curves (normalized concentration verses time graphs) and MRT manually from the model curves to compare with the water age determined by the model.

1.2.1.3 Durham, North Carolina tracer study, which started on April 15, 1999, was also conducted by DiGiano et al. [2005]. This study determined the percentage of flow contribution from two source water treatment plants. A change in coagulant and fluoride addition was used as the tracers. Weeks prior to the study, the steady state fluoride feed was turned off at the

Brown Water Treatment Plant (WTP). Then a switch was made from ferric chloride ($FeCl_3$) to aluminum sulfate ($Al_2(SO_4)_3 \cdot 14H_2O$), at their Brown WTP on April 15th, while the Williams WTP continued to use aluminum sulfate, and the fluoride feed was turned off at the Williams WTP as well. The decreasing Cl^- and increasing SO_4^{2-}, measured with ion chromatography, was representative of the Brown WTP, and the changing fluoride concentrations, measured electrochemically by an ion-specific electrode, was representative of the Williams WTP [DiGiano, Zhang et al., 2005].

At the time of the study, the Durham distribution system serviced 190,000 customers with two pressure zones and did not have a hydraulic model. DiGiano et al. [2005] used the results of the field tracer data from the 10 sampling locations to determine a flow rated average of the MRTs in the system and contributions from each treatment plant.

1.2.1.4 Phoenix, Arizona utilities, like many other utilities, were concerned about Stage 2 DBPR compliance. At the time of this study, the Initial Distribution System Evaluation (IDSE) to identify areas of high DBP formation was not required for this utility, but Passantino et al. [2005] anticipated the IDSE requirements for the Stage 2 DBPR and began planning early. Passantino et al. [2005] began evaluating the distribution system's infrastructure and operational procedures early to minimize DBP formation. At the time, Phoenix only had a steady-state out of date hydraulic model. Therefore, the Phoenix hydraulic model was updated to represent existing conditions and perform EPS. To better represent the hydraulics of the distribution system and enable water quality estimations, the model need to be calibrated.

A tracer study was conducted in January 2002 through the Phoenix water distribution system. The data collected, including fluoride, total chlorine residual, pH, temperature, total trihalomethanes (TTHM), and haloacetic acids (HAA5), from this study were used to calibrate the hydraulic and water quality models. The main objective of Passantino et al. [2005] for the Phoenix tracer study was to collect date to calibrate the water ages and source water contribution in the system in the model. The DBP and chlorine residual data were also used by Passantino et al. [2005] to calibrate the water quality models.

The city of Phoenix has four water treatment plants. During the Phoenix tracer study, two of the plants were not operating. The two plants that were in operation, were located furthest from the heart of the distribution system, maximizing water age. Phoenix also receives water from the Verde Wells. During the study, no fluoride was added to the well water and Passantino et al. [2005] increased the fluoride feed to 1.3 mg/L at their Rio Salado Feed Station on January 14, 2002. Samples were collected throughout the system until there was a steady increase of fluoride concentration throughout the system. Then, on January 24, 2002, the fluoride was turned off and fluoride samples were collected at 17 locations throughout the Phoenix distribution system.

The Phoenix routine sampling locations were not secure enough for autosamplers, so they utilized Water Service Department properties and fire stations since they were secure, accessible, and located throughout their distribution network. Passantino et al. [2005] used 13 autosamplers and collected twice daily grab samples from four other locations, with the aim of collecting samples at 12 hour periods. At the grab sample locations, the taps were flushed for at least two minutes prior to collecting the sample. The city of Phoenix also had an on-line fluoride analyzer at valve 602. The analyzer readings were verified by collecting multiple grab samples. The error between the readings were always plus or minus 10 percent, therefore, the response curve from this analyzer was not adjusted.

The city of Phoenix also conducted a simulated distribution system (SDS) test during their study. Passantino et al. [2005] made a point to have utility personnel record treatment operational patterns during the study, including chemical dosages, flow rates, and water quality to assist in model verification and calibration. A comparison of the SDS test to field results of TTHMs and water age found that SDS test to be a good prediction of DBP formation [Passantino, Chowdhury et al., 2005].

Because the city of Phoenix has multiple water sources, the tracer study results were used to calculate travel time and source water percentage. To determine water age, Passantino et al. [2005] took a 48 hour average of the initial concentration of fluoride and a 48 hour average was calculated after the fluoride leveled off to the background concentration. The corresponding time to the average concentration between these two points, T_{50}, was determined to be the travel time, or average water age. The tracer response curves were also used to determine the percentage of water coming from different sources.

1.2.1.5 Denver, Colorado water utility, Denver Water (DW), is comprised of three treatment plants, 160 pressure zones, with 17 major pump stations. The utility have over 1.2 million customers and provide up to 500 MGD. In 2004, DW completed a fluoride tracer test and used water usage data to calibrate the DW EPS model. This system and the results of the tracer study were discussed by Strasser et al. [2005].

The DW EPS model, which is an all pipes model (APM), was developed, calibrate, and verified in preparation for the IDSE System Specific Study (SSS) for the Stage 2 DBPR. DW also added enhanced coagulation on an “as-needed” basis to increase removal of DBP precursors at one of the plants. The DW APM was developed for operational purposes. As discussed by Strasser et al. [2005], DW decided to use the APM to complete a SSS, instead of completing the

Standard Monitoring Program (SMP) for the ISDE. In order to accomplish the SSS, the APM was first calibrated and verified. One of many verification methods included conducting a fluoride tracer test.

The system wide tracer test was used to confirm the EPS APM water quality model by verifying the hydraulics and water age. DW preformed an increasing step tracer. The fluoride feed was shut off at the three plants two weeks prior to the study to let the fluoride concentration levels drop down and stabilize at the background concentrations of approximately 0.5 mg/L. On November 5, 2002 at 12:00 A.M., fluoride feed was resumed at the three feed location with a target of 1.0 mg/L. Samples were collected 24 hours a day, on the hour, for five days. Each sample was labeled with the date, time, and location. For analysis of the samples, DW used SPADNS colorimeter method in the field test and the ion-selective electrode methods in the laboratory [APHA, 1998]. The results of the tracer study were then compared to the model results. The EPS model was simulated using settings that were typical of operations during the tracer experiment. Strasser et al. [2005] stated that the results were close, adding confidence to the model.

In addition to the tracer study, Strasser et al. [2005] also ran three model scenarios (in spring, summer, and later summer) and used telemetry settings to verify and calibrate the model. The three selected dates were both representative of typical operations and were during optimal times for peak DBP formation. Water age analysis and source tracing to each plant was modeled to correlate water age with TTHM formation. Field testing results were used to make slight adjustments to the model. Another scenario was performed in efforts to reduce water by changing valve and pump settings to recirculate water through the extremities. This operational change lowers ages in the extremities, however, it was found to increase age in the internal area of the system. There was no net change, but it did eliminate sever water ages in the fare reaches of the DW system. Strasser et al. [2005] also tried changing the plant water contributions. The change in the amount of water supplied from each plant ended up reducing water age and DBP formation with an increase of only $50/day in pumping, a cost considered small by Strasser et al. [2005] for the exchanged water quality improvement in their large system. These hypothetical scenarios, which were developed using the calibrated model, allowed DW to determinate optimal operational modifications at minimal cost.

From the model calibration and verification methods and model simulations, and the requirements of the Stage 2 DBPR guidance manual, DW was able to select 32 preliminary monitoring sites. It was later found that the majority of the sites were applicable for the IDSE goals and only slight model modifications were needed [Strasser, Hale et al., 2005].

The entire process took DW over six years to complete. The cost for both internal and consulting fees was almost $2 million dollars, however, they ended up saving over $26 million in system improvements that were previously recommended. The DW calibrated and verified APM is proof that large systems can be modeled non-skeletonized and that this is a necessary method for predicting and improving water quality and complying with tightening regulations at minimal cost. Strasser et al. [2005] stated that "tracer testing is a necessary verification tool for comparing computer and observed residence times in the distribution system and should be perform in addition to ordinary hydraulic verification."

1.2.1.6 Fort Collins, Colorado has one treatment facility, over 530 miles of transmission and distribution pipelines, four finished water storage facilities, and two finished water pumping stations and serves over 125,000 customers. Two tracer studies were conducted in Fort Collins, Colorado by Fort Collins Utilities (FCU) between February 20, 2006 and March 17, 2006. The FCU studies and the results were discussed by Simon et al. [2006].

The study was completed to provide data to verify the FCU H20MAP model, to comply with IDSE requirements, to determine water quality sampling locations, to evaluate DBP formation, to determine a flushing program, to evaluated source water contributions, and to evaluate contamination scenarios [Simon, Billica et al., 2006]. Prior to initiating the study, the H2OMAP model was used to simulated the fluoride study and help select sampling locations. The model was updated with historical demand and operational data to anticipate demand conditions and variations in diurnal demands during the fluoride tracer study. Then FCU ran EPS to validate how closely the model predictions matched the historical operational data. Simon et al. [2006] reported that the H20MAP model was used, after verifying a high degree of confidence between the model and historical data, to simulate water quality, determine water age at different points in the distribution system, and estimate the duration of sampling. The water ages were plotted on maps of the FCU distribution and used for sample site identification.

FCU decided to run their tracer study during February and March of 2006 because during this time of year, they have low water demands with smaller variations. Under these circumstances, FCU felt there was better opportunity to validate their model and find the longest system retentions times. The first study involved a negative step tracer after the fluoride was shut off at time zero. Immediately after the fluoride levels dropped down to background levels at all locations, the fluoride feed was reestablished to produce a positive step with a goal concentration of 1.0 mg/L with the background fluoride concentrations.

Samples were collected twice daily from grab locations and a mid-day samples was added during the beginning of the study to capture the step drop. Autosamplers were located at the inlet and outlet of storage facilities and were set to collect samples every 3 hours. The autosampler at the entrances to the distribution system was set to collect every one hour for the first two days, and then it was increase to two hours. The fourth autosampler was place at a grab site, collecting every two hours. Simon et al. [2006] stated that the redundancy of sampling served as a good quality control to the grab samples and validated that two daily grab samples were sufficient. FCU used service line information and faucet flow rates to determine how long each site was to be flushed prior to collecting a samples. The average flushing time was 5 minutes, with a maximum and minimum of 1 and 18 minutes, respectively. This was done to assure representative samples of water in the distribution system [Simon, Billica et al., 2006].

FCU designated how their finished water reservoirs would operate during the fluoride tracer study. They lowered the reservoir levels and maintained a lower level to show a sharper fluoride response curve throughout the system. It also reduced the time of the study. During the study, storage facility levels were kept between a specific range and the operators were instructed on pump station and valve operation. FCU even used data during the tracer study to update the model to adjust sampling frequencies at sampling points throughout their system.

After the study was complete, FCU incorporated the actual operational treatment and distribution data during the tracer study into the H2OMAPS model. This allowed them to replicate the study on the computer for the determination of model confidence degree and it also verified the ability to use the H2OMAPs model for IDSE compliance [Simon, Billica et al., 2006].

1.2.2 Properties of Tracers

In the tracer studies described in Section 1.2.1, different types of tracers were used to collect distribution system operational information. A tracer is a material used to follow the change of movement with in a system. The properties of tracers are important for the success of a tracer study. Substances used as tracers, which are added into drinking water, should meet the following criteria (modified from [Lawler and Benjamin, In Press] and [Metcalf & Eddy, 2003]):

1. Neutrally buoyant (hydraulically behave the same as water)
2. Conservative/non-reactive (for mass balance analysis with no generation)
3. Controllable (able to develop a defined input within a short period)
4. Detectable (easily analyzed at low concentrations).

Within a distribution system it may take weeks for water to pass through the far reaches, therefore, it is essential that the tracer does not decay or absorb onto or react with exposed surfaces or within the bulk water [Metcalf & Eddy, 2003]. Regulatory requirements, cost, and public perception should also be taken into consideration when choosing a tracer [Maslia, Sautner et al., 2004].

Dyes or chemicals are used as tracers for many applications, but in drinking water systems, the addition of dyes is not acceptable. Instead, chemicals like fluoride, calcium chloride, and lithium chloride may be added to the water while still maintaining aesthetic quality at the consumer's tap. Switching process chemicals, such as the disinfectant (i.e. chlorine to chloramines) or coagulant (i.e. ferric chloride to aluminum sulfate), at the treatment plant [AWWA and EES, 2002]; temporarily increasing, decreasing, or shutting off a chemical which is continuously fed; or monitoring naturally occurring parameters, such as high conductivity or hardness, are alternative methods for tracing a distribution system. Monitoring naturally occurring parameters is effective with systems which have more than one source water treatment plant with varying water qualities [DiGiano, Zhang et al., 2005]. If available, alternative water sources may also be used to send a tracer though the system [DiGiano, Zhang et al., 2005]. Lithium chloride is the chemical which is used for distribution system tracer studies in the United Kingdom, however the United States water consumers have not accepted this method so it is not widely used by United States water utilities [AWWA and EES, 2002].

1.2.3 Conducting a Tracer Study

Tracers are a diagnostic tool used to evaluate reactors efficiency [Lawler and Benjamin, In Press]. There are two types of tracer experiments, which use either a pulse or step-input. Deciding which type of input to use depends on the characteristics of the reactor. Within a drinking water distribution system, the pipes and storage facilities make up a network of reactors acting in series and parallel. Some points in the system behave similar to an ideal continuously stirred tank reactor (CSTR) or an ideal plug flow reactor (PFR), while others operate somewhere in between.

1.2.3.1 Types of Reactors are classified as either ideal or non-ideal. There are two types of ideal reactors in reactor theory: zero mixing and instantaneous mixing. When there is no mixing in the axial direction, the reactor is considered a PFR. Whereas, when the reactor mixes completely, the concentration throughout the reactor is equal to the effluent concentration and is referred to as a CSTR [MWH, 2005]. Pipelines and storage facilities act somewhere between a PFR and CSTR and therefore have non-ideal flow [Lawler and Benjamin, In Press]. Typically non-ideal flow happens when there is dead-zones or stagnant zones within the distribution system or storage facility, or if there are bypass sections [AWWA and EES, 2002].

Tracer studies are used to compare the flow and hydraulic conditions through a distribution system to the ideal models [MWH, 2005]. By doing so, the type of mixing and the pattern of mixing may be determined. This is important because the extent of mixing which takes place in the distribution system influences the amount of reaction that can take place, degrading water quality [Lawler and Benjamin, In Press].

1.2.3.2 Pulse Input Tracer Test involve adding a designated amount of tracer to the influent of a CSTR or a PFR instantaneously at time zero, and then the change in concentration with time is recorded at the effluent until the total mass of tracer passes through the system [MWH, 2005]. Depending on the type of ideal reactor, the response curves from a plus tracer look very different as show in Figure 3. The normalized graph shows that there is an ideal C-curve for CSTRs and PFRs. As the C-curves flatten out, the response is described as the number of CSTRs in series. A PFR is considered an infinite number of CSTRs.

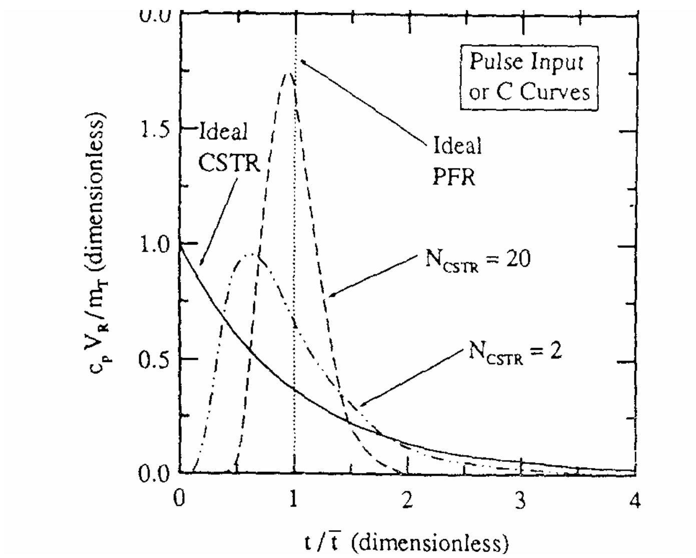

Figure 3. Normalized pulse output for ideal CSTR, CSTR in series, and PFR. Source: [Teefy, 1996]

Pulse tracer studies are only useful for situations where the total tracer input can be accounted for at the effluent. In a distribution system, parcels travel in many different directions; therefore, pulse tracer studies are only useful for reactors with closed boundary conditions and will not be discussed in further detail.

1.2.3.3 Step Input Tracer Test is where a sudden input of tracer (either negative or positive) is continuously added at a set concentration, until the same concentration stabilizes at the effluent [MWH, 2005]. The tracer response curve for a positive, or step-up, input involves an increase of tracer with time, whereas, a negative, or step-down input results in a decrease in tracer with time. Figure 4 displays the normalized concentration versus time response curves, or F-curve, for an ideal CSTR, CSTRs in series, and an ideal PFR.

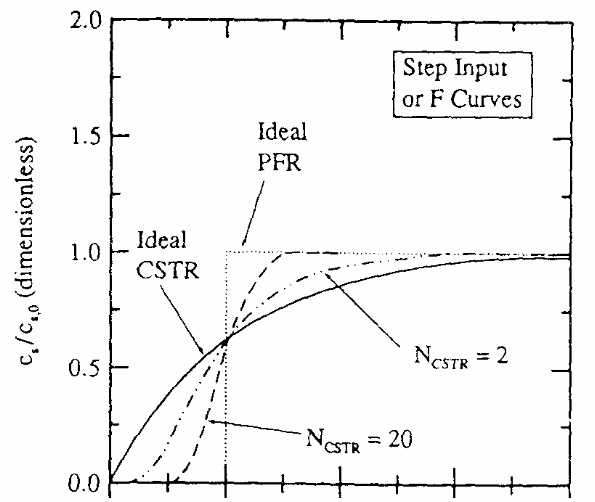

Figure 4. Normalized step-output for an ideal CSTR, CSTRs in series, and PFR. Source: [Teefy, 1996]

For finished water distribution systems, one type of tracer study involves a negative step, followed by a positive step input of fluoride. This can be accomplished by turning off an existing chemical feed, such as fluoride, so the tracer concentration decreases with time down to the background fluoride levels. The time it takes for the decreased fluoride levels to reach sampling points through the distribution system is representative of the time it takes for a water parcel to move through the system. Then the chemical feed can be resumed sending a positive step through the distribution system. With a controlled change in chemical addition and one source water locations, eventually all points within the distribution system will have the same tracer concentration as at the tracer feed location at the end of the step-input tracer study.

1.2.4 Transport Time Scales and Formulations

Three transport scales, including water age, residence time, and flushing time were discussed by Monsen et al.[2002]: a researcher who completed and analyzed multiple tracer studies in natural environments. These three terms were described as being used in and important to the hydrologic, biological, and geochemical fields to describe the amount of time water, or another substance, is retained or the time for transport. Monsen et al. [2002] defined water age as the amount of time it required for water to travel from the entrance of a boundary to a point within the system. Residence time (or retention time) is the complement, or the amount of time it takes for go from the system point to exit boundary. Therefore, in order to discuss age or residence time, the boundary conditions must be defined. Flushing time describes the exchange of mass in the system verses the scalar locations [Monsen, Cloern et al., 2002]. Retention time differs from age in that is describes the time of travel through a network element(s) with similar characteristics [Brandt, Clement et al., 2004]. For example, the time of travel through a storage facility. Brandt et al. [2004] stated that retention time is a better indication of water quality because the time is associated with infrastructure condition. The third transport formula shown in Figure 5 is the transit time, or the time it takes to travel from entrance to exit boundary conditions. Deleersnijder et al. [2005], who worked on constituent-oriented age and residence time theory, developed Figure 5 to aid in visualizing the age and residence time transport variables described above.

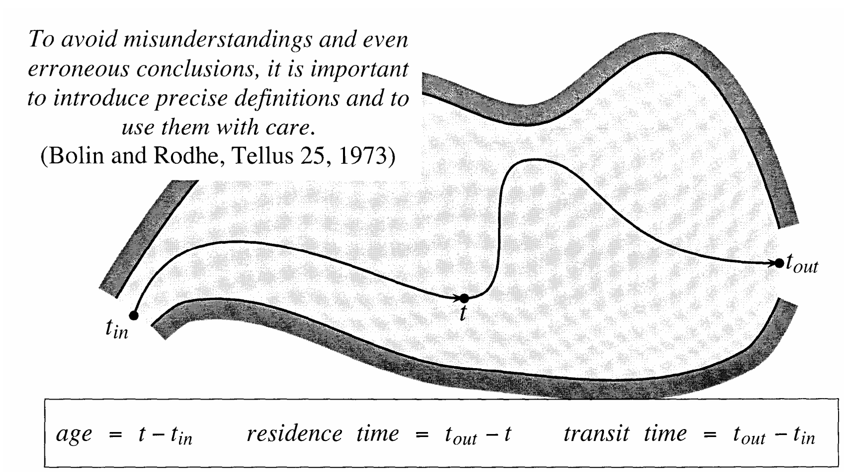

Figure 5. Difference between water age and residence time. Source: [Deleersnijder and Delhez, 2005]

Hydraulic residence time, or theoretical residence time, t_d, is calculated by dividing the volume, V, by the influent flow rate, Q, as shown in Equation 1.

$$t_d = \frac{V}{Q}$$ (Equation 1, [Lawler and Benjamin, In Press])

When dealing with reactors, there may be volumes of water with minimal movement, or stagnant water (dead-zones), and volumes that travel directly from the inlet to the outlet (short-circuiting zones). The volume of the short-circuiting and dead-zones must be subtracted from the total volume to determine the useful volume. Therefore, the residence time with the new smaller volume is less than theoretical residence time [Lawler and Benjamin, In Press]. In reactors such as finished water storage facilities in drinking water distribution system, the volume of dead and short-circuiting zones is typically unknown. However, it has been found that the tracer study response curves from step-input tracer studies (Figure 4) can be used independently of hydraulic models to estimate the average water age in distribution system [DiGiano, Zhang et al., 2005].

Water age fluctuates spatially with changing water diurnal demands, temporal system changes, and mixing. The F-curve, developed from plotting normalized concentrations, F(t), versus time as shown previously in Figure 4, can be used to estimate the average water ages from the tracer input location to a point within the distribution system, or the mean residence time (MRT). However, the F-curve is not able to depict the age variations caused by fill/draw cycles, blending, and other operational parameters, such as valve orientation. The difference between average water ages calculated from sequential points in the distribution system describes the MRT, or the average amount of time any given water parcel spends in the reactor [Lawler and Benjamin, In Press].

The function, F(t), for the F-curve is calculated by normalizing the concentrations at difference times, $C(t_i)$, by the influent concentration, C_{in}, as shown in Equation 2. When there are background concentrations of the C_{in}, F(t) at time t_i, or $F(t_i)$ in Equation 2, is modified to Equation 3, where 'C' is the concentration of tracer and the before and after subscripts represent the tracer concentrations before and after the step input.

$$F(t_i) = \frac{C(t_i)}{C_{in}} \quad \text{(Equation 2,[Lawler and Benjamin, In Press])}$$

$$F(t_i) = \frac{C_{Before} - C(t_i)}{C_{Before} - C_{After}} \quad \text{(Equation 3, [DiGiano, Zhang et al., 2005])}$$

Therefore, as shown in Figure 6, graph A, the concentration verses time response curve to a positive step input increases to C_{in}, or C_{After}, but when normalized the F(t) function increases with time from zero to one (Figure 6, graph B).

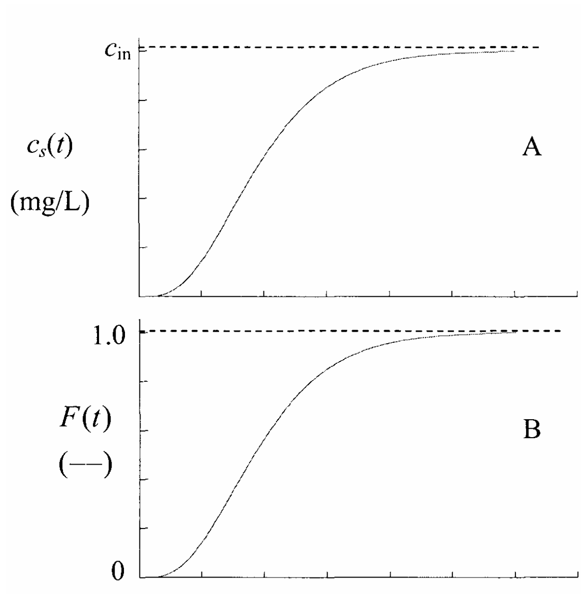

Figure 6. Step-up tracer response curve of concentration versus time (A) and F-curve or normalize concentration versus time (B). Modified from [Lawler and Benjamin, In Press]

The area above the F-curve is summed, as shown in Figure 7, to determine the average water age or MRT by the simplified trapezoidal rule in Equation 4 where 'i' is the i-th sample, t_i is the time between the sample and start of the step input, and $\Delta F(t_i)$ is the fraction concentration change between samples. However, not all F-curves increase monotonically, resulting in negative areas. To eliminate this problem, Equation 4 can be slightly modified to Equation 5, which sums vertical areas instead of horizontal areas shown in Figure 7. However, DiGiano et al. [2005] did not modify Equation 4, instead a smooth line was fit to the experimental data and the negative areas were set to zero. The age calculated from the area above the F-curve can be compared to hydraulic model water age, which is typically defined by the model as an average of the age variations estimated through EPS at a location [DiGiano, Zhang et al., 2005].

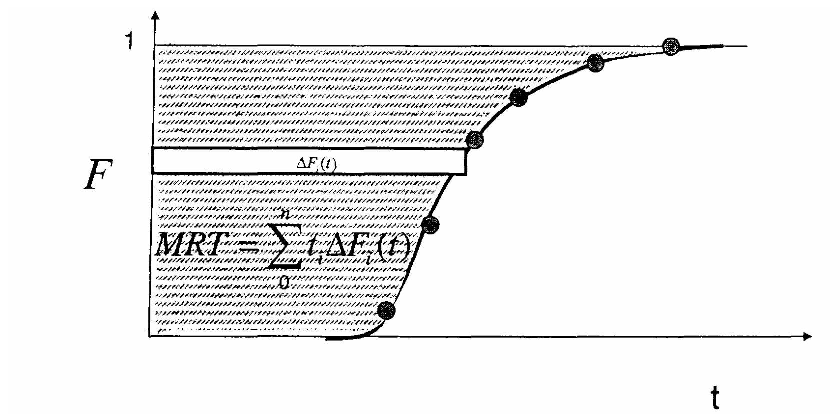

Figure 7. Area above the F-curve determines the MRT. Source: [DiGiano, Zhang et al., 2005]

$$MRT = \sum_{i=0}^{i=N} \frac{\Delta F_i}{2}(t_i + t_{i+1}) \qquad \text{(Equation 4, [DiGiano, Zhang et al., 2005])}$$

$$MRT = \sum_{i=0}^{i=N} \frac{\Delta t}{2}(1 - F(t_i) + 1 - F(t_{i+1})) \qquad \text{(Equation 5, [Stewart, 1999])}$$

The F-curve is also called the cumulative age distribution function or residence time distributions (RTD). This unitless parameter introduced by Danckwerts [1953], and described by DiGiano et al. [2005], , represents the fraction change of input step tracer concentration at a measured locations up to time, t. Therefore, for both step-up and step-down tracer experiments, this function increases from zero to one from the start to finish of the tracer study, respectively.

When $F(t_i) = 0.5$, it is said that 50 percent of the influent molecules have passed through the sampling location and the time, t_i, is referred to as T_{50}. Therefore, T_{50} is considered the average amount of time spent in the system, since 50 percent of influent molecules spent less than time T_{50} and 50 percent remained longer than time T_{50}. Alternatively, for a single molecule, there is a 50/50 percent change that is it will pass through by time T_{50}. So the F-curve is a weighted fraction of how much new water, or tracer, has mixed with the old water, which does have the tracer [DiGiano, Zhang et al., 2005].

The F-curves can highlight mixing conditions and hydraulics of the reactor [Lawler and Benjamin, In Press]. For example, when a packet of water molecules enters a reactor, such as a finished water storage facility, they all do not spend the same amount of time in the reactor. The fraction of molecules remaining in the reactor or that have exited can be described by F-curve. For example, 10 percent may short-circuit and spend a very short period in the reactor, 40 percent may spend an day or less, 20 percent may sit in dead-zone and spend more than 10 days, and so on to account for 100 percent [Lawler and Benjamin, In Press]. These transport times, since molecules cannot be followed directly, can be determined from conducting a tracer experiment (see Sections 1.2.2 and 1.2.3).

From previous tracer studies, such as the city of Phoenix study, it has been shown that the average water age can be determined without normalizing the concentration versus time curve as shown in Figure 8 [Passantino, Chowdhury et al., 2005]. Instead, of developing the F(t) function, a C_{50} value is determined to find the concentration which is 50 percent of the difference between influent concentration, C_0, and the final concentration, C_F.

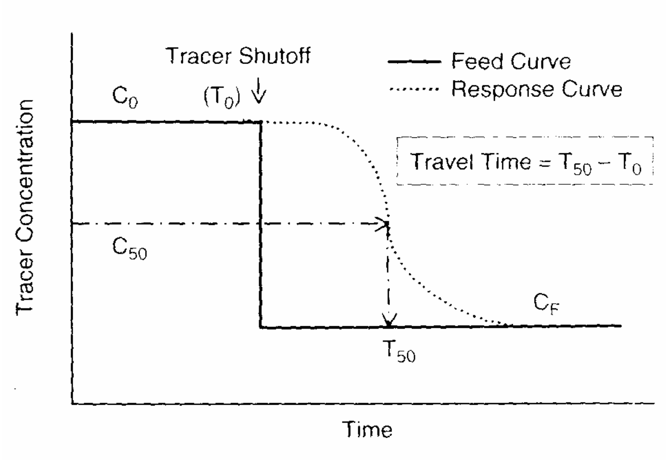

Figure 8. Step-Down tracer response curve in response to ideal step-down tracer feed. Source: [Passantino, Chowdhury et al., 2005]

The concept of using the hydrodynamic data to determine water ages in the distribution system allows for the identification of areas with excessive water ages and can be further analyzed to determine system operational improvements to decrease the ages within a distribution system [Passantino, Chowdhury et al., 2005]. This key parameter or water age has also been used to characterize the extent of water quality deterioration in the distribution system, including parameters such as disinfectant loss and DBP formation [DiGiano, Zhang et al., 2005].

1.3 WATER QUALITY IN THE DISTRIBUTION SYSTEM

The quality of drinking water is determined by multiple parameters including source water, treatment and disinfection processes, and distribution system. It is easy to monitor and alter the quality of water as it enters and moves through the treatment train. However, once the water leaves the treatment plant and enters the distribution system, multiple reactions may take place, or there may be points of contamination that degrade the quality of drinking water. Therefore, the distribution system, including pumps, storage facilities, piping, and appurtenances throughout a service area, needs to be operated and maintained to protect water quality. The USEPA has increased their attention to the distribution system and regulating finished water within the distribution system. The Stage 2 DBPR is the most recent USEPA regulation, which focuses on increasing water quality in distribution systems by requiring that the rolling annual average of DBPs at identified sampling locations is less than the maximum contaminant levels.

1.3.1 Water Age and Disinfection Byproduct Formation

Excessive water age is one of the major causes of water quality deterioration [AWWA and EES, 2002]. Once finished water leaves the treatment plant, reactions take place within the bulk water and between the bulk water and the pipe wall. These interactions cause chemical, physical, and aesthetic changes, degrading the water quality. The extent of these reactions is dependant of flow rate, pipe material, infrastructure age, biofilm formation, and material deposits in the pipelines [AWWA and EES, 2002]. The AWWA and EES [2002] white paper further discussed many problems that were determined to be associated with aging water. Table 1 summarizes these chemical, biological, and physical issues.

Table 1. Water quality problems associated with increased water age. Source: [AWWA and EES, 2002]

Summary of water quality problems associated with water age		
Chemical issues	**Biological issues**	**Physical issues**
*Disinfection by-product Formation	*Disinfection by-product Biodegradation	Temperature increases
Disinfectant decay	*Nitrification	Sediment Deposition
*Corrosion control effectiveness	*Microbial regrowth / recovery / shielding	Color
Taste and odor	Taste and odor	

* Denotes water quality problem with direct potential public health impact.

Although PWSA is concerned with all of the water quality issues listed in Table 1, they are currently preparing to meet the Stage 2 DBPR so the chemical issue of DBP formation is a priority. Studies conducted on the Denver Water's system concluded that water age determines DBP concentration [Strasser, Hale et al., 2005]. The more time water spends moving through distribution networks, the more time chemical reactions have to take place [AWWA and EES, 2002]. Areas with low chlorine residual or high DBP formation are target areas for regulation compliance [DiGiano, Zhang et al., 2005]. Therefore, gaining a better understanding of how the PWSA distribution system operates will allow PWSA to improve system operation, decrease water age, lower DBP formation to meet the EPA Stage 2 DBPR, and confirm water quality monitoring locations. Water age is highly variable between systems and even within a system, making it a significant driver for water quality.

1.3.2 Causes of Excessive Water Age

Water age and is dependent on how the system is designed, operated, and demands in the system [AWWA and EES, 2002]. As more water is demanded, more water is pumped and more water moves by gravity through the system. Water being used on a frequent basis helps decrease the age of water. The problem of excess water age typically occurs when storage water supplies are underutilized [AWWA and EES, 2002]. Short-circuiting in reservoirs, water bypassing reservoirs, and system dead-zones can also cause pockets of extremely old water to enter the system. The Water Industry Database classifies "short" water ages as less than 3 days. Anything longer than 3 days is considered "long". Also, based on a study of 800 utilities, the average water age, or mean retention time, was determined to be 1.3 days [AWWA and EES, 2002].

Water ages and MRTs in the distribution system may be controlled and decreased by altering the valving networks, installing time varying valves, manual and/or automated flushing, abandoning mains, downsizing mains, increasing storage facility turnover, adjusting pump schedules, decreasing maximum operational storage facility water levels, taking a facility or cell out of service, and/or altering storage facility configurations [Brandt, Clement et al., 2004]. Each of these methods is discussed in further detail by Brandt et al. [2004] in Phase I of the AwwaRF funded review of the ability to control water quality with retention time. Phase II of the review is a guidance manual which includes tools and methodologies for controlling retention time [Brandt, Powell et al., 2006].

1.3.3 Disinfection Byproduct Formation

The water storage facilities and pipelines that make up complicated distribution systems are not designed to carry out chemical reactions [Lawler and Benjamin, In Press]. They are designed to transport water from the treatment plant to customers with adequate pressure and quality. In efforts to assure quality, disinfectant is added to the finished water. The clearwell at the end of the plant is designed as a disinfection reactor for contact time, but it also provides equalization and storage. Additional contact time is achieved throughout the distribution system.

Formation of DBPs is a function of type and concentration of disinfectant, type and amount of organic DBP precursors, contact time between disinfectant and organic precursors, temperature, and pH. The presence of DBPs in finished drinking water is discussed further by Singer et al. [2002]. DBP formation is of concern because water containing DBPs in excess of the maximum contaminant levels (MCLs) has been identified by the USEPA [2006] to increase risk of cancer in long term consumers. In addition to cancer, TTHMs may also cause liver, kidney, and central nervous system problems [USEPA, 2006].

Disinfectant decay rate is a function of organics and inorganics in the water, external contamination, temperature, exposure to ultraviolet light, nitrification, and the type and concentration of disinfectant [AWWA and EES, 2002]. However, it is typically due to bulk water decay, not reservoir wall effects due to the large volume to surface area ratio [AWWA and EES, 2002]. Microbial water quality is maintained by boosting finished water with disinfectant at multiple locations through the system, but rechlorinating water with high concentrations of chlorine in storage facilities may actually increase DBP formation [AWWA and EES, 2002]. Therefore, a balance must be made to reduce overall health risks. As the chlorinated water ages, oxidation reactions occur between the bulk water and the pipe surface and within the bulk water, resulting in loss of disinfectant residual [DiGiano, Zhang et al., 2005]. This is of concern when the reactions are between free chlorine and organic matter, resulting in formation of TTHMs and HAA5, notable DBPs. Therefore, the more time water stays in the distribution system, the more time DBPs have to form [AWWA and EES, 2002]. Removing DBP precursors and reducing reaction time are two effective ways of reducing DBP formation.

The Phoenix water quality study results showed an inverse relationship between DBP formation and chlorine residual, as was expected.[Passantino, Chowdhury et al., 2005]. The results showed that as the water aged, total chlorine residual decreased, and TTHM formation increased. It was not clear if the system had chlorine booster stations throughout their system or not. Passantino et al. [2005] stated that monitoring free chlorine residual “may be an inexpensive method of identifying DBP “hotspots” for the Stage 2 DBPR IDSE.”

Most cities, including Pittsburgh, experience highest DBP formation in early spring when there is large amounts of runoff containing high concentrations of organic matter and in late summer when temperatures increase [Strasser, Hale et al., 2005]. This is because DBP formation increases with water age and with temperature. As temperature increases, reactions go further and faster and causes increased free chlorine demand. Therefore, higher dosages are added which ultimately results in higher DBP formation potential [AWWA and EES, 2002].

DBP formation is also affected by water pH [AWWA and EES, 2002]. To reduce production of DBP, fluctuation in finished water pH should be minimized and pH should be maintained at lower levels. However, the pH of finished water may experience changes in the distribution system. It has been found that new concrete basins may have a higher pH, which increases TTHM formation [AWWA and EES, 2002].

In the city of Phoenix study, it was found that at high water ages, HAAs concentrations actually decreased while TTHMs increased [Passantino, Chowdhury et al., 2005]. As disinfectant residual reacts in the distribution system, the amount of residual in the water decreases. Without residual, bacteria can grow and bacteria regrowth has been shown to actual biodegrade HAAs [DiGiano, Zhang et al., 2005]. These reactions are dependent on time as well as disinfectant concentration. Therefore, quantifying water age is important to understanding water quality and the extent of reactions. It is also important to note that the sites with the longest travel times and highest TTHM concentration may not correspond to the highest HAA sites due to the biodegradation [Passantino, Chowdhury et al., 2005].

1.3.4 Disinfectant/Disinfection Byproduct Regulations

DBPs have been regulated since 1979 to protect public health, when the Trihalomethanes Rule was promulgated [Strasser, Hale et al., 2005]. In 2002, the Stage 1 Disinfectant and Disinfection Byproduct Rule (Stage 1 DBPR) was implemented. PWSA currently monitors for DBPs at four specific locations throughout their distribution system quarterly for the Stage 1 DBPR. Compliance is based on the average concentration of the quarterly samples. These quarterly samples are used for a running annual average (RAA) of DBP is the system. The RAAs must be below the MCL thresholds of 0.08 mg/L and 0.06 mg/L for the TTHMs and HAA5s DBPs, respectively, otherwise PWSA is not in compliance with the Stage 1 DBPR [EPA, 2006].

The Stage 2 DBPR was promulgated on January 4, 2006 to increase public health protection against the adverse health effects associated with DBPs in drinking water. This Rule builds onto the Stage 1 DBPR and focuses on the “hot spots”, where DBP levels are continuously high. EPA has developed multiple quick reference guides and an IDSE Guidance Manual for the Final Stage 2 DBPR to aid in utility compliance [EPA, 2006]. Therefore, monitoring is a key part of the Stage 2 DBPR to identify and lower the DBP formation rate at the “hot spots”. At these locations, a locational running annual average (LRAA) will be evaluated instead of the general system RAAs. The LRAA must be lower than the MCL thresholds for overall system compliance. The Stage 2 DBPR requires that utilities put effort into the identification of high DBP sites by completing an IDSE.

PWSA is required to complete a SMP for their IDSE. The SMP requires utilities to collect bi-monthly samples from selected sites for one year. This is in addition to the sites that are sampled quarterly for the Stage 1 DBPR and the sites are different. The number of sampling sites for the SMP is dependent on the population served and the number of entry points in the system. If a system does not wish to complete a SMP, the utility may submit a SSS describing an alternate strategy for sampling point locations. The Denver Water case study, discussed previously, is an example of a SSS [Strasser, Hale et al., 2005].

The USEPA regulation trend is toward reducing chlorinated byproducts. This is a challenge for utilities such as PWSA who struggle to balance chemical benefit/risk factors with microbial risk factors. Therefore, many water distribution systems are considering changing their disinfectant chemical to comply with tightening regulations.

1.3.5 Chlorine vs. Chloramines Disinfectant

To comply with new byproduct regulations, many US drinking water treatment systems are switching their disinfectant residual from free chlorine to chloramines. At this point, changing to chloramines is one of the easiest ways to assure compliance with the new byproduct regulations. However, PWSA is committed to free chlorine and plans to make system adjustments to continue its use. PWSA is not in favor of switching to chloramines because free chlorine is approximately 100 times as effective as chloramines for inactivation of protozoan, bacteria, and viruses. With Pittsburgh’s aging infrastructure, there is always the possibility of system integrity compromises, such as leaks, breaks, back syphonages, etc. Therefore, PWSA believes that it needs the distribution residual protection of free chlorine to guarantee high quality water for their customers.

PWSA also does not want to change to chloramines, for fear of changing the distribution system’s oxidizing environment. After changing over to chloramines, Washington, D.C. encountered extensive changes in lead corrosion and solubility [Edwards and Dudi, 2004]. Unfortunately, it was not detected quickly, resulting in significant population exposure to high concentrations of lead. Other cities have experienced similar problems to Washington, D.C. after the switch to chloramines. Data from Greenville, North Carolina drinking indicated that the Washington D.C. case was not unique[Renner, 2005]. Renner [2006] also reported on corrosion studies which concluded that more lead scales dissolve with chloraminated water.

The aging distribution system in Pittsburgh and its three consecutive water systems still contains many lead service lines. If PWSA switches over to chloramines, there is risk of increasing lead exposure to their customers. However, with PWSA's current operating procedures and their long water ages in their system, PWSA cannot meet the Stage 2 DBPR using free chlorine. Consequently, to avoid change over to chloramines, PWSA must optimize the hydraulics of the distribution system, with a focus on the large DBP formation in finished water storage facilities, to meet the compliance standards.

1.4 FINISHED WATER STORAGE FACILITIES

Storage facilities in distribution systems provide sufficient pressure and quantities of water to customers, serve as equalization rectors to alleviate water demands and flow fluctuations, and provide residence time for reactions to occur within the bulk water. The design, operation, and maintenance of storage tanks can minimize the finished water storage facility's degradation of water quality.

1.4.1 Reservoir Mixing

Reservoirs are non-ideal reactors, so the extent of mixing in these reactors is typically uncertain. However, the amount of time allowed for reactions to occur is dependent on the mixing and mixing patterns in the reactor [Lawler and Benjamin, In Press]. Therefore, the effluent of a reactor can be monitored for the varying compositions of a material, such as a tracer, to determine mixing characteristics. From the AWWA water distribution systems handbook, reservoir mixing was stated to be a parameter which needs to be optimized to minimize the MRT [Grayman and Kirmeyer, 2000]. Reservoirs that do not mixing well may increase the MRT and water quality deterioration in the distribution system. This lack of mixing in reservoirs is likely due to poor facility design and operations management [AWWA and EES, 2002] or water stratification. A study conducted by Mahmood et al. [2005] reported the occurrence of water stratification in storage facilities which received water varying less than 1 °F from the water in the storage facility. The duration of the stratification effects were dependent on the operation of the storage facility. Dead and short-circuiting zones are results of poor facility design and operation, which result in volumes of water that have MRTs much greater than the rest of the water in the in the storage facility. Since reservoirs are such large reactors, they typically do not have a problem with contact time. Therefore, reservoirs should promote mixing instead of plug flow prevent dead-zone formation, since mixing conditions are easier to achieve [Kirmeyer, Friedman et al., 2005].

Mixing requires energy. One source of mixing comes from the momentum of having a turbulent jet inlet to the storage facility [AWWA and EES, 2002]. When jetting water enters the storage facility, it entrains the ambient water allowing for water to be mixed [AWWA and EES, 2002]. Mixing is highly dependent on this influent flow rate, but also on the quality of water within the storage facility as discussed in Section 1.3. Other ways to encourage mixing include separating tank influent and effluent piping, changing the orientation of existing influent piping to provide a maximum flow path, altering the water level fluctuations between fill/draw cycles or adding a mechanical or hydraulic means. Kirmeyer and Friedman et al. [2005] described a hydraulic circulation system with pumps and diffuser pipes as the best method for mixing a reservoir.

The Kirmeyer and Friedman et al. [2005] stated suggestions from Kirmeyer and Kirby et al. [1999], who studied how to maintain and operate storage facilities efficiently, to completely turn over water stored in reservoirs every three to five days at a minimum. From German experience, Lauer [2005] reported suggestions of five to seven day maximum residence time in reservoirs with cement-based internal surfaces. However, both of these suggestions assume ideal mixing conditions with no dead-zones or short-circuiting, which can increase or decrease the residence time significantly.

They hydraulics of the reactor are based on the design, and until recently, the design was based off of previous experience and rules of thumb [Lawler and Benjamin, In Press]. Now there is a field called computation fluid dynamics (CFD), which uses software to develop design alternatives that look at hydraulics characteristics and sensitivity of the characteristics during design. Lawler et al. [In Press] stated that the CFD model can generate design performance information before constructing the design. This information was previously only obtainable by conducting tracer studies. A case study of using CFD to determine water stratification in storage facilities was completed for the City of Virginia Beach discussed by Mahmood, et al. [2005].

1.4.2 Potential Risks

Storage facilities pose risks to the distribution system since they can be a point of contamination. Debris or contaminants may enter into storage facilities through hatches, sidewall joints, vents, or overflows [AWWA and EES, 2002]. These gaps and openings cause sanitary problems to the storage facility since they allow bugs, animal droppings, and other unwanted contaminants to enter the finished water. These sanitary issues may, and have in the past, caused waterborne disease outbreaks such as Salmonella Typhimurium and Campylobacter. The AWWA and EES [2002] literature review of finished water storage facilities summarized the risks associated with finished water storage facilities in Table 2. They all degrade the quality of the finished water, but the ones that are marked with an asterisk pose potential health risks to consumers.

Table 2. Summary of water quality problems associated with finished water storage facilities. Source: [AWWA and EES, 2002]

Chemical Issues	Biological Issues	Physical Issues
Disinfectant Decay	Microbial Regrowth*	Corrosion
Chemical Contaminants*	Nitrification*	Temperature/Stratification
DBP Formation*	Pathogen Contamination*	Sediment*
Taste and Odors	Tastes and Odors	

*Water quality problem with direct potential health impact.

1.4.2.1 Sediment is material that is allowed to settle as water moves through the distribution system. When water in the storage facilities is not in demand, water becomes stagnant and creates conditions that are ideal for particle sedimentation. The sediment that accumulates in the storage facilities degrades water quality by creating additional disinfectant residual demands, microbial growth, and DBP formation [AWWA and EES, 2002]. During typical operations, sediment does not enter the bulk water, but it still poses risks. However, when reservoirs are filled, there may be high turbidity episodes due to sediment build up on the floor of the storage facility.

In 2000, the City of Massachusetts detected total coliform bacteria in samples from one of their storage tanks. AWWA [2002] reported that this tank had an open hatch which may have allowed the water to be contaminated, however, it also had inches of sediment. This tank, along with three others, was cleaned to remove almost six inches of sediment at some locations. After returning these tanks to service, the system saw high levels of total coliform throughout the system. This resulted in the need for citywide flushing and increase free chlorine residual tank. To prevent a similar problem from happening in the future, Massachusetts now cleans all their storage tanks every three years, which corresponds to the recommendations outlined by Lauer [2005], which discussed how to prevent water quality deterioration in finished water storage facilities. The Lauer [2005] paper stated that covered storage facilities should be cleaned and inspected every five years for structural conditions and uncovered reservoirs should be once or twice per year.

1.4.2.2 Physical Contamination is a large concern for consumers. Especially since AWWA and EES [AWWA and EES, 2002], who reported findings of Kirmeyer and Kirby et al. [1999], stated that inspection companies often find storage facilities with no bug screens on vents and overflow, unlocked access hatches, lead based paints, paints that are not approved by National Sanitation Foundation, and unoperational cathodic protection systems. Uncured paints are also of concern since they may leach chemicals into the finished water [AWWA and EES, 2002].

1.4.2.3 Uncovered Reservoirs pose the most risk to distribution systems since there is great potential for contamination. Entry of contamination from birds, humans, algae, debris, etc. into the reservoir can transmit disease-causing organisms into the finished water supply. The contamination may also cause aesthetic problems, such as taste and odor or color, and the addition of organic material may increase DBP formation.

1.4.2.4 Floating Covers also pose risk to finished water. These covers collect rainwater, animal and bird feces, and anything else that lands on the cover. The water needs to be pumped off the cover daily, however, pumps are not always operational allowing pools of water to form. From the AWWA literature review of storage facilities [2002], these pools were classified as a great source of contaminated untreated water which may attract wild life, adding to the contamination. Floating covers are susceptible to tears from ice damage, changing operating levels, and vandalism which intern causes contamination of the finished water as pooling water mixes into the storage facility. In addition, materials used to clean or repair floating covers may pose health risks. These solvents, adhesives and other materials may contaminate the stored water if used improperly [AWWA and EES, 2002].

1.4.3 Indication of Water Quality Problems

Water quality problems at storage facilities may be identified by operations personal, but unfortunately, water consumers are typically the first to identify the problem. The problems identified by consumers are typically aesthetic and can be caused from old water age, insufficient water treatment, pipeline materials, old infrastructure, or the storage facility itself [AWWA and

EES, 2002]. The AWWA literature review of finished water storage facilities [2002] further discusses detectable signs at the tap including temperature, taste, odor, color, and possible sources of the water contamination and deterioration.

2.0 MATERIALS AND METHODS

Prior to the execution of the tracer study, thorough planning was completed to ensure successful results. Planning for the tracer study started more than six months prior to the execution of the study. For their potable water distribution system, PWSA had to make sure that the tracer study of either adding or removing a substance form the water, would not cause any health effects or compromise the integrity of the distribution system.

Pittsburgh decided to use fluoride for their tracer study. Kennedy et al. [1991] found fluoride to be an effective tracer for water age studies and model calibration. Fluoride is a stable chemical, naturally occurring in the source water. PWSA continuously adds fluoride to the finished water for dental benefits. As long as the concentration is below the MCL of 4.0 mg/L, fluoride is not harmful to the general public [USEPA, 2006]. However, dental benefits are cumulative over time, therefore, turning off or reducing the fluoride levels for a short period should not have a dental affect for the general populations [ADA, 2005].

While preparing for and conducting the PWSA fluoride tracer study, no universally accepted guidelines were available for conducting or interpreting data results from the comprehensive distribution system tracer study. There was also limited published material comparing tracer study results to hydraulic model simulations. However, successful case studies and guidance manuals were helpful in designing and setting up the study.

2.1 PERMITTING

PWSA had to communicate with all parties involved in order to conduct the fluoride tracer study. The State was contacted to ensure approval of the study. PWSA was required to fill out a water supply application prior to conducting the study for PADEP since the treatment process changed during the study [States, 2006]. PWSA applied for the permit from PADEP to turn off the fluoride temporarily via a written request on July 5, 2006. The Allegheny County Health Department (ACHD) and PADEP also requested a formal letter explaining the study's purpose as well as a general study plan from PWSA. The State of Pennsylvania decided that public notification was not required since there was not public health effect.

PWSA applied for the permit to turn off the fluoride for a two week period, with the option to increase or decrease the fluoride suspension period based on the early results of the study. PWSA's main concern was with the far reaches of their distribution system and the consecutive users' distribution systems. With great uncertainty of water age, PWSA wanted to make sure to keep the fluoride off for a long enough period to determine the actual water age. The IDSE survey was incorporated into the tracer study for the required Stage 2 DBPR. The IDSE incorporation was explained in the formal letter to ACHD and PADEP, and thought to be one of the main reasons why the fluoride shut off was approved by ACHD and PADEP [States, 2006].

Some State health departments may not permit fluoridation to be discontinued. If fluoridation cannot be discontinued, other tracers must be evaluated as discussed in Section 1.2. On August 14, 2006, PADEP issued PWSA Water Supply Permit No. 0206507 for the fluoride tracer study approval. The expiration date on this permit was October 15, 2006 [Tarara, 2006]. Due to installation and setup delays, the permit expiration date was extended. The fluoride was shut off at PWSA on October 16, 2006 at 8:00AM and remained off for a four week period. Samples were collected during the first three weeks (Phase I). The fourth week was used to prepare for step-up tracer study (Phase II) starting on November 13, 2006 @ 8:00AM when the fluoride feed and sampling was resumed.

2.2 FLUORIDE SAMPLING

The PWSA fluoride study included the sampling within the Pittsburgh distribution system, as well as, Millvale, Reserve, and Fox Chapel, Pennsylvania (three areas that purchase water from PWSA).

2.2.1 Selection of Sample Locations

A sampling plan was developed to ensure that the system was properly represented. The PWSA hydraulic model was used to aid in the selection of sites, which represented the wide range of water qualities within the distribution system. Sampling sites were selected with appropriate geographic distribution to target nodes within different pressure zones and at specific distances close to and far from the plant. The number of sampling sties within the sub-areas was determined proportionally to the size of the area and number of customers served. Water quality data and the knowledge of the flow regimes through the existing system were taken into account in choosing the sites and sample intervals. Areas with historically low or fluctuating chlorine residuals and areas with high TTHMs were also targeted. Many of these sites were located at the far reaches of the distribution system. Studying these areas with high TTHMs was imperative since they will be the focus of the Stage 2 DBPR and the levels must be lowered for compliance.

It was necessary to make sure the all selected sites were viable locations for the study. PWSA has 60 routine laboratory sampling sites where they have permission to collect samples. These routine sites are typically visited multiple times throughout the week. From previous studies, it has been found that sites with historic data are desirable for tracer studies since the data can be used for comparisons and analysis [Passantino, Chowdhury et al., 2005]. Multiple routine sampling locations were selected within the three consecutive systems (Fox Chapel, Reserve Township, and Millvale Borough). However, in Pittsburgh the routine sites are not accessible during the weekends.

Alternative accessible sampling locations in Pittsburgh were selected instead of the routine sampling locations to capture the flow regime. It was important to have access to the tracer study sites for sampling seven days a week and in the early morning and late evening. Therefore, pump stations, storage facilities, hydrants, and PWSA employee homes were selected as sampling sites. Many of these locations were along the main flows paths so the data would be useful for model calibration. All sampling points, except the hydrants and reservoir surface sampling locations, were indoors to prevent freezing with cold weather. Freezing was an issue for the hydrants. Two of the hydrants had to be relocated due to complaints about the continuous flow from the hydrants causing sidewalks to become icy during the study period.

The finalized sampling site listing is summarized in Table 3. Each site was given a sample identification number and organized by sampling type, or location with in the system, and sampling frequency. The spatial representation of the sampling locations is shown in Figure 9.

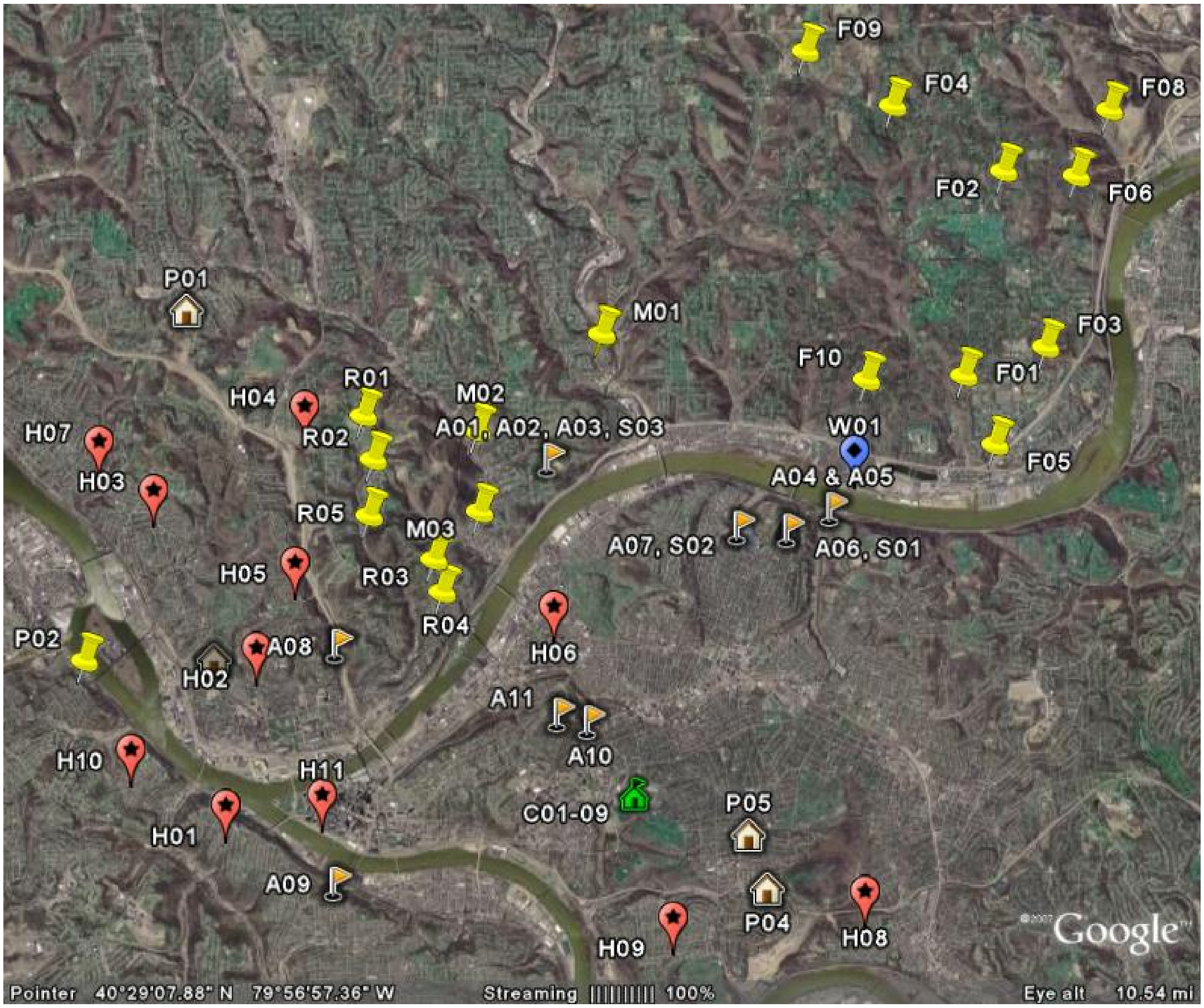

Figure 9. Fluoride sampling locations.

Table 3. Fluoride sampling location identification names and descriptions.

Distribution System Entry Point: 15-minute samples	
W01	clearwell (AWTP)
Auto Samplers: 4-hour samples	
A01	Lanpher Reservoir East Effluent
A02	Lanpher Reservoir West Effluent
A03	Lanpher Reservoir Influent (Aspinwall Pump Station)
A04	Bruecken Pump Station (Influent Highland No. 1)
A05	Bruecken Pump Station (Influent Highland No. 2)
A06	Highland Reservoir No. 1 Effluent
A07	Highland Reservoir No. 2 Effluent
A08	Howard Pump Station (Lanpher Reservoir)
A09	Mission Pump Station (Highland No. 2 Reservoir)
A10	Herron Hill Pump Station (Herron Hill Reservoir Influent)
A11	Herron Hill Reservoir Effluent
Pittsburgh: 12-hour grab samples	
P01	27 Perryview Avenue (Brashear Tanks)
P02	3133 Brunot Avenue (Allentown Tanks)
P03	1114 Colfax Street (McNaugher Reservoir)
P04	6433 Forward Avenue (Herron Hill Reservoir)
P05	5838 Darlington Road (Lincoln Tank)
Hydrants: periodic grab samples	
H01	Hydrant 1 - 401 Well Street (Allentown Tanks)
H02	Hydrant 2 - 1713 Brighton Road (Lanpher Reservoir)
H03	Hydrant 3 - Termon Ave, between McClure and California Ave (McNaugher Reservoir)
H04	Hydrant 4 - 4260 Evergreen Road, intersection with Ivory Avenue (Brashear Tanks)
H05	Hydrant 5 - Perrysville Avenue, intersection with Legion Street (Brashear Tanks)
H06	Hydrant 6 - Penn Avenue, between 39th and 40th Street (Highland No. 1 Reservoir)
H07	Hydrant 7 - Lincoln Avenue, intersection with Joshua Street (Lincoln Tank)
H08	Hydrant 8 - Love St., first hydrant on left off Whipple St. (Highland No. 1 Reservoir)
H09 H10	Hydrant 9 - Bigelow and Tesla St. intersection, Hazelwood Ave. (Squirrel Hill Tank) Hydrant 10 - Chartiers Street and Lorenz Street intersection (Allentown Tanks)
H11	Hydrant 11 - Mon Warf Parking Lot (Highland No. 2 Reservoir)
Storage Reservoirs: periodic surface grab samples	
S01	Highland No. 1 Reservoir
S02	Highland No. 2 Reservoir
S03	Lanpher Reservoir

Table 3 (continued)

Millvale Borough: daily grab samples	
M01	114 Grant Avenue, Grant's Bar (Aspinwall Pump Station)
M02	1201 North Avenue, Hardees (Aspinwall Pump Station)
M03	232 North Avenue, Lincoln Drug/P&G Diner (Aspinwall Pump Station)
Reserve Township: daily grab samples	
R01	4000 Mt Troy Road, Saint Mary's Cemetery (Brashear Tanks)
R02	116 Biscayne Terrace, Fire House (Brashear Tanks)
R03	33 Lonsdale St., Municipal Bldg/Mt Troy Volunteer Fire Co. Sta. 239 (Brashear Tanks)
R04	2000 Mt Troy Rd., Mt Troy Savings Bank (Brashear Tanks)
R05	3367 Spring Garden Rd., Spring Garden Volunteer Fire Co. Sta. 240 (Brashear Tanks)
Fox Chapel: daily grab samples	
F01	PWSA Feed at Rockwood Valve Station (Aspinwall Pump Station)
F02	1003 Fox Chapel Road (Aspinwall Pump Station)
F03	280 Kappa Drive (Aspinwall Pump Station)
F04	Hampton Township Interconnect (Aspinwall Pump Station)
F05	Blawnox Boro Interconnect (Aspinwall Pump Station)
F06	928 Field Club Road (Aspinwall Pump Station)
F07	341 Kittanning Pike (Aspinwall Pump Station)
F08	503 Guys Run Road (Aspinwall Pump Station)
F09	3563 Harts Run Road (Aspinwall Pump Station)
F10	502 Guyasuta Road (Aspinwall Pump Station)
Carnegie Mellon University: daily grab samples	
C01	Baker Hall (Bruecken Pump Station)
C02	Hunt Library (Bruecken Pump Station)
C03	Porter Hall (Bruecken Pump Station)
C04	Purnell Hall (Bruecken Pump Station)
C05	Robert's Hall (Bruecken Pump Station)
C06	Tepper School (Bruecken Pump Station)
C07	University Center (Bruecken Pump Station)
C08	Warner Hall (Bruecken Pump Station)
C09	Wean Hall (Bruecken Pump Station)

All of the autosamplers, denoted by orange flags in Figure 9, were located at PWSA properties around the city. These locations, including chlorine booster stations, pump stations, and the membrane plant, are entrance points to different parts of they system. The collection interval at these sites was four hours, allowing the autosampler to operate continuously for four days straight. The autosampler sites were secured by lock and key entrance. Although, the Herron Hill Reservoir effluent autosampler was located in the chlorine house, the suction line to the sampler ran outside through a fan vent fan to a pressure main in an underground vault. There were concerns about the line being cut by vandals or by the fan. The fan was supposed to be disconnected, but it kicked on during Phase II of the tracer study and cut the sampling line.

The red balloons in Figure 9 are hydrant locations used for the tracer study. The hydrant locations were chosen to monitor water movement from different storage and pumping facilities within the distribution system. Although some of the sampling locations were in higher crime areas of the city, no tampering of the equipment occurred. In addition to these sampling locations, laboratory employees collected samples from their homes twice daily. These sampling locations are denoted in Figure 9 by beige houses. The yellow tacks represent all the consecutive system sampling locations in which samples were collected daily.

The three primary finished water reservoirs, sampling IDs S01, S02, and S03, were sampled at a number of locations over the surface of the reservoirs. Depth samples were collected to obtain information on how well the reservoirs mix and how the reservoirs influence water age and DBP formation. The hatch sampling locations for S02 and S03 are label in Figure 10 and Figure 11, respectively. At site S02, 27 hatches were sampled. The hatches around the perimeter of the Highland No. 2 Reservoir in Figure 10 were labeled with letters from ‘A’ to ‘P’, and the hatches inside of the reservoir floating cover folds were numbered 1 through 11. Lanpher Reservoir, or site S03, had 12 hatch sample locations. As shown in Figure 11, there were six hatches over the west basin (labeled R-1 through R-6) and six sites over the east basin (labeled L-1 through L-6). Due to excess water on the floating covers, a few hatch sampling sites could not be reached safely at the Highland No. 2 and Lanpher Reservoirs, especially on sampling days which followed heavy rainfall, or when the sump pumps were not operating.

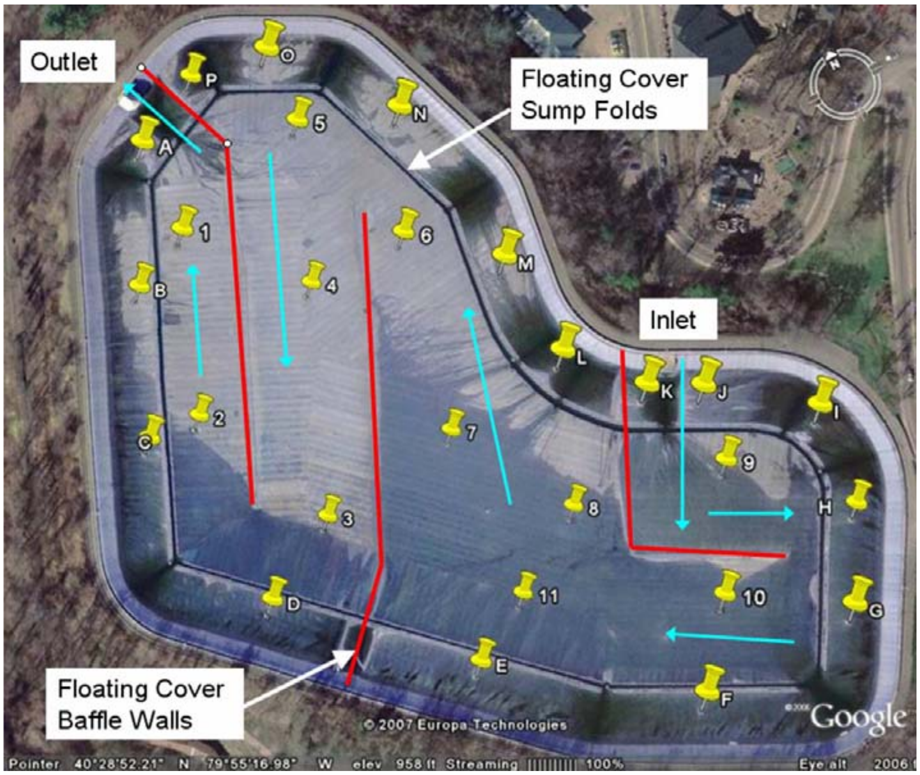

Figure 10. Highland No. 2 Reservoir hatch sampling sites and ID names.

Figure 11. Lanpher Reservoir hatch sampling sites and ID names.

2.2.2 Field Equipment and Set-up

Standard materials needed at all the sites while collecting samples included:

- Clean sample bottles with caps (one per site);
- Bottle rack or box;
- Labeling tap (tap was typically applied to bottles in the laboratory);
- Sharpee (to label bottle with time, date, and location);
- Map of sampling locations;
- Sampling field sheets and
- Cell phone.

When taking grab samples from the surface of the reservoir and at the hydrants, additional materials were required. The site specific materials were as follows:

- Highland No. 1 Surface Samples
  - Boat;
  - Gas Motor;
  - Global Positioning System (GPS) handheld unit;
  - Sampler with weight attached and 10-feet of rope;
  - Three to four people (boat driver, sample collector, navigator/GPS location recorder, and person watching from the edge of the reservoir with a cell phone for emergencies) and
  - Life Jackets.
- Highland No. 2 and Lanpher Reservoir Floating Cover Hatch Samples
  - Waders;
  - Gloves;
  - Sampler and 15-feet of rope;
  - Two people (sample collector and safety rope leader) and
  - Safety Equipment
    - Harness;
    - 100-feet of rope;
    - Garden hose reel;
    - Knife and
    - Life jacket..

The safety equipment wore while collecting samples from the floating covers is shown in Figure 12.

Figure 12. Safety apparel for collecting floating cover hatch samples.

- Hydrants
  - Pliers to turn on an off the sampling port (only if the knob is removed from the valve for security purposes);
  - Chlorine residual colorimeter and DPD total chlorine reagent
  - Fluoride data collector
  - Hydrant wrench
  - Measuring container to set the flow rate at approximately two gpm.

2.2.2.1 Autosamplers were acquired for the tracer study. There were 13 Hach Sigma 900 Standard Portable Samplers (12 for the sampling locations and 1 autosampler for backup). These samplers came equipped with 24 glass bottles, 25 feet of tubing, and a filter apparatus. According to the autosampler instruction manual, the standard setup was to place the autosampler above the sampling point, drawing sample up from a wetwell through the filter at a maximum depth of 25 feet. The auto-calibration feature worked for the standard setup; any setup that deviated from the standard setup had to be time calibrated.

Prior to installing the autosamplers in the field, one unit was set up in the PWSA Water Quality Laboratory. The autosampler was connected to a carboy from which it could draw samples. The carboy was connected to a continuous flow faucet (pressure tap). The flow rate to the carboy was set to create a steady flow and turn over of water in the bottle. A third tube was connected to the top of the carboy to allow the carboy to drain into the sink. This setup simulated how all pressure tap sampling points would be installed. The autosampler interface (Figure 13) was used to develop programs with different parameter settings. Test runs were completed to become familiar with the autosampler's capabilities. Standard parameters, as listed in Table 4, were selected in the laboratory to save field set-up time. The parameters labeled as "site specific", including volume, tube length, auto/time-calibration, were determined in the field while setting up the autosamplers. The volume parameter was changed during the auto-calibration to assure enough sample was being collected. For this study, it was not important for the actual volume collected to match the volume programmed into the autosampler. Measuring the length of tubing between the sampler pump and sampling site was important for the auto-calibration so the autosampler could estimate how long the pump needed to run to collect the programmed volume. With time-calibration locations, the amount of pumping time needed to pull the sample from the sample source was manually programmed, therefore, the length of pipe parameter at these locations was negligible.

Figure 13. Autosampler digital display interface.

Table 4. Standard settings for autosamplers.

Standard Settings	
Program Number	1
Total # of Sample Bottles	24
Units for Bottle Volume	mL
Volume	site specific*
Tubing Length Units	feet
Enter Tubing Length	site specific*
Program Lock	NO
Verify Program	Yes
Program Delay	Yes
Program Stop	NO
Time Mode	Yes
Variable Interval	NO
Interval	240
Discrete Mode	Yes
Bottle per Sample	1
Change Volume	YES/NO**
Sample Volume	above
Calibrate Volume	YES
Auto/Time Calibration	site specific*
Intake Rinses	Yes-3
Intake Faults	Yes-3

* Parameters were determined based on setup at each sampling location

** Hit Yes to calibrate, hit NO if autosampler was already calibrated

The field installation of the autosamplers began two weeks before starting the tracer study. Autosamplers A01, A02, A03, and A07 were auto-calibrated. These samplers drew water either from a wetwell, similar to the setup in Figure 14, or from an open channel, as show in Figure 15. Time-calibration was required for A04, A05, A06, A08, A09, A10, and A11 since theses sampling points were located on pressure mains. An example of the carboy/pressure main apparatus is shown in Figure 16. A sampling tap was installed by a plumber at pressure main sampling locations prior to the start of the study. The installation process was a time consuming, so sites that were already tapped were utilized when possible. Once an autosampler was installed and calibrated, it was programmed and started. The autosampler was allowed to run for one or two days, then the unit was checked to see if it was collecting samples correctly. If the autosampler was operating correctly, the program was reset with a delay to start eight hours, or two sample intervals, prior to the commencement of the tracer study. Otherwise, the autosampler was recalibrated and/or the program setup was checked to troubleshoot the collection problem. The autosamplers, which did not collect samples correctly, were retested until the problem was solved. All the samplers were set up similarly, allowing multiple staff members to collect the samples during the study with ease.

Figure 14. Highland No. 2 autosampler (A07) - Collecting samples from wetwell.

Figure 15. Site A01 - Sampling the effluent channel from the East Lanpher Reservoir Cell.

Figure 16. Herron Hill Pump Sta. (A10) - Autosampler connection to pressure main.

2.2.2.2 Hydrants and installation support for the 11 hydrant samplers were provided by the Agency for Toxic Substances and Disease Registry (ATSDR). A week before the start of the study, two ATSDR employees brought the hydrant equipment to the AWTP. A demonstration was completed on a fire hydrant at the plant to show PWSA employees exactly how the continuous samplers work in the field. Following the demonstration, one ATSDR employee went out in the field with a PWSA employee to start setting up the equipment (all equipment shown in Figure 17, except the fluoride continuous analyzer) and checking the hydrant locations. The other ATSDR employee stayed at the AWTP and calibrated all the continuous fluoride analyzers. It took a total of four days to have all the hydrants setup and ready for the study. The hydrant displayed in Figure 17 is actually from the continuous monitoring tracer study completed at Camp Lejeune, North Carolina, also in conjunction with the ATSDR [Maslia, Sautner et al., 2005]. The same sample equipment was used for the PWSA hydrants samples with exception of the yellow hose (D). The protective jug used for the PWSA fluoride tracer study had holes cut in the bottom that allowed water to flow freely out onto the sidewalk.

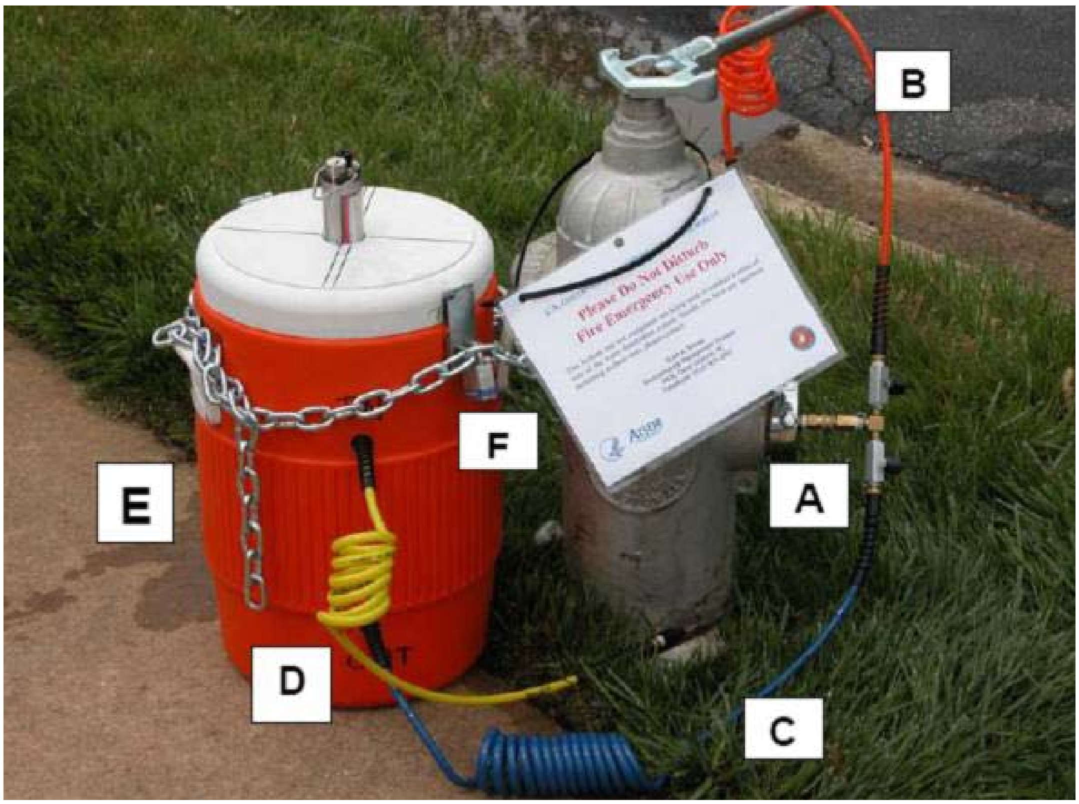

Figure 17. Hydrant continuous monitoring equipment setup including (A) hydrant adaptor, (B) orange hose for grab sample collection, (C) blue hose supplying water to the flow cell in the water jug, (D) yellow hose for discharging water, (E) plastic water jug housing for flow cell and dual-probe ion detector, and (F) security lock, chain, and information sign. Source: [Maslia, Sautner et al., 2005]

2.2.3 Sample Collection

2.2.3.1 Fluoride samples were collected and analyzed from approximately 4,000 throughout the course of this study. The intervals between samples at the different locations were as follows:

- 4-hour intervals from the 11 autosamplers,
- Periodic grab samples from the 11 fire hydrants,
- Twice daily grab samples from five homes,
- 18 daily samples from consecutive system sample sites,
- Nine daily sample from Carnegie Mellon University's campus, and
- Several rounds of samplings from multiple locations within the three primary finished water reservoirs.

Since the sampling frequency varied per locations, collection procedures were adjusted accordingly.

The autosamplers were set to collect discrete samples at 4-hour intervals. Since the autosamplers were equipped with 24 bottles, the autosampler sites were visited at least every four days. Extra bottles were not ordered to switch out between collections, so some samplers were equipped with less than 24 bottles at any given period. The program was not modified to reflect the change in number of bottles. The bottles were aligned from the start location as if 24 bottles were to be used (placing bottles directly next to one another from the start point). Autosamplers with less than 24 bottles were typically serviced every day or every other day to change out the bottles. Figure 18 displays how an autosampler with 22 sample bottles was taken apart in three pieces to access the sample bottles during the collection process. The protective lid was taken off, followed by the control interface to access the sample bottles positioned around the white basket.

Figure 18. Autosampler sample bottle collection.

Each time the autosampler was serviced, the program was reset to start at the next 4-hour interval (12 A.M., 4 A.M., 8 A.M., 12 P.M., 4 P.M., 8 P.M.) to maximize the sampling duration. The reset time and date was recorded on a label and placed on the user interface as shown in Figure 13. The sample collector added four hours sequentially to the time on the label to identify and mark when each sample was collected, (Figure 19). It should be noted that each time the program was reset, the sample dispensing arm rotated back to the same sample starting point. The boxes in which the sample bottles were shipped were kept and used to transport clean bottles and collected samples back and fourth between the sample sites and the PWSA Water Quality Laboratory.

Figure 19. Labeled sample bottles in collection box.

The goal was to visit the fire hydrants at least twice a week. Hydrant sites, which were more accessible, were sampled on a daily basis. The continuous monitoring data were collected from the two HORIBA W-23XD dual probe ion detector probes (Figure 20) which were secured inside of the water jug pictured in Figure 17. The dual probe was equipped with two fluoride ion sensors to assess the reliability of the data, along with a temperature and total chlorine residual sensors located inside of the perforated metal housing. The real time fluoride concentration values and the continuously recorded data from the dual probe ion detector were collected by attaching the blue HORIBA W-23XD water-quality control unit with the cable shown in Figure 21. The grab sample port (orange hose) was also used to collect a grab sample to be used for quality control against the continuous monitor readings and real time data. The sample port was flushed for a few minutes, and then the sample bottle was rinsed three times with sample water before collecting the sample. While at the hydrant location, the field person took notes on how the continuous sampler monitoring equipment was working and took a grab sample for total the chlorine residual concentration analysis.

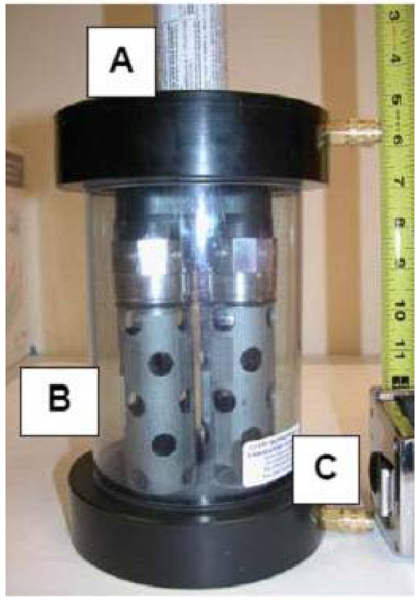

Figure 20. Hydrant continuous sampler including (A) dual prove ion detector, (B) flow cell, and (C) brass connectors for water feed. Source: [Maslia, Sautner et al., 2005].

Figure 21. Collecting data from hydrant continuous fluoride analyzer.

Grab samples were collected at different times and intervals depending on the location and person sampling. The five houses, P01 through P05, were sampled twice daily by laboratory employees. A sample was collected seven days a week in the morning between six and seven A.M. and in the evening between six and seven P.M. Twice daily samples were determined to be sufficient in the Fort Collins Tracer Study [Simon, Billica et al., 2006]. Crews in Fox Chapel, Millvale Boro, and Reserve Twp. collected samples once daily, seven days a week from sites F01 through F10, M01 through M03, and R01 through R05, respectively. Since these three areas are interconnected to PWSA's distribution system, once daily samples were determined to be sufficient.

As for reservoirs in the PWSA distribution system, the goal was to sample the surface of each reservoir twice per week. A boat was taken out on the Highland No. 1 Reservoir to collect the depth samples and a PWSA employee walked on the reservoir covers to collect samples from hatches over the Highland No. 2 and Lanpher Reservoirs. The frequency of sampling was dependent on weather. Sampling over the three primary reservoirs was cancelled or rescheduled multiple times during both Phase I and II due to heavy wind, rain, and snow.

At Highland Reservoir No. 1 Reservoir, a three foot long, narrow tube sampler was used to collect the samples. The sampler had a ball valve at the top and bottom, which controlled the sample collection. To collect a sample, the sampler was dropped down 10-feet into the reservoir. The upward force of the water on the bottom ball valve kept water from entering the sampler. Once the sampler stopped descending, water was allowed to enter the sampler. A weight was attached to the sampler to make it sink faster and prevent water from entering prematurely. Prior to collecting the sample, the sampler was filled and rinsed with water from the sampling location three times. Paddles were used during this time to help maintain the GPS location. Although the same exact locations were not sampled each time, the GPS unit was used to navigate close to the same sampling sites. The GPS unit was a Garmin eTrex Legend and was accurate within 10-feet or less of the marked points. On the fourth run, the sample was collected and the GPS location was marked on the GPS unit and recorded on paper (Figure 22). The sampler was not disassembled to collect a sample. Water could be poured out of the top ball valve.

Figure 22. Highland No. 1 Reservoir - Collecting sample and recording GPS location.

To collect samples from the hatches on the Highland No. 2 and Lanpher Reservoirs floating covers, the hatch was unlocked and the sampler was dropped down 15-feet and allowed to fill (Figure 23). Then, the sampler was retrieved and emptied onto the reservoir cover, not back into the reservoir, to avoid finished water contamination. Care was also taken to keep the sampler and rope off the unsanitary cover. At each hatch, the sampler filled with water at a depth of 15-feet three times to condition the sampler. Then, the sampler was lowered a fourth time to collect the sample. After the bottle was filled a fourth time, the hatch was closed and locked, and an aliquot was poured into a pre-labeled sample bottle (Figure 24). Since this sampler was weighted and there were two small inlet holes, minimal water was allowed to enter while descending to the desired depth of 15-feet. From conditioning the sample bottle at each hatch, some vertical mixing was induced, however, the sample was still considered representative of the fluoride concentration at the hatch location.

Figure 23. Lanpher Reservoir, dropping sampler down through hatch.

Figure 24. Collecting sample from cover of Lanpher Reservoir.

2.2.3.2 Disinfection Byproduct Samples, for TTHM analysis, were also collected once during Phase I and Phase II to provide a "snapshot" of the water quality at different points within the system. Since PWSA will be conducting the IDSE to meet the Stage 2 DBPR, the TTHM samples were collected at the fluoride sample collection points for comparison with tracer study water age results.

2.2.4 Sampling Crews and Routes

Laboratory personnel were identified for sample collection and analysis support. A temporary employee was hired during the study to collect daily chlorine residual samples, allowing all full time staff to focus on the tracer study. All of the collectors were trained in how to use to use the equipment (for the hydrants and autosamplers), collect samples, and locate the hydrants and autosamplers. The protocol at each autosampler and hydrant did not vary. The same sample staff routinely went to the reservoirs to collect surface samples, so general training was not provided to all collectors. A clip board included field data collection sheets, a description of sampling locations, and a map of the sampling location. This clipboard was taken out by the sample collector to aid in collecting samples efficiently. Depending on which sites needed to be serviced each day, sampling routes varied. Typically, one to two people went out each day to collect fluoride samples. The employees collecting the samples were very familiar with the location of the sampling points. If there were any problems during collection, the sample collector called back to the PWSA Water Quality Laboratory for assistance, or called the laboratory manager's cell phone. Crews were instructed to explain the study to any curious residences around the sampling locations.

2.2.5 Laboratory Analysis

All of the fluoride samples were analyzed within 28 days (the fluoride maximum holding time) after collection. Fluoride samples do not need to be preserved after collection, therefore, no refrigeration was required. PWSA's Water Quality Laboratory completed the fluoride sample analysis. The laboratory is located at the AWTP.

Field samples were analyzed by the PWSA employees via the ion-selective electrode method [APHA, 1998] once they arrived at the laboratory. With the large number of samples, laboratory employees were encouraged to work overtime, when possible, to analyze the samples as quickly as possible. Analyzing the samples during the study provided immediate information on how the study was progressing. This early feed back also helped determine when the sampling at specific sites could be discontinued. During the analysis, a quality control sample was tested, between ever 10 field samples, with a 1.0 mg/L of fluoride standardized solution.

The samples collected for DBP formation determination were analyzed by purge and trap gas chromatography for bromodichloromethane, bromoform, chloroform, and dibromochloromethane to determine the concentration of TTHMs. The PWSA system does not have a problem with high HAA5 formation; therefore, the samples were only tested for TTHMs.

2.2.6 Tracer Study Execution

The PWSA process chemical tracer study was comprised of two phases, a step-down tracer test (Phase I) followed by a step-up tracer test (Phase II). Phase I of the trace study started on October 16, 2006 8:00 A.M. when the fluoride was shut off at the influent to the AWTP clearwell. No changes were made to the distribution system prior to the start of the study, and operators were instructed to maintain “normal” operating procedures.

Sample collection began at all sites on or before October 16, 2007 to develop a baseline concentration of fluoride. Samples were collected as the fluoride concentrations dropped throughout the system. Once the fluoride concentration started to tail off to the background level of fluoride, sampling at that site was discontinued. The tailing occurred at approximately 0.1 to 0.2 mg/L of fluoride. Phase I sampling continued to November 3, 2006, when all sampling was ceased. By this date, most of the sampling locations had already been terminated.

After the completion of Phase I, the fluoride remained off for a week while preparing for Phase II. The time between studies was used to catch up on sample analysis, reset all the autosamplers, and review preliminary results from Phase I. The grab samples from the Phase I Lanpher Reservoir floating cover hatches were found to be consistently higher from the west basin. To attempt to balance the two cells, the effluent gate to the east cell was closed 50 percent. Other adjustments to the distribution system included closing three of the river-crossings, located at North Franklin Street, Fort Duquesne Bridge, and 26th Street. As discussed in Section 1.1, PWSA plans to add three additional booster chlorine stations. Closing the three river-crossings was done to prepare for the install of the booster station by attempting to eliminate the large fluctuations chlorine residual between the two pressure zones located on either side of the Allegheny and Ohio Rivers. Now water is no longer able to flow back and fourth and the Lanpher and Highland No. 2 Supersystems are completely divided.

Phase II began on November 13, 2006 at 8:00 A.M. At this time, the fluoride was turned back on with the goal of reaching 1.0 mg/L with background fluoride concentrations. It was found that the fluoride concentration versus time response curves at some of the Phase I sampling locations were not complete, so concentrations were monitored carefully prior to discontinuing sampling early in Phase II. The last sample for Phase II was collected on December 30, 2006. The fluoride feed during Phase II was hard to keep constant. Levels varied and at one point the fluoride pump turned off, resulting in no fluoride feed. In addition, the AWTP intakes were closed on November 20, 2006 to repair the traveling screens. The inconsistent fluoride feed and intake closing was taken into consideration during the analysis of the tracer response curves. Since the completion of the fluoride tracer study, the river-crossings have remained closed.

The fluoride concentration data collected from both Phase I and Phase II were found to be useful in estimating travel times throughout the distribution system, mixing characteristic in the reservoirs, balance of the water between the three pressure zones and within two of the primary reservoirs. The TTHM data was used in coordination with the water age data to assess water quality deterioration at the sampling site. The results of the PWSA fluoride tracer study are further discussed in Section 3.0 of this document.

3.0 RESULTS AND DISCUSSION

3.1 DETERMINATION OF AVERAGE WATER AGE

The travel time from the clearwell to the sample points (the average water age) was estimated for the locations where sufficient data were collected. Since there are temporal variations in water demands, pumping rates, and storage facility elevations, water ages were constantly changing throughout the PWSA distribution system during the tracer study [Maslanik, 2007]. These variations in water age throughout the day can be estimated by EPS modeling. However, the variations are not evident from the data collected from the tracer study. Therefore the average water age was calculated from the concentration versus time tracer study results using the method similar to the one described by Passantino et al. [2005]. EPS models actually average the age variations over a 24-hour period to estimate one age, therefore, the tracer study water age can be compared to model water age. This computer model to tracer study results comparison was completed by Maslanik [2007], a consulting engineer for PWSA, in his analysis of the PWSA tracer study results.

The water ages in this analysis were estimated from a C_{50} value of 0.535 mg/L. The C_{50} value was determined by finding the concentration between the baseline and typical finished water concentrations of fluoride. The baseline concentrations observed at the beginning of Phase II at all of the sampling locations and the concentrations after the step-down response curve passed through the clearwell during Phase I were also included in the calculation to determine a baseline concentration of C_B=0.07 mg/L. These plots are attached in Appendix A. It was decided at the start of Phase I, that sampling would be terminated once concentration levels tailed off. Therefore, during Phase I, sampling was stopped once concentrations were between 0.2 and 0.1 mg/L. After evaluating the background concentrations at the start of Phase II, it was found sampling was discontinued prematurely at some of the sampling sites during the Phase I resulting in incomplete response curves. From the review of records from the clearwell during week prior to the start of Phase I (before the fluoride was turned off) and Phase II (after the fluoride was resumed), it was determined that the fluoride concentration in the finished water, C_F, was 1.07 mg/L with background levels, but the goal is always 1.0 mg/L. Therefore, the C_{50} value, the value half way between 0.07 mg/L and 1.0 mg/L, determined to be 0.535. Using this C_{50} value, the T_{50} value was estimated from interpolating the time on the concentration verses time plots. All of the response curves from Phase I and Phase II are presented in Appendix A and the T_{50} values are listed in Section 3.1.1. Table 6. Using the same C_B and C_F range, the C_{10}, C_{20}, C_{80}, and C_{90} values for both Phase I and Phase II were determined to estimate the amount of time it took for 10, 20, 80, and 90 percent of the tracer to pass a sampling point, T_{10}, T_{20}, T_{80}, and T_{90}, respectively. The resulting concentrations used to determine these time values are listed in listed in Table 5. To confirm which percentage was representative of the average water age, the concentration versus time curves were normalized using Equation 3 and the area above the F-curve was found using Equation 5. However, because some sites did not reach the baseline during Phase I, the fluoride feed during Phase II was fluctuating, and insufficient data were collected at some sampling sites (complete concentration vs. time curves from C_B to C_F were not captured), the area above F-curves were not representative of the water age at the different sites.

Therefore, instead of developing F-curves using the incomplete data and the minimum and maximum concentration from each site as C_{Before} and C_{After}, it was found that the area below the Phase I concentration verses time graphs and above the Phase II graphs enabled more flexibility for calculating the water age for each site. This simplification was possible since the difference between the baseline and fluoride feed concentration was approximately 1.0 mg/L during both Phases. Equation 5 was modified to Equation 6 and Equation 7 for Phases I and II, respectively, where the total number of water samples, N, included in the Equation 6 and 7 formulas was determined objectively by picking the time when the fluoride step-output leveled off or neared C_B or C_F .for Phase I or Phase II, respectively. Comparing the average water ages determined from Equations 6 and 7 to the T_{10}, T_{20}, T_{50}, T_{80}, and T_{90} values it was confirmed that the T_{50} is the best approximation of the average water age. Therefore, T_{50} was used as the standard measure in this analysis of water age at all sampling site locations. Using T_{50} allowed for the estimation of water ages at sites where water age could not otherwise be estimated by Equations 6 or 7, due to incomplete response curves.

Table 5. Adjusted concentrations used to determine the amount of time for 10, 20, 50, 80, and 90 percent of tracer to pass through the sampling point.

	Phase I mg/L of fluoride	Phase II mg/L of fluoride
C_{10}	0.907	0.163
C_{20}	0.814	0.256
C_{50}	0.535	0.535
C_{80}	0.256	0.814
C_{90}	0.163	0.907

$$AverageWaterAge(PhaseI) = \sum_{i=0}^{i=N} \frac{\Delta t}{2} \left(\frac{C(t_i) - 0.07 + C(t_{i+1}) - 0.07}{1mg / L} \right) \quad \text{(Equation 6)}$$

$$AverageWaterAge(PhaseII) = \sum_{i=0}^{i=N} \frac{\Delta t}{2} \left(\frac{(1 - C(t_i) + 1 - C(t_{i+1}))}{1mg / L} \right) \quad \text{(Equation 7)}$$

3.1.1 Average Water Ages in the PWSA Distribution System

The average water ages estimated from the T_{50} values are presented in Table 6. The location of each of the sampling points was previously described in Figure 9. According to the Water Industry Database classifications of long and short water ages, where "long" is greater than three days and "short" is less than three days [AWWA and EES, 2002], 80 percent of the sampling site during Phase I and 67 percent of the sampling site during Phase II had water ages classified as "long". Many of the sampling locations in Table 6 have T_{50} valves that varied from Phase I to Phase II. The Phase I to Phase II hour difference column shows that either the water age increased from Phase I to Phase II (positive value) or the water age decreased (negative value). The increase in the Highland No. 2 Reservoir and decrease in Lanpher Reservoir sampling locations may be due to the closing of the river-crossings as discussed in Section 3.2.5. However, within the three supersystems, there were both increases and decreases in T_{50} values. These variations may be attributed to different water demands in the system, the amount of water depth fluctuations in the storage tanks (fill/draw cycles), diurnal variations, changing pumping rates, and sampling frequency [Maslanik, 2007].

Table 6. Average water age estimates (T_{50} values) from fluoride tracer response curves.

Location ID	Sample Location Description	Phase I T_{50} (Hours)	Phase II T_{50} (Hours)	Phase I to Phase II Hours Difference
Autosamplers: 4-hour samples				
A01	Lanpher Reservoir East Effluent	250	148	-102
A02	Lanpher Reservoir West Effluent	300	195	-105
A03	Lanpher Reservoir Influent (Aspinwall Pump Sta.)	17	< 24 *	n/a
A04	Bruecken Pump Station (Influent Highland No. 1)	29	< 24*	n/a
A05	Bruecken Pump Station (Influent Highland No. 2)	29	27	-2
A06	Highland Reservoir No. 1 Effluent	103	116	13
A07	Highland Reservoir No. 2 Effluent	98	121	23
A08	Howard Pump Station (Lanpher Reservoir)	147	146	-1
A09	Mission Pump Station (Highland No. 2 Reservoir)	115	127	12
A10	Herron Hill Pump Station, Herron Hill Reservoir Influent (AWTP & Highland No. 1 Reservoir)	-----	55	n/a
A11	Herron Hill Reservoir Effluent	88	100	12
Pittsburgh Homes: 12-hour grab samples				
P01	27 Perryview Avenue (Brashear Tanks)	319	332	13
P02	3133 Brunot Avenue (Allentown Tanks)	321	280	-41
P03	1114 Colfax Street (McNaugher Reservoir)	206	203	-3
P04	6433 Forward Avenue (Squirrel Hill Tanks)	180	156	-5
P05	5838 Darlington Road (Herron Hill Reservoir)	75	> 72 *	n/a
Hydrants: periodic grab samples				
H01	Hydrant 1 - 401 Well Street (Allentown Tanks)	196	202	10
H02	Hydrant 2 - 1713 Brighton Road (Lanpher Reservoir)	208	207	-1
H03	Hydrant 3 - Termon Avenue, between McClure and California Avenue (McNaugher Reservoir)	n/a	218	n/a
H04	Hydrant 4 - 4260 Evergreen Road, intersection with Ivory Avenue (Brashear Tanks)	272	307	35
H05	Hydrant 5 - Perrysville Avenue, intersection with Legion Street (Brashear Tanks)	170	180	10
H06	Hydrant 6 - Penn Avenue, between 39th and 40th Street (Highland No. 1 Reservoir)	130	59	-71
H07	Hydrant 7 - Lincoln Avenue, intersection with Joshua Street (Lincoln Tank)	140	87	-53
H08	Hydrant 8 - Love Street, first hydrant on left off Whipple Street (Highland No. 1 Reservoir)	90	75	-15
H09	Hydrant 9 - Bigelow Street and Tesla Street intersection, Hazelwood Ave (Squirrel Hill Tank)	190	229	39
H10	Hydrant 10 - Chartiers Street and Lorenz Street intersection (Allentown Tanks)	164	184	20
H11	Hydrant 11 - Mon Warf Parking Lot (Highland No. 2 Reservoir)	154	160	6

Table 6 (continued)

Millvale Borough: daily grab samples				
M01	114 Grant Avenue, Grant's Bar (Aspinwall Pump Station)	152	159	7
M02	1201 North Avenue, Hardees (Aspinwall Pump Station)	168	166	-2
M03	232 North Avenue, Lincoln Drug/P&G Diner (Aspinwall Pump Station)	158	159	1
Reserve Township: daily grab samples				
R01	4000 Mt Troy Road, Saint Mary's Cemetery (Brashear Tanks)	320	321	1
R02	116 Biscayne Terrace, Fire House (Brashear Tanks)	352	348	-4
R03	33 Lonsdale Street, Municipal Building/Mt Troy Volunteer Fire Co., Station 239 (Brashear Tanks)	332	364	32
R04	2000 Mt Troy Road, Mt. Troy Savings Bank (Brashear Tanks)	358	372	14
R05	3367 Spring Garden Road, Spring Garden Volunteer Fire Co., Station 240 (Brashear Tanks)	389	382	-7
Fox Chapel: daily grab samples				
F01	PWSA Feed at Rockwood Valve Station (Aspinwall Pump Station)	16	12	-4
F02	1003 Fox Chapel Road (Aspinwall Pump Station)	38	41	3
F03	280 Kappa Dr. (Aspinwall Pump Station)	106 **	55 **	-51 **
F04	Hampton Twp. Interconnect (Aspinwall Pump Station)	75	60	-15
F05	Blawnox Boro Interconnect (Aspinwall Pump Station)	> 96 *	60	n/a
F06	928 Field Club Road (Aspinwall Pump Station)	69	61	-8
F07	341 Kittanning Pike (Aspinwall Pump Station)	71	66	-5
F08	503 Guys Run Road (Aspinwall Pump Station)	81	90	9
F09	3563 Harts Run Road (Aspinwall Pump Station)	114**	136**	22**
F10	502 Guyasuta Road (Aspinwall Pump Station)	196**	> 216*	n/a
Carnegie Mellon University: daily grab samples (Bruecken Pump Sta./Herron Hill Reservoir)				
C01	Baker Hall	74	74	0
C02	Hunt Library	78	68	-10
C03	Porter Hall	197	133	-64
C04	Purnell Hall	77	70	-7
C05	Robert's Hall	41	40	-1
C06	Tepper School	46	65	19
C07	University Center	74	68	-6
C08	Warner Hall	75	74	-1
C09	Wean Hall	79	68	-11

* Value is either greater or less than listed number. Value is uncertain due to incomplete fluoride data at the end of the tracer response curve.

** T_{50} was determined from minimal data collected at the sampling site, therefore, the value is uncertain.

Of the 54 sampling locations in Table 6, sufficient data were collected from 47 locations during both Phases I and II to compare the changes in water age. Approximately half of the 47 pairs of data varied by less than ±10 hours from Phase I to II. Considering the amount of variability within the system itself and the duration between sample collection, a 10 hour difference is negligible. Of the 23 sites that did experience water age difference greater than 10 hours, approximately half increased and half decreased. The most significant decreases (greater than two days) were at both of the Lanpher Reservoir effluents (A01 and A02), Hydrant 6 and 7 (H06 and H07), Brunot Ave. (P02), and Porter Hall (C03). Again, Lanpher Reservoir effluent water age was likely to have decreased due to the river-crossing. The Brunot Ave. was a residential location, so the decrease may have been due to demand in the area or the turnover rate of Allentown Tanks). Hydrants 6, Hydrant 7, and Porter Hall are all in the Highland No. 1 Supersystem where water enters either directly from the AWTP or from Highland No. 1 Reservoir. Since the ages in Highland No. 1 Reservoir decreased during Phase II, it is likely that more water was fed directly from Bruecken Pump Station during Phase II. The flow rate of water from Bruecken Pump Station entering the distribution system directly instead of entering Highland No. 1 Reservoir is dependent on the pumping rate, the treatment capacity of the membrane plant, the water level in Highland No. 1 Reservoir, and the demand from the distribution system [Maslanik, 2007]. No sampling sites had a water age that increase by more than two days from Phase I to Phase II. Sites where higher increases (greater than one day) in water age occurred include A07, H04, H09, H10, and R03. The water leaving Highland No. 2 Reservoir (A07) was almost a day older, which likely increased the age at sites H09 and H10 because both Squirrel Hill Tank and Allentown Tanks are part of the Highland No. 2 Supersystem. H04 and R03 are sampling sites off Brashear Tanks. The sampling intervals at the hydrants were periodic and in Reserve Twp., samples were collected every 24 hours. Therefore, for sites with longer durations between samples, there is less confidence in the T_{50} values because they are estimated from the collected data, explaining the greater variance in water ages.

From Table 6 it was evident that the oldest T_{50} values occur in Reserve Twp. because the estimated water ages were higher than the other sampling areas. Average water ages in Reservoir Twp. were consistently greater than 300 hours (12.5 days) during Phase I and Phase II with a maximum age of 389 hours (16.2 days) observed at site R05 (Spring Garden Road). The closest sampling site prior to Reserve Twp. was Howard Pumping Station. Water ages here already reached 146 hours (6 days). Site R01 is close to the Reserve Twp. Interconnection to the PWSA distribution system. This site had a water age around 320 hours (13.3 days) during both phases of the tracer study. Therefore, water entering Reserve Twp. had already aged significantly in the PWSA distribution system. Site R05 is located near the end of the Reserve Twp. distribution system. Water ages at this site were 389 hours (16.2 days) and 382 hours (15.9 days) during Phase I and II respectively. From comparing the Reserve Twp. entrance point to site R05, it is theorized that water only ages by three days in Reserve Twp.. The majority of aging actually occurs in the PWSA distribution system prior to being sold to Reserve Twp..

Three sites within the PWSA distribution system also had water ages over 300 hours. The sites P01 and H04, 27 Perryview Avenue and Hydrant 4 at 4260 Evergreen Road respectively, are serviced by Brashear Tanks and site P02, 3133 Brunot Avenue is serviced by Allentown Tanks. The P01 and H04 are serviced by the same storage facilities as Reserve Twp.. All three sites are located at the far reaches of the distribution system, so it is logical that there are high water ages. From the collected data, it is theorized that water ages by six days between the clearwell and Howard Pumping Station, then takes seven additional days to travel through

Brashear Tanks. To quantify the extent of water quality deterioration at all of the sites listed in Table 6, TTHM samples collected for each of the sampling locations during both Phase I and Phase II were compared with the average water age at each site.

3.1.2 TTHM Formation in the PWSA Distribution System

The Stage 2 DBPR has PWSA focusing on DBP formation in their system. Therefore, one round of sampling was conducted during Phase I and Phase II to analyze for bromodichloromethane, bromoform, dibromochloromethane, and chloroform (additively referred to as TTHMs). As discussed in Section 3.1.1 of this document, a significant number of the sampling locations had "long" or old water ages. A timeline was developed, as seen in Figure 25, to help depict how water ages changed between Phases I and II. Both the T_{50} values from Phases I and II were plotted on the timeline and labeled with the sampling location, the source water location in parenthesis, and TTHM concentration in brackets. All of the data from the PWSA system was included and select sites from the three consecutive systems and Carnegie Mellon University were listed. The most apparent observation from Figure 25 is that sampling sites in Reserve Twp. and sites serviced by Brasher and Allentown Tanks and McNaugher Reservoir/Spring Hill Tanks are of concern for compliance with the Stage 2 DBPR. The TTHM concentrations at the majority of the sites exceed or are at the borderline of the MCL of 80 µg/L. Looking at Phase I data, high (greater than 70 mg/L) TTHM concentrations were also observed at sites with T_{50} values ranging from 154 to 208 at sites serviced from Highland No. 2 Reservoir, Allentown Tanks, Brashear Tanks, Squirrel Hill Tank, Lanpher Reservoir, and McNaugher Reservoir/Spring Hill Tanks. The high TTHM concentrations are of concern since the TTHM samples from Phase I were collected on October 25, 2006 when temperatures were low compared to the summer months. The TTHM samples from Phase II were collected on 11/29/06 when temperatures were even colder. Therefore, the lower TTHM concentrations during Phase II reflect decreased DBP formation due to slower reaction rates and less DBP precursors.

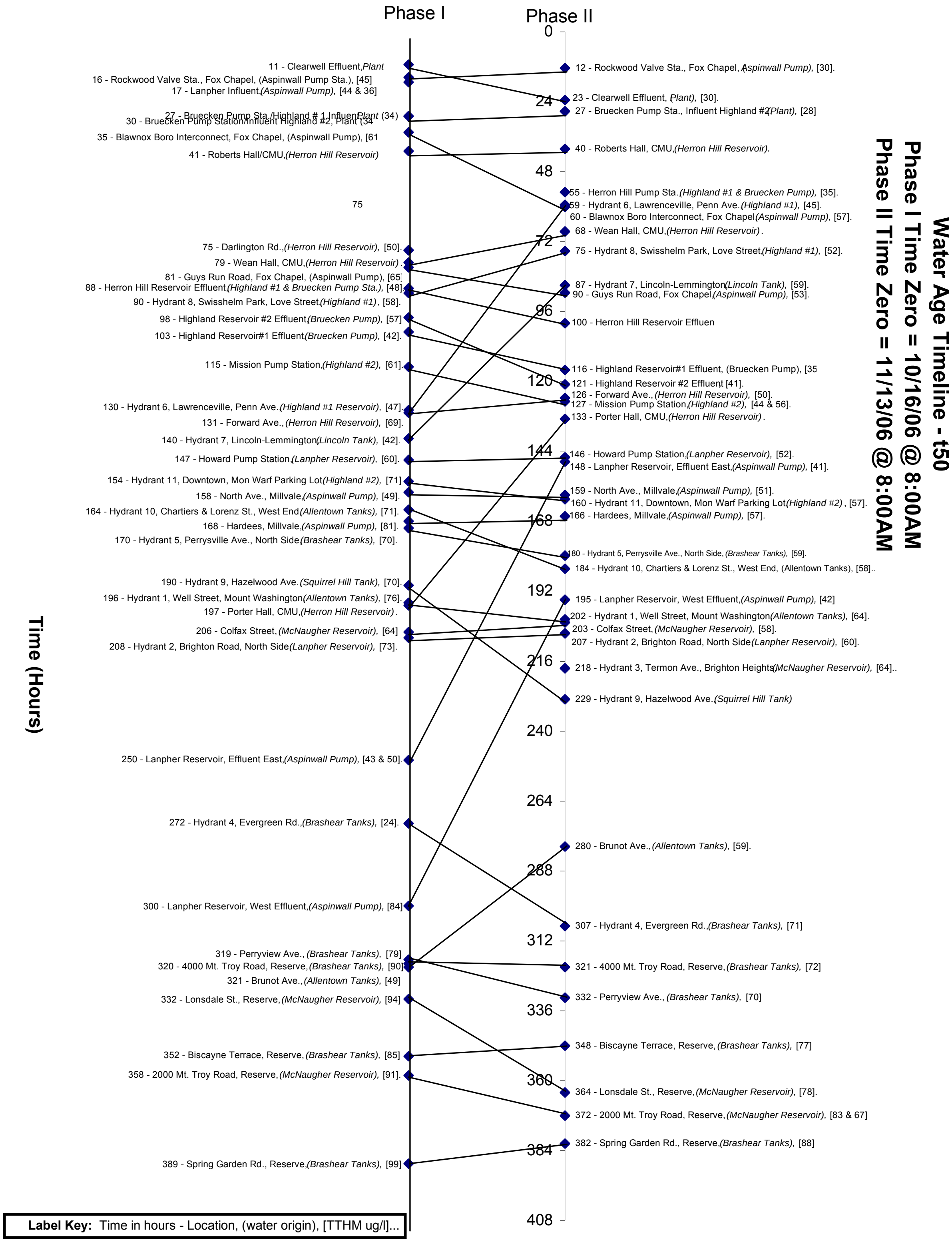

Figure 25. Average water age timeline, Phase I and II comparison.

A significant imbalance of TTHM formation was also observed between the two Lanpher Reservoir basins in Phase I (see Figure 25). Minimal TTHM formation occurred in the east basin, but 100 percent increase of TTHM formation occurred in the west basin. These results were very alarming as they suggested that water was moving through the east basin, but not the west. When compared to Phase II, the formation of DBPs in Lanpher Reservoir was balanced. Therefore, lowering the effluent gate of the east basin may have helped balance the MRT between the two cells.

All of the collected TTHM concentrations were organized against the average water ages, determined from the corresponding sampling site concentration versus time graphs, and listed in Table 13 (Appendix B). The TTHM values from this table were then plotted against the corresponding T_{50} values, as shown in Figure 26, to analyze the correlation between increasing age and increasing DBP formation. Phase I and Phase II were plotted separately since TTHM concentrations very significantly with temperature as well as the other factors discussed in Section 1.3.3. The decrease in temperature is likely the reason that Phase II trendline is below the Phase I trendline. The relationship between TTHMs and time is not necessarily linear or logarithmic. In Figure 26, the trend appears to be more linear between hours 24 and 400 due to the increase in formation rate between hours 300 and 400. The two outliers in Figure 26 were excluded from the trend line analysis. Figure 26 was replotted (Figure 27) excluding the points with high water age and TTHM formation from sampling sites located off of McNaugher Reservoir/Spring Hill Tanks, Brashear Tanks, and Allentown Tanks. In Figure 27, a logarithmic trendline fit the data better, as the shape showed the increase of TTHMs with time and the decreased formation rate. The lower R^2 values in Figure 27 are attributed to increased scatter observed between hours 0 and 250. So although formation is not directly related to age (based on factors discussed in Section 1.3.3), both plots still show that there is increasing formation of TTHM formation with increasing water age. Therefore, this relationship adds confidence to the notion that if system operations can be improved to decrease water age, TTHM formation will also decrease. Appendix C includes Figures 112, 113, and 114 which show the chlorine residual results collected at the same site and time as the TTHM samples. A further analysis of water age was completed on the three primary reservoirs and a secondary reservoir that were included in the PWSA fluoride tracer study. These reservoirs are a focal point for the PWSA distribution system because a significant amount of TTHM formation occurs within these facilities.

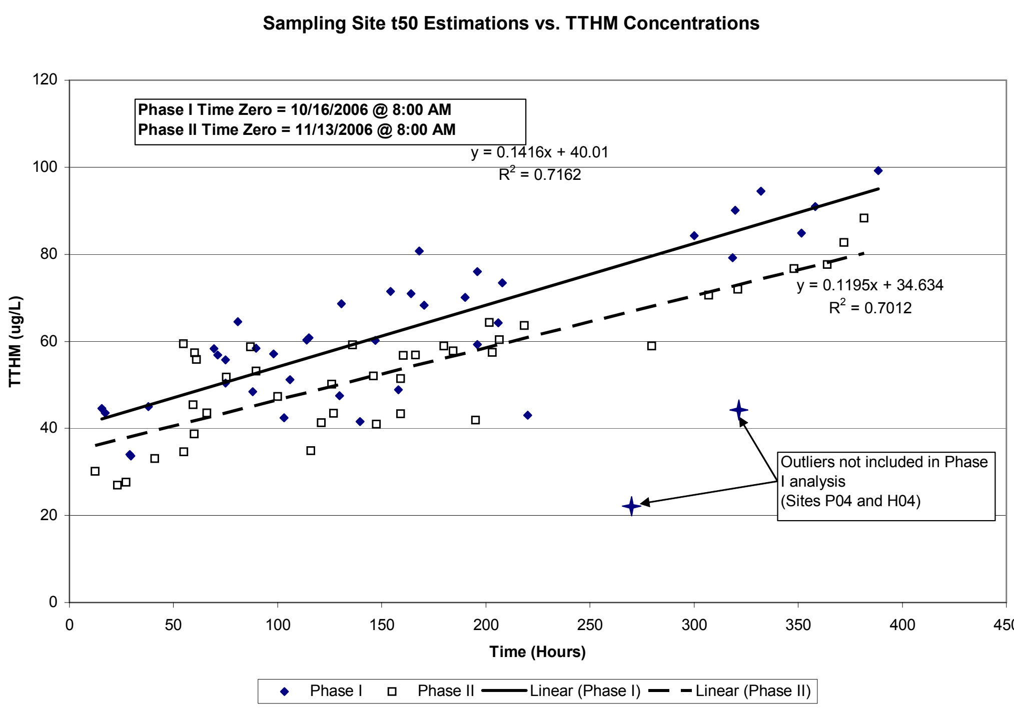

Figure 26. Sampling site T_{50} estimations vs. TTHM concentrations.

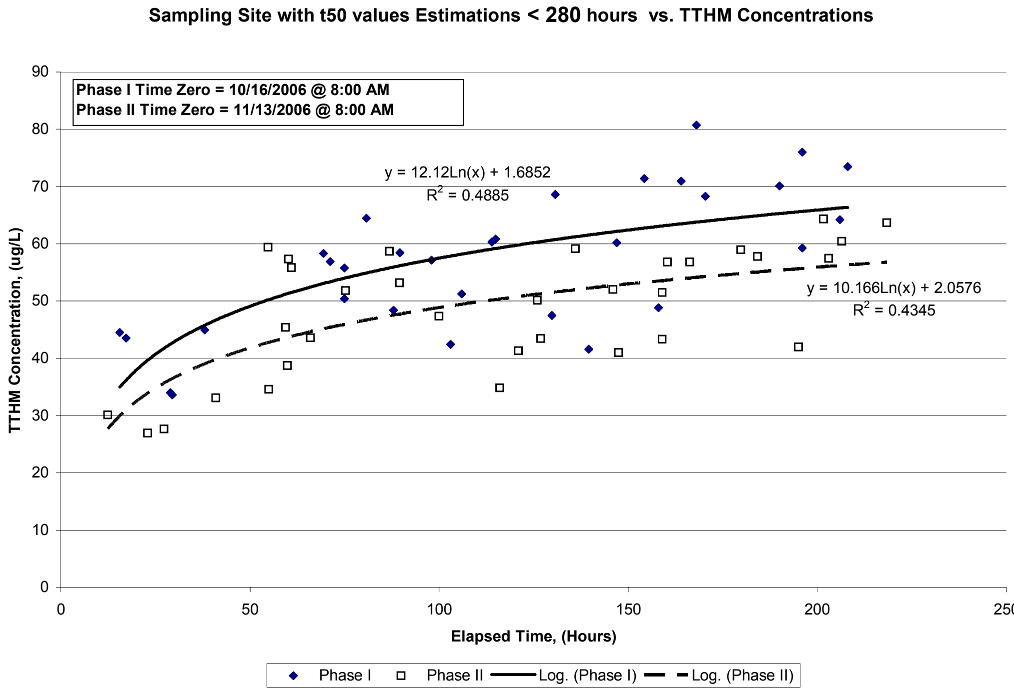

Figure 27. Sampling site with T_{50} values estimations < 280 hours vs. TTHM concentrations.

3.2 EFFECTS OF FINISHED WATER STORAGE FACILITIES

Water quality may vary widely within a storage facility and at the intake or outlet. Therefore, fluoride samples were collected both at the influent, effluent and spatially throughout the three primary reservoirs. The influent and effluent of Herron Hill Reservoir, a secondary reservoir, were also monitored. The sampling results provided insight into the MRT, mixing regimes, dead-zoning, and short-circuiting within these non-ideal reactors. Only one of the three reservoirs is baffled, therefore, the concentrations were tracked over the surface of the reservoirs to determine if the other two basins needed baffles, skirts, or other hydraulic modifications to better circulate water. The fluoride concentrations at different points within the reservoirs were plotted over images of the reservoirs at the sampling locations for analysis.

3.2.1 Highland No. 1 Reservoir

Highland No. 1 Reservoir is unique since it is the only finished water storage facility in the PWSA distribution system, which remains uncovered. The data collected during the tracer study was used to estimate the volume, MRT, and describe the mixing in Highland No. 1 Reservoir.

3.2.1.1 Highland No. 1 Sediment Accumulation: The current operating volume of Highland No. 1 Reservoir is uncertain due to sediment accumulation. The last time Highland No. 1 Reservoir was taken down and cleaned was in 1982. Therefore, there is currently 25-years of sediment accumulation in the reservoir. The sediment does not pose a direct health effect, since this open finished water reservoir is considered a raw source water and is treated again by the membrane plant. The sediment does, however, decrease chlorine residual, provide precursors for DBP formation, and increase the backwashing frequency at the membrane plant.

The surface samples, which were collected from multiple locations spatially over the Highland No. 1 Reservoir during the tracer study, were collected at a depth of approximately 13-feet. The depths of Highland No. 1 Reservoir on the surface sampling days are presented in Table 7. The depths are based on a reading that was taking once per day, between 9 A.M. and 12 P.M., off the side of the reservoir. The level indication lines on the reservoir wall shown in

Figure 28 are believed to start from the floor of the reservoir. Since the depths of the reservoir were constantly above 13-feet during the time of sampling, hitting bottom was not anticipated.

Figure 28. Highland No. 1 depth meter.

Table 7. Highland No. 1 Reservoir depth.

Highland No. 1 Water Level (Visual Reading @ Reservoir)	
Date	Depth (feet)
10/19/2006	No Reading
10/24/2006	16.9
10/27/2006	16.9
11/14/2006	17
11/17/2006	15.8
11/20/2006	16.8
11/22/2006	17
11/27/2006	16.9

Prior to lowering the sampler down, the location was visually inspected, especially near the walls, to avoid dropping the sampler down too low and stirring up sediment. On 11/17/2006, the reservoir level was 15.8 feet, a foot lower than any of the other sampling days. When the sampler was lowered down, it hit sediment at a location in the center of the reservoir. Unless there was an underground structure at the sampling point, it leads to the idea that there may be more than 2.5-feet of sediment in some locations along the bottom of the reservoir. Even without hitting the bottom, sediment was visible from the water surface spanning across the majority of the reservoir with extensive accumulation, such as the sediment shown in Figure 29, along the south walls and corners of the east and west basins (Figure 30). At this point, the actual extend of sedimentation is unknown. However, there are a couple of simply ways to quantify the depth of sediment without taking the reservoir out of service including:

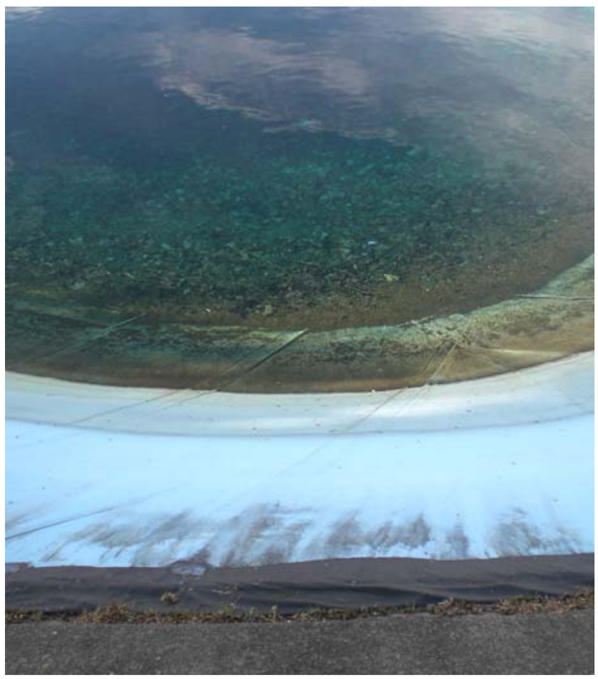

Figure 29. Sediment accumulation in the southeast corner of the east Highland No. 1 Basin.

Figure 30. Locations of extensive sediment accumulation in Highland No. 1 Reservoir.

1. Take a boat out with a digital handheld sonar system (depth finder) to find depths at GPS locations and compare to the depth meter measurements. (However, measurements may be nebulous due to the soft bottom.)
2. Take a boat out, slowly drop down a weight on a rope, measure the rope length, and compare measurements to as built drawings. (This method may re-suspend sediment and it may be difficult to keep the boat right above the weight.)
3. Send a diver or robot into the reservoir with a GPS unit to record sediment depth at different points in the reservoir.

As stated previously, its recommended that storage facilities are cleaned and inspected every one to five years [AWWA and EES, 2002]. However, there is concern that cleaning the Highland No. 1 Reservoir may result in reopening dead-zones and short-circuiting. Therefore, careful consideration of mixing characteristics should be taken prior to cleaning, including the possible develop of a model, such as a CFD model, to better represent the reservoir's hydraulic characteristics.

3.2.1.2 Mean Residence Time in Highland No. 1 Reservoir: The influent and effluent concentrations from Phase I of the tracer study were plotted against elapsed time in Figure 31. The T_{50} values for both the influent and effluent were estimated based on the C_{50} value of 0.535 mg/L of fluoride as discussed previously in Section 3.1. Based on the difference between the T_{50} values of the influent and effluent from Phase I, the average time that it took a water parcel to travel from the influent of Highland No. 1 Reservoir (Bruecken Pump Station @ hour 26.7) to the effluent (membrane plant @ hour 103) was 76.3 hours (3.2 days). At hour four, there was a significant drop in fluoride concentration. This point was determined to be an outlier since the change in fluoride concentration had not reached the effluent of the clearwell at this hour. Sufficient data were not collected at the Bruecken Pump Station during Phase II to calculate a second MRT for Highland No. 1 Reservoir. However, the response curve from the Phase II membrane plant was used to determine that the average age of water from the clearwell entrance to membrane plant was 116 hours. Although the effluent age was higher during Phase II, there is only 11 percent difference that may be attributed to a slight increase in storage volume during Phase II or decrease flow rate or demand from Highland No. 1 Reservoir.

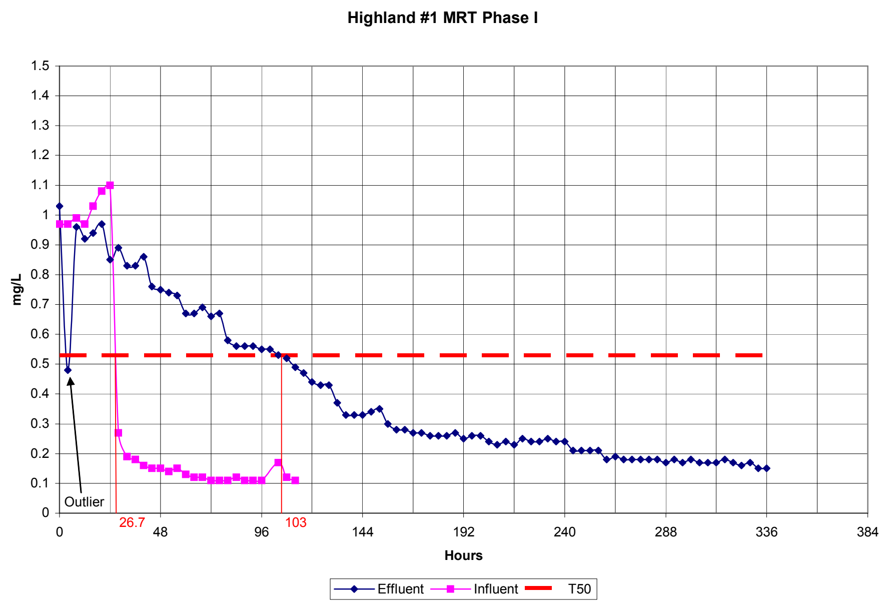

Figure 31. MRT of Highland No. 1 Reservoir Phase I.

During Phase I, the average flow rate treated by the membrane plant from time zero to 103 hours (the average time it took the water to travel from the clearwell inlet to the Highland No. 1 reservoir outlet) was 19.5 MGD. Also, during this 103 hour period, the average depth of Highland No. 1 Reservoir was determined to be approximately 16.5-feet from the daily visual level readings (from 10/16/06 to 10/20/06 the levels decreased from 17 to 15.9-feet). The PWSA water system schematic [1995] listed Highland Reservoir No. 1 as having a capacity of 117 MG with a water depth of 21.65-feet. The new volume estimated at a depth of 16.5-feet was calculated to be 84 MG. Therefore, the theoretical hydraulic detention time is approximately 103.4 hours. The flow rate out of the reservoir was used instead of the flow rate in because the Bruecken Pump (which pumps up to Highland No. 1 Reservoir) also pumps water directly to the distribution system. Therefore, the flow rate into the Highland No. 1 Reservoir is uncertain.

Since sediment was hit or avoided while taken depth samples, there is reason to believe the capacity of the reservoir is less than 84 MG. In Table 8 the change in viable water depth was determined based on the amount of estimated sediment depth. Then using these new viable water depths and the geometry of the reservoir, the storage volume of water was estimated. The theoretical detention time was estimated using Equation 1, where volume of water, V, in Table 8 was divided by the 19.5 MGD, the average flow rate, Q, through the membrane plant to determine t_d. The MRT determined from Figure 31 was then divided by the hydraulic detention times in Table 8 to determine the percent error. Therefore, Table 8 shows that as sediment depth increases, viable depth and storage volume decreases. Given that the exiting flow rate is fairly constant through Highland No. 1 Reservoir, the t_d decreases with increased sediment and the percent difference between the tracer study MRT and theoretical hydraulic detention time is within a reasonable error range of less than 20 percent with a minimum of one foot of sediment. Note that the volume of sediment at each depth was estimated using the surface area enclosed by the perimeter of the west and east basins. This area is greater than the actual flat floor area, and therefore, the volume of sediment calculated at each depth is a conservative estimation which accounts for areas with additional accumulation (i.e. corners), and sediment which has accumulated up the sloped side walls.

Table 8. Highland No. 1 Reservoir theoretical hydraulic detention times.

Estimated Sediment Depth*	Total Depth of Water	Volume of Water, V	Hydraulic Detention Time, t_d	Percent Error to MRT (Reservoir influent to effluent 76.3 hours**)
feet	feet	MG	hours	%
0	16.5	84.01	103.4	26.2%
1	15.5	77.34	95.2	19.8%
1.5	15	74.00	91.1	16.2%
2	14.5	70.67	87.0	12.3%
3	13.5	64.00	78.8	3.1%

*Sediment was estimated over the entire surface area of the west and east basins.
** MRT estimated from tracer study response curves

The theoretical detention time, t_d, should be approximately the same as (but not less than) the MRT, or the difference in T_{50} estimated values [Teefy, 1996]. The percent error values of the theoretical detention time to the MRT in Table 8 are within a reasonable range. The percent error can be attributed to unknown level fluctuations over a 24-hour period that may increase/decrease the volume stored in the reservoir. In addition, the volume and pumping rate used to calculate the theoretical detention times were average values and the flow rate into the reservoir is typically not equal to the flow rate out. Therefore, short-circuiting is not considered to be a significant problem for Highland No. 1 Reservoir. It should also be noted that if there were significant short-circuiting, pockets of "new" water (water with lower fluoride concentration (valleys) in Phase I and higher concentration (peaks) in Phase II) would have moved through the system. Only very small valleys and peaks were not evident on the fluoride tracer response curves, leading to the conclusion that the Highland No. 1 Reservoir is fairly well mixed. Furthermore, with the four hour sampling interval, it is unlikely that evidence of short-circuiting was missed.

3.2.1.3 Highland No. 1 Mixing: The fluoride concentrations from the effluent of Highland No. 1 Reservoir were plotted against the elapsed time for Phase II in Figure 32 to determine the average water age of 116, as discussed in Section 3.2.1.2, and evaluate the extent of mixing. Time zero in Figure 32 is 11/13/2006 at 8:00 A.M. when the fluoride concentration was resumed. The shape of both effluent curves from Phase I (Figure 31) and Phase II (Figure 32) are approaching a completely mixed response curve, since the curves are flattened out compared to the influent step in Figure 31. The variation in fluoride concentrations in Figure 32 after hour 216 is due to inconsistent fluoride feed at the AWTP. The depth samples collected over the surface of the reservoir also support the notion that the reservoir is mixing well. Figure 33 displays the fluoride concentrations on 10/24/2006 during the phase I. This figure corresponds to hour 196 on Figure 31. Additional plots of the fluoride samples taken over Highland No. 1 Reservoir during both Phases I and II are included in Appendix D, Figures 115 through 121.

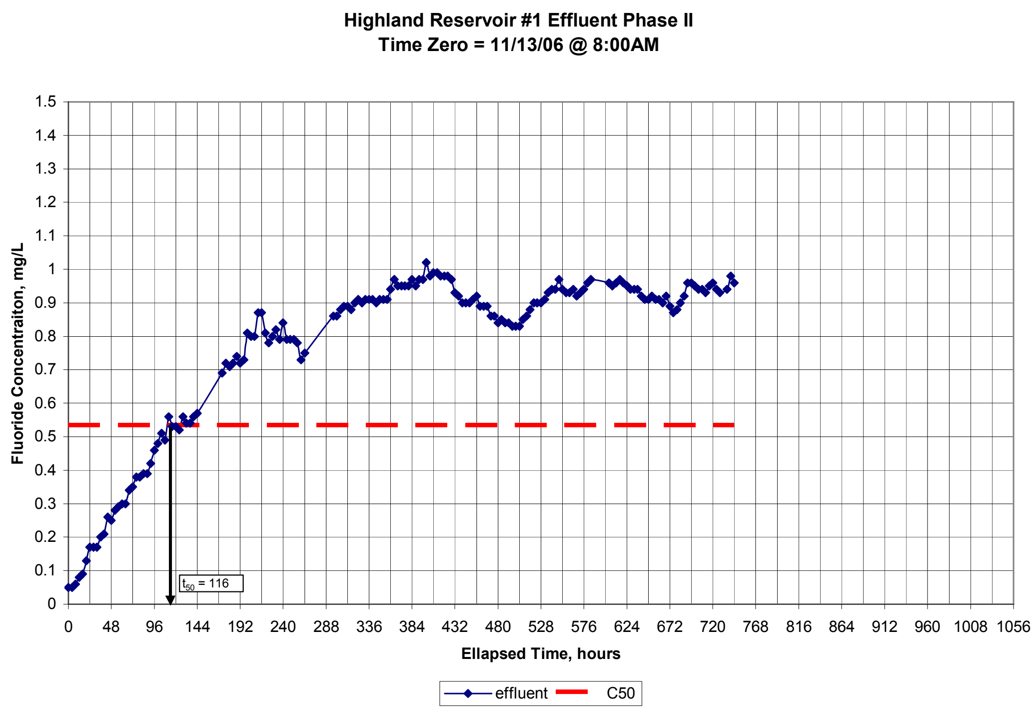

Figure 32. Highland No. 1 Phase II response curve.

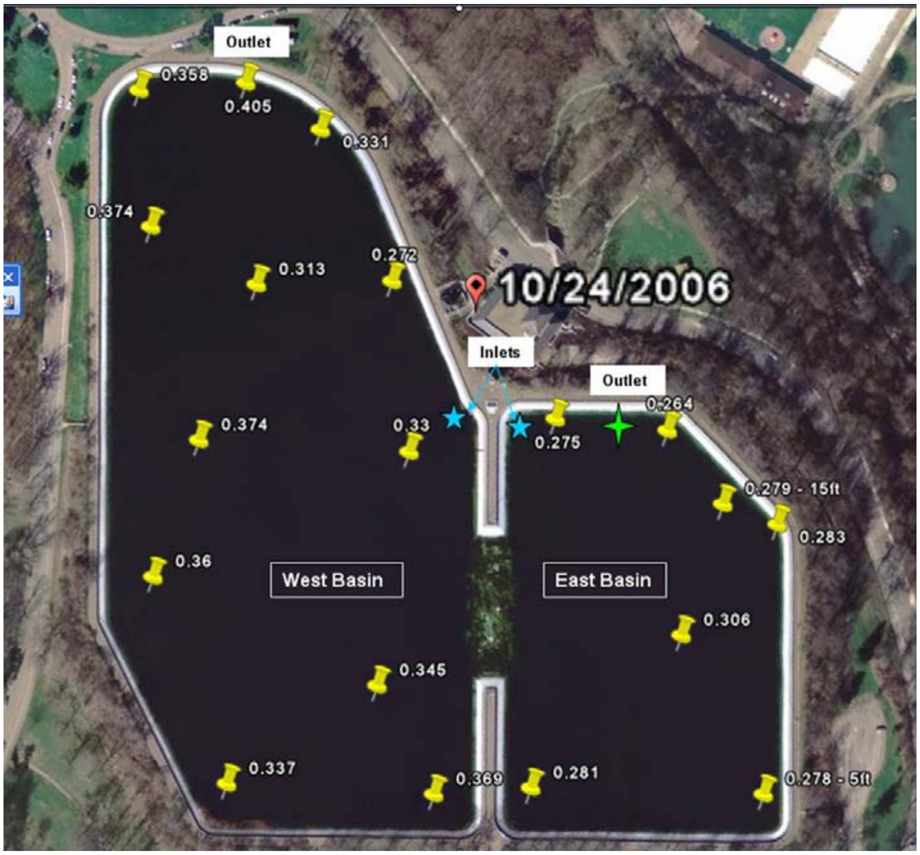

Figure 33. Highland No. 1 Reservoir surface grab samples (mg/L) 10/24/2006.

A mixing pattern has yet to be determined from visually analyzing the concentration change over the reservoir. However, Figure 33, as well as Figures in Appendix D, consistently shows the west basin with concentrations lagging by 0.07 to 0.09 mg/L to the east basin. Since during Phase I the fluoride concentrations were decreasing from 1.0 mg/L, Figure 33 shows that it takes more time for the west basin to turn over than the east. The difference in concentrations is logical because the west basin is twice the size of the east, and the flow pumped up to the reservoir is split between the two basins. These results imply that, even though the reservoirs are connected by a shallow central channel, the west and east basins operate as two separate cells. Perhaps future GIS analysis of the results may provide a future insight on how this reservoir operates based on the surface sample data.

It is thought that the sediment accumulation, discussed in Section 3.2.1.1, may actually be encouraging mixing. Currently the majority of sediment is located along the southern walls, where momentum is lost when water entering from across the basin hits the opposite wall. When debris enters the reservoir and is blown by the wind or moved by flow and allowed to settle, the cross-sectional area for water to flow through decreases with increased sediment, resulting in a velocity increase. Removing the sediment may result in low velocities in areas that are currently filled with sediment, resulting in dead-zones.

The location of the excess sediment in Highland No. 1 Reservoir accumulation may be due to the location of the inlets and outlets. Before the installation of the membrane plant, there was one inlet and two outlets in each of the Highland No. 1 Reservoir cells (Figure 34). Now there is only one inlet and outlet in each cell and the excess sediment accumulation is located near the abandoned outlets. Therefore, water that was once circulated to these areas to exit, must change direction and flow to the operating outlet. This change in flow regime may have lowered velocities, promoting sediment accumulation. However, since there is evidence of water circulated in these areas from the surface samples, it is thought that the dead-zones may have been filled with sediment or missed during sample collection.

Figure 34. Location of abandoned outlets in Highland No. 1 Reservoir.

The mixing results were not anticipated. Since this reservoir is not baffled and considering the location of the operating inlets and outlets , there was thought to be considerable short-circuiting and dead-zones in both the west and east basins. Yet the results from the surface grab samples and effluent response curves illustrate that the reservoir is in fact mixing. Sources of mixing energy include wind and turbulent jet inlets. The influent to the basins is approximately 20 x 15 feet. If it is assumed that 20± MGD is pumped up to the reservoir and that flow is split, so 10 MGD (6945 gpm) into each basin, the ratio of flow (gpm) to diameter (use 20-feet height to be conservative since the entrance is rectangular) is much greater than 17.3. Therefore, according to the guideline listed in the Finished Water Storage Facilities White Paper [AWWA and EES, 2002], there is turbulent jet flow since

$$Q/d > 17.3 \text{ at } 5°C \qquad \text{(Equation 8)}$$

During the winter months, there was visual evidence of the turbulent jet as ice and snow did not form over an area projecting straight out from each of the two inlets. The lack of ice formation may have also been due positive buoyancy. Water traveling through the ground may have been slightly warmer that the water exposed to the elements in Highland No. 1 Reservoir. As discussed in a case study conducted in Virginia Beach, Virginia, temperature measurements were determined to effect mixing in storage tanks [Mahmood, Pimblett et al., 2005]. Water which differed by less than 1 °F caused thermal stratification in the study. Mahmood et al. [2005] found through CFD modeling that mixing conditions are best when water entering the storage facility has the same temperature as the stored water, whereas, when water entering is warmer there is positive buoyancy and when water entering is colder there is negative buoyancy. If the influent is at the bottom of a storage facility, negative buoyancy causes increased short-circuiting, as the colder water does not want to mix. However, given the proper storage facility design with sufficient inlet momentum, the fill/draw cycles prevent stratification [Mahmood, Pimblett et al., 2005]. Developing CFD models for the PWSA storage (including all on-ground tanks, reservoirs, and elevated tanks) and conducting a similar study to the Mahmood et al. [2005] study may provide PWSA with further insight on how well the water inside the storage facilities is being utilized. The results may be especially useful in the summer when water in the tanks is heated by the sun and there is increased negative buoyancy and also increase DBP formation.

3.2.1.4 Highland No. 1 Reservoir Security: Another concern with the existing Highland No. 1 Reservoir structure is the location of the outlets. They are right up against the side of the reservoir and visible from the surface. There is fear that the outlets may be intentionally contaminated. One potential security design solution would be to extend the outlet pipe out into the reservoir. However, extending the outlet pipe may have negative mixing effects. Additional design calculation should be completed or a model should be developed to evaluate the impacts on water circulation through the reservoir.

3.2.2 Highland No. 2 Reservoir

The mixing regime and MRT of Highland No. 2 reservoir were evaluated based on the fluoride tracer study results.

3.2.2.1 Highland No. 2 Mean Residence Time: The rate of water pumped to Highland No. 2 Reservoir varies based on the time of day (typically pump when electric rates are low) and demand. During the fluoride tracer study, the recorded pumping rates varied by hour from 0 MGD, when no water was pumped, to a maximum of 54.2 when two pumps were operating. The flow rate daily average up to Highland No. 2 Reservoir ranged from 7 MGD to 24 MGD, with a total average of 14.5 MGD during Phase I and 14.9 MGD during Phase II. The variation in pumping rate by the hour, and corresponding fluctuation in water depth and fluoride concentration during Phase I and Phase II are displayed in Figure 35. When the pumping rate was increased, the water level rose and the fluoride concentration fluctuated.

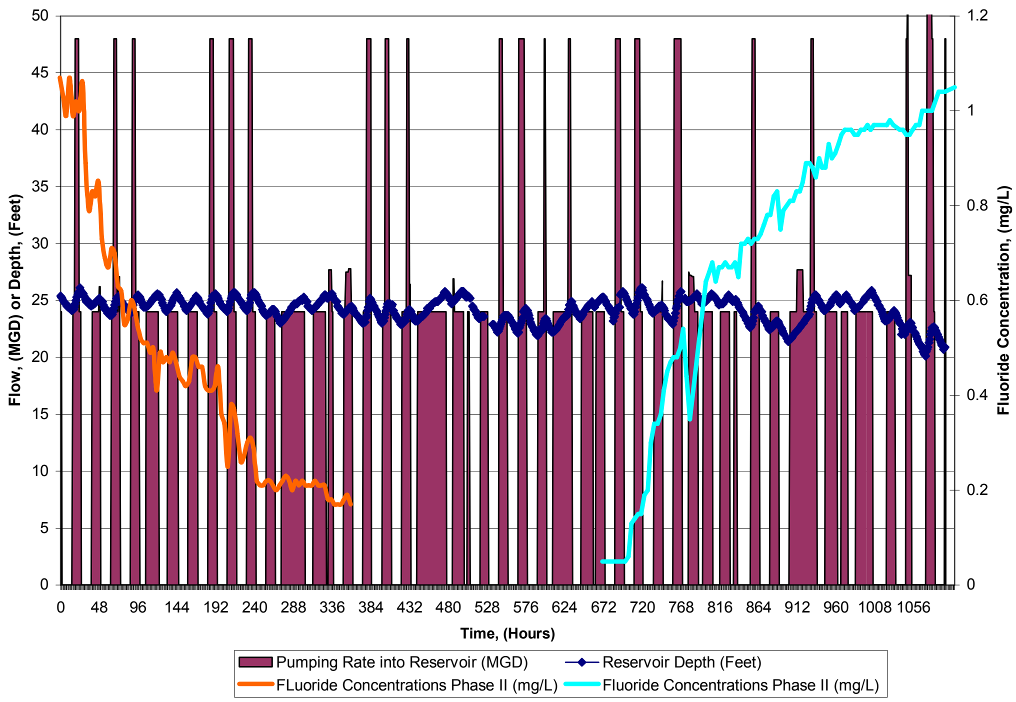

Figure 35. Highland No. 2 Reservoir pumping rates, depths, and fluoride concentrations.

At a depth of 28.6-feet, it is estimated that there is a 125 MG capacity [PWSA, 1995]. Using this volume estimate and knowledge of the reservoir geometry, volume estimations were calculated at the maximum (26.1-feet), average (24.0-feet) and minimum (20.1-feet) depths recorded during the tracer study (Table 9). The flow rate out of the reservoir is uncertain, therefore, a mass balance was not developed. The estimated theoretical detention times for Highland No. 2 Reservoir are listed in Table 9. There is a range in values due to the uncertainty of how much flow is actually moving through the reservoir at any given time. In addition, it should also be noted that the volume estimation does not account for space capacity lost due to water filling the reservoir folds or the volume lost due to the baffle walls. Therefore, the theoretical detention times are over estimates. As shown in Figure 35, when water was being pumped up to

Highland No. 2, the pump typically operated at a rate of 24 MGD. The theoretical detention time when Q = 24 MGD and the reservoir was at the average depth of 24.0 was estimated to be 4.3 days (103 hours).

Table 9. Highland No. 2 Reservoir theoretical detention time estimation (based on varying water elevations and pumping rates).

Depth	Volume	td @ Q=15 MGD	td @ Q=24 MGD	td @ Q=48 MGD
Feet	MG	days	days	days
28.6	125.0	8.3	5.2	2.6
26.1	112.5	7.5	4.7	2.3
24.0	102.1	6.8	4.3	2.1
20.1	83.4	5.6	3.5	1.7

The fluoride concentration data from the tracer study was used to estimate comparison MRTs. Based on the time between the T_{50} values of the influent and effluent from Phase II (Figure 36), the average time that it took a water parcel to travel from the influent of Highland No. 2 Reservoir (Bruecken Pump Station) to the effluent (chlorine house) was **3.01 days** (hour 27.3 to 99.5). However, there was a drop in the concentration between hours 100 and 128. An old pocket of water is believed to have passed through the outlet during this period. There are only two sample points to support this decrease, followed by a 20 hour data gap. The duration of decreased fluoride concentrations is unclear. From pumping records, it was found that the day before the drop, the average pumping flow rate was lower than normal (12 MGD as shown in Table 10). It is thought that when the flow rate increased, the dead-zone(s) was eliminated, sending old water into the distribution system. This trend of high pumping rate pushing water through the system is evident in Figure 35. There is a lag period between the increased pumping rate periods and fluoride effluent concentration change, but it appears that the concentration of fluoride decreases and increase, during Phases I and II respectively, after the fill cycle, when water is being drawing from the reservoir. As the distribution system demanded water, new water that was pumped up to the reservoir may have short-circuited through the reservoir. Then when the reservoir was filling and the effluent flow rate was less than influent, the pumping may have been able to mix the old and new water, resulting in higher (Phase I) or lower (Phase II) fluoride concentration at the Highland No. 2 outlet.

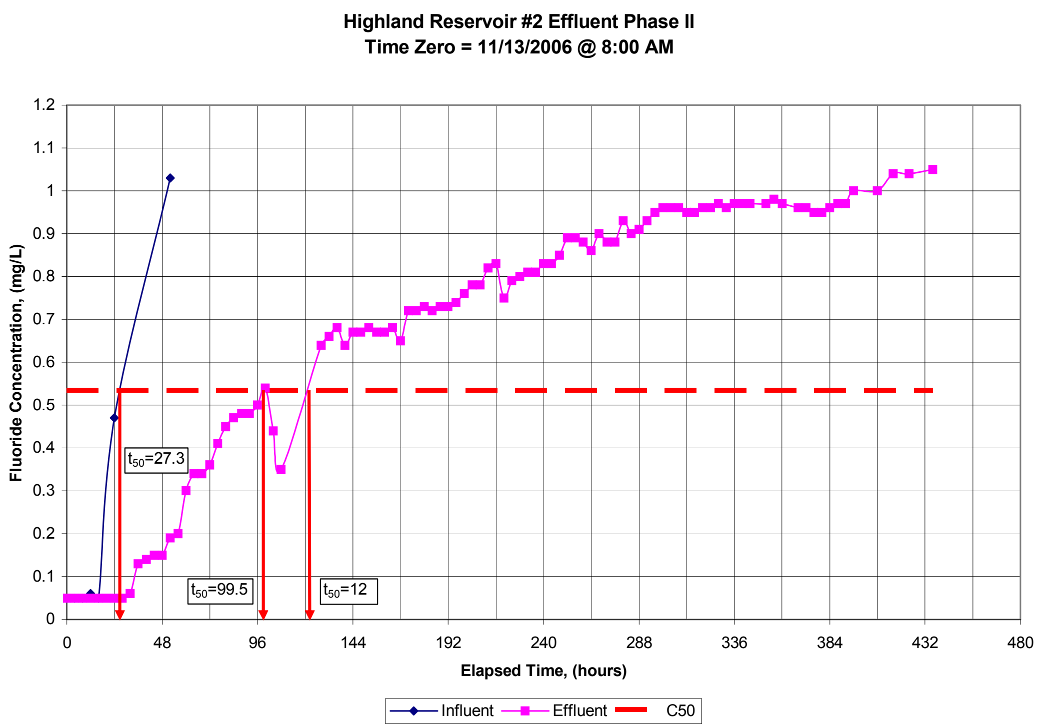

Figure 36. Highland No. 2 Reservoir response curves.

Table 10. Average flow rate pumped to Highland No. 2 Reservoir during Phase II.

Date	Time Elapsed, hours	Average Daily Pumping Rate, MGD
11/13/2006	0	13
11/14/2006	24	18
11/15/2006	48	15
11/16/2006	72	12
11/17/2006	96	24
11/18/2006	120	17

Provided that the data points are accurate, then the time to allow the old pocket of water to pass through increased the MRT up to **3.90 days** (hour 27.3 to 121) **(**Figure 36**)**. During Phase I, the MRT was estimated from Figure 37 to be **2.86 days** (hour 29.4 to 98). Since the pumping rate and reservoir water level fluctuations were consistent for both Phase I and Phase II, the MRT in Highland No. 2 increased by either 3.6 or 25.1 hours (depending on the validity of the large concentration drop during Phase II). This 5 to 27 percent increase in MRT reflects that the reservoir was utilized less during Phase II. Closing the river-crossings (not allowing Highland No. 2 Reservoir to service the Lanpher Reservoir pressure zone) is likely to have decreased the demand from Highland No. 2 Reservoir and thereby increased the MRT.

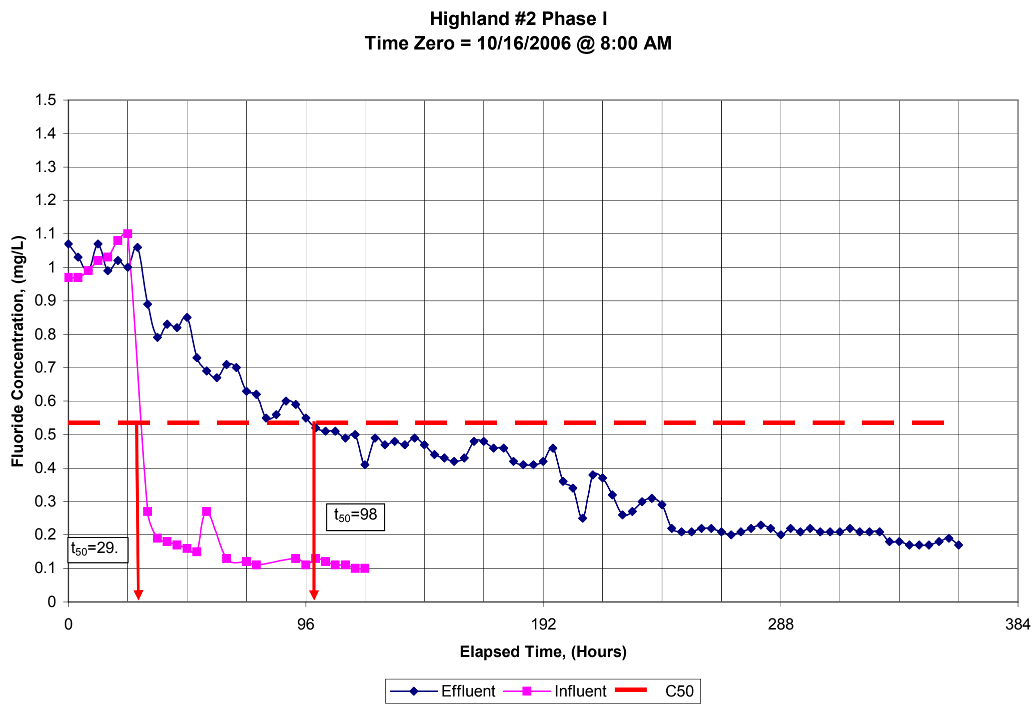

Figure 37. Highland No. 2 influent and effluent response curves and T_{50} values.

3.2.2.2 Highland No. 2 Mixing: The shape of both Figure 36 and Figure 37 area approaching completely mixed response curves. The small valleys in Figure 36 and peaks in Figure 37 are periods where older water passed through the reservoir. It should also be noted that the autosampler readings from the Highland No. 2 outlet house corresponded to the grab samples from hatches that lead to the effluent chlorine house. The analogous values increased confidence that the water collected at the outlet house was representative of water in the Highland No. 2 Reservoir.

Sufficient data were not collected at the Bruecken Pump Station to know exactly what the influent concentration to Highland No. 2 Reservoir was on 11/15/2006. However, based on the fluoride response curves at the end of the clearwell from Phase I, it was determined that it took approximately a day for Bruecken Pump Station to respond to the fluoride shut off. After the fluoride feed concentrations to the clearwell and the minimal data collected at Bruecken Pump Station were reviewed, it was estimated that the influent concentration on 11/15/06 was approximately 1.0± mg/L. Given this influent concentration, Figure 38 shows mixing upon entry to the Highland No. 2 Reservoir. The water entering into the reservoir is likely to have a turbulent jet entry. Typical flow rates into reservoir are between 4860 and 16,6667 gpm, meaning the inlet diameter would have to be 280-feet for there not to be turbulent flow, according to Equation 8. However, the 'L' shaped baffle wall near the entrance makes water flow around through the eastern corners, decreasing the flow path for the turbulent jet mixing and hindering turbulent jet mixing potential.

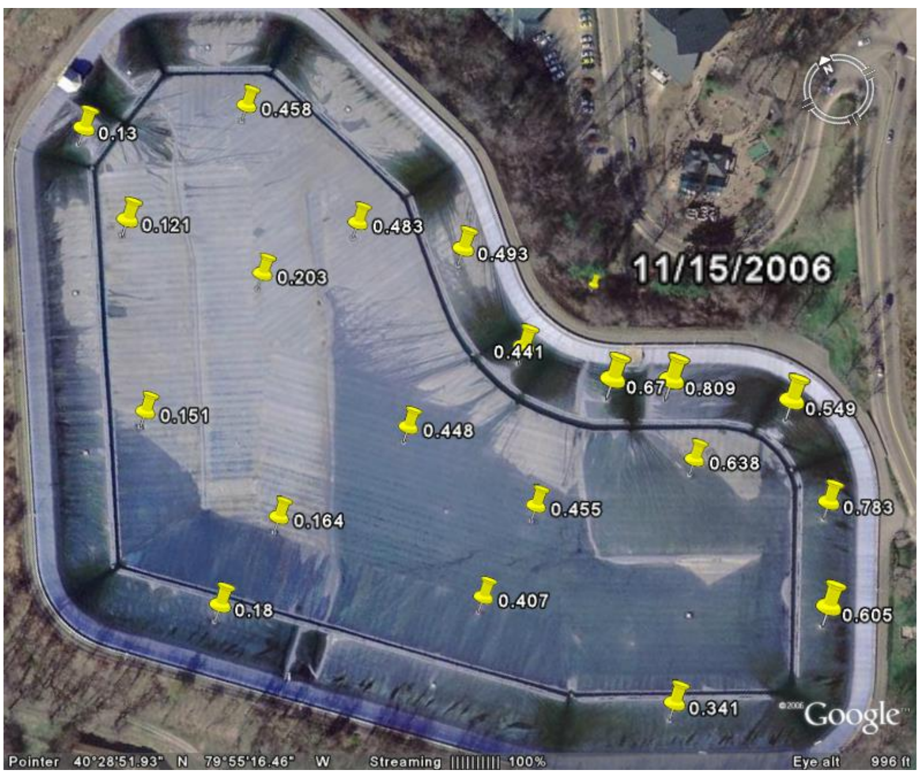

Figure 38. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 11/15/06.

On 11/15/06, the fluoride had been turned back on for two days. Based on the estimation that it took a day for Bruecken Pump Station (the entrance point to Highland No. 2 Reservoir) to see the step-increase, fluoridated water was entering the basin for approximately one day. From Figure 38 it appears that the newly fluoridated water moved through the reservoir as a plug, only changing fluoride concentration half way through the baffles. By 11/20/2006, the fluoride concentration at the end of the clearwell was consistently greater than 0.8 mg/L for the previous six days. So again, Figure 39 displays plug like flow movement through the reservoir. The concentration of fluoride steadily increases from the inlet to the outlet. Therefore, the baffle walls are effective in moving the water through the reservoir with minimal mixing in the axial direction. However, there does appear to be a dead-zone in the lower right corner of Figure 38. Figure 39 also appears to have a lower concentration in the same point. The folds may be causing water to wrap between the baffle walls and the folds quicker than between the fold and the exterior wall. This difference in concentration is not significant enough to affect water quality greatly. Grab samples collected from hatches over Highland No. 2 Reservoir on two other dates are shown in Figures 122 and 123 in Appendix E. Based on the response curves and grab samples collected over the reservoir floating cover, it is perceptible that there was some short-circuiting and dead-zoning occurring in Highland No. 2 Reservoir.

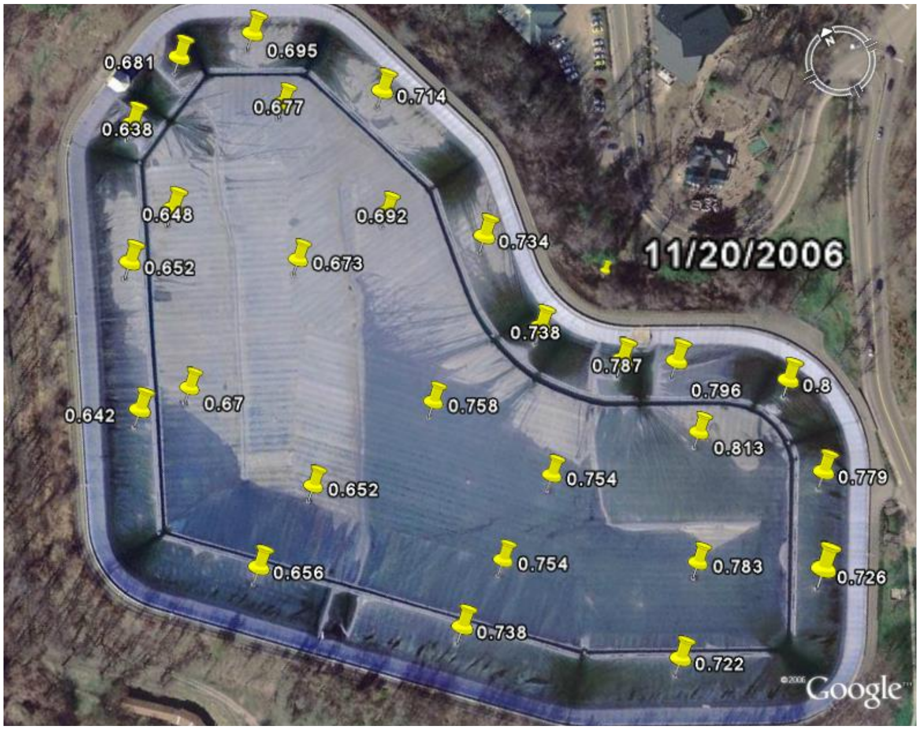

Figure 39. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 11/20/06.

3.2.3 Lanpher Reservoir

Lanpher Reservoir is the largest of the three primary reservoirs, servicing the PWSA and the three consecutive systems north of the Allegheny and Ohio Rivers. The results from the samples collected from the three Lanpher autosamplers were used to estimate the MRT of the reservoir and evaluate the mixing regime within the reservoir. The grab samples collected from the hatches of the west and east basin floating reservoir covers were also used to examine the mixing within and the balance between the two basins.

3.2.3.1 Lanpher Reservoir Mean Residence Time: Operating records during the tracer study were used to develop theoretical detention times for the Lanpher Reservoir (Equation 1). These calculated detention times were then used for comparison to the MRTs estimated from the tracer response curves. The automated surface level reader at the reservoir was not working during the fluoride tracer study. Consequently, only one water level reading was recorded, from the side of the reservoir, daily by a PWSA employee. Some variation was observed in both the pumping rate and reservoir water level between Phase I and Phase II. The hourly pumping rate from Aspinwall Pump Station to Lanpher Reservoir in MGD, water levels in feet, and change in fluoride concentration in mg/L during both Phases I and II of the tracer study are plotted against the elapsed time in Figure 40. Time zero is 10/16/06 at 8:00AM when the fluoride was turned off at the start of Phase I. Hour 672 (28 days from the time that the fluoride was initially turned off) marks the start of Phase II on 11/13/2006 @ 8:00AM, when the fluoride feed was resumed. The hourly pumping data from Figure 40 was averaged to determine the typical daily pumping rate during Phase I and Phase II. The average daily pumping rate increased from 17.9 to 18.7 MGD from Phase I to Phase II. Throughout the majority of the study, one pump operated at a rate of 15-18 MGD and occasionally a second pump was utilized to increase the total pumping rate to 32 MGD. The water levels during Phase I and Phase II were also evaluated to find the minimum, maximum and average depths values that were used to estimate the storage capacity during the two phases of the tracer study. The concentration versus time tracer response curves were also plotted in Figure 40 to evaluate if the fluctuation in concentration was due to pumping or fill/draw schedules. The shape of the response curves and the impact of pumping and demand are discussed further in Section 3.2.3.2.

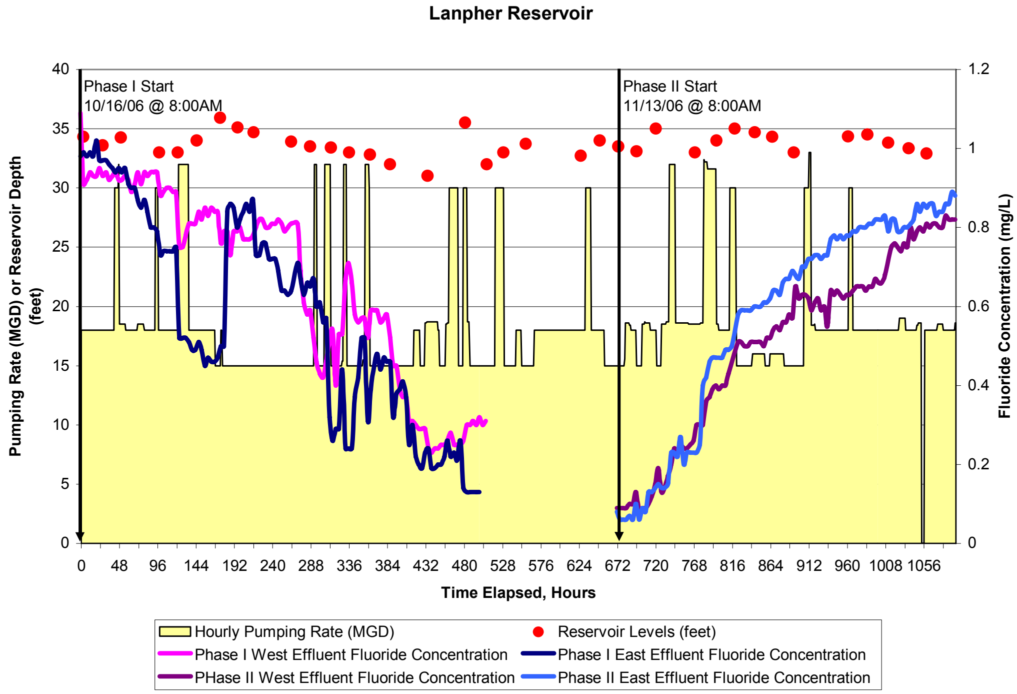

Figure 40. Lanpher Reservoir depth, fluoride response curves, and rate of pumping to the reservoir.

In the past, when Lanpher Reservoir was filled to a depth of 37.15-feet, it had a capacity of 133 MG [PWSA, 1995]. Based on the estimated volume at 37.15-feet, the capacity at the minimum (30.5-feet), maximum (35.9-feet), and Phase I and II average depths (33.6 and 33.8-feet respectively) was approximated. The estimated volumes do not take into account the storage space lost due to the reservoir cover folds, the volumes may be slightly overestimated. The capacities were divided by pumping rates to determine the range of theoretical detention times, t_d, displayed in Table 11. The rates included the low hourly rate of 15 MGD, the average values of 17.9 and 18.7 MGD during Phase I and Phase II respectively, the maximum daily pumping rate of 24 MGD, and the high hourly pumping rate of 32 MGD. Because the storage volume is constantly changing due to diurnal and temporal variations, the t_d is constantly changing. The values calculated provided a range of theoretical values for comparison to the MRTs estimated from the tracer study. The average pumping rate and recorded level values from Phase II were used to estimated that the average t_d, for both the west and east basins, of 159.0 hours (Table 11). An average t_d was calculated for both basins because capacity and amount of flow split between the two basins is uncertain. This average t_d from Phase II was 6.5 hours less than the average t_d calculated from the Phase I data. Therefore, it is thought that more water turned over in the reservoir during Phase II after closing the effluent gate to the east Lanpher Reservoir effluent channel by 50 percent and closing the river-crossings. Closing the effluent channel, discussed further in Section 3.2.3.2, increased balanced between the two basins of the reservoir and the closing the river-crossings is thought to have increased the demand from Lanpher Reservoir by preventing water from Highland No. 2 Reservoir from crossing over into the Lanpher Supersystem. See Section 3.2.5 for further discussion of the separation of the pressure zones by closing the river-crossings. Overall, there was less time for water quality to degrade in Lanpher Reservoir during Phase II when compared to Phase I.

Table 11. Lanpher Reservoir capacity and theoretical detention time estimates.

Depth	Volume*	t_d @ Q=15MGD	t_d @ Q=17.9 MGD[1]	t_d @ Q=18.7 MGD[2]	t_d @ Q=24 MGD	t_d @ Q=32 MGD
Feet	MG	days	days	days	days	days
37.15	133.0	212.8	178.3	170.7	133.0	99.8
35.9	129.5	207.2	173.7	166.2	129.5	97.1
33.8	123.9	198.3	166.2	**159.0**	123.9	92.9
33.6	123.4	197.5	**165.5**	158.4	123.4	92.6
30.5	115.8	185.2	155.2	148.6	115.8	86.8

* Volume assumes negligible capacity loss due to folds or sediment.
1 Average pumping rate during Phase .I
2 Average pumping rate during Phase II.

To validate the average t_d values, the MRTs were estimated from the west and east basin tracer study response curves and averaged. However, sufficient data were not collected during Phase II from the Lanpher Reservoir influent channel to determine the average travel time between the clearwell inlet and Lanpher Reservoir inlet. The first data point collected from the Lanpher influent channel was at hour 24 with a concentration of 1.1 mg/L, completely missing the step input passage time. Therefore, the MRT of Lanpher Reservoir (from influent to effluent) was not calculated. Instead, the age of water exiting the Lanpher Reservoir was estimated directly from the concentration verses time fluoride response curves (Figure 41). The T_{50} value for the east Lanpher basin was 148 hours and the west was 195 hours, a difference of two days. It is logical that the east basin has a lower MRT because it is smaller. The imbalance of the values was also seen during Phase I, which is why the east basin effluent gate was closed 50 percent before the start of Phase II. This mechanical change was in attempt to decrease the fraction of flow that enters the east basin, thereby, increasing the east basin t_d and decrease the west basin t_d.

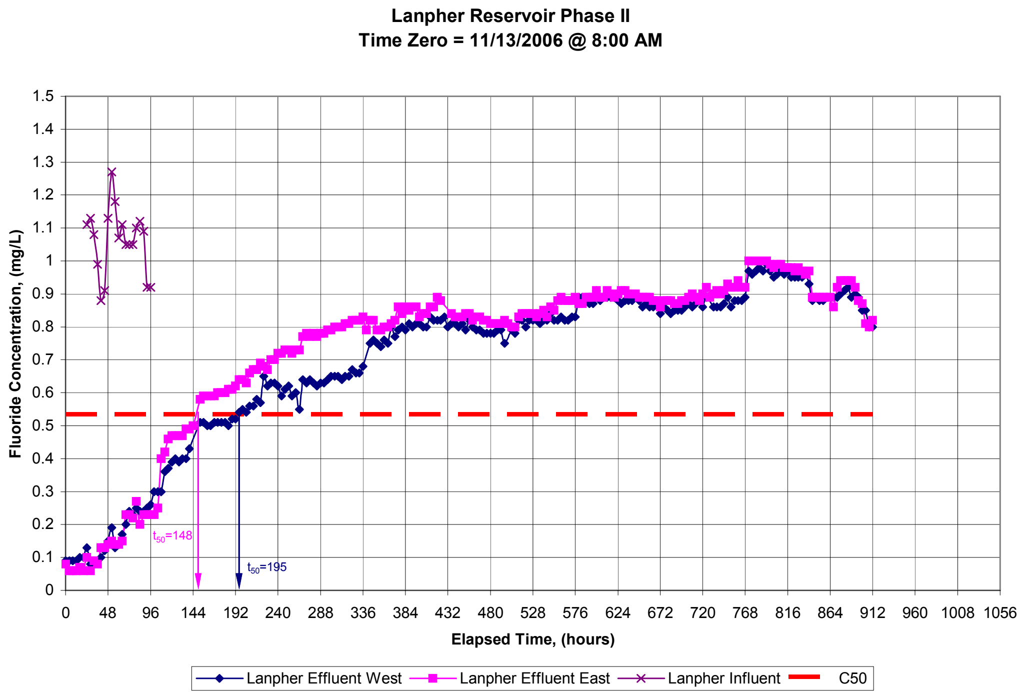

Figure 41. Lanpher Reservoir Phase II - T_{50} approximation.

The influent T_{50} value during Phase II was determined to be between 0 and 24-hours from Figure 41. At time zero, it is known that the water drawn to Aspinwall Pump Station was still at baseline since the concentration at the clearwell was still at the baseline fluoride concentrations of 0.07 mg/L and the first recorded point at hour 24 was already at 1.11 mg/L. Therefore, the step-up response occurred between hours 0 and 24, resulting in a MRT in the east and west basins within the ranges of 124-148 hours and 171-195 hours, respectively. The average of the low and high ends of the ranges from both basins resulted in a final T_{50} value range of 147.5 to 171.5 hours. The t_d at the average hourly pumping rate, 18.7 MGD, and average water level, 33.8 feet, during Phase II falls within the final tracer range, adding confidence to the tracer study results and concluding that there was minimal short-circuiting and dead-zoning during Phase II.

There was, however, a dramatic decrease in effluent water age between Phase I and Phase II. The Phase I fluoride concentrations at the effluent of the west and east Lanpher Reservoir basins were plotted against time in Figure 42 to determine the average water ages. The influent concentrations versus time were also plotted in Figure 42 to show how quickly the step reached Lanpher Reservoir from the clearwell. The water age at the influent was determined to be 17 hours and the east and west effluents were 309 and 387 hours respectively. Yet the validity of these points is uncertain. Due to all the oscillating data and the data gap between hours 508 and 672 in Figure 40, the concentration of fluoride may or may not have peaked again after hour 508. Using Equation 6, the average water age was calculated from the area below the concentration versus time curve and found to be as low as 250 hour for the east and 300 hour for the west with, an average of 275 hours for both basins, (assuming the fluoride concentration dropped to the baseline after hour 508). If this area approximation is correct, then the imbalance between the two cells was similar to Phase II with a difference of approximately 50 hours and there was a 104 hour decrease of effluent water age between Phase I and II. If the concentration of fluoride increased to 0.4 on the east and 0.6 on the west for hours 508 through 672, the average water ages calculated from Equation 6 were found to be equivalent to the T_{50} values estimated in Figure 42, with an average water age of 346 hours and imbalance of 78 hours. If there was 78 hours between the west and east cells during Phase I, then when compared to the imbalance observed during Phase II, closing the effluent gate increased the balance between the basins.

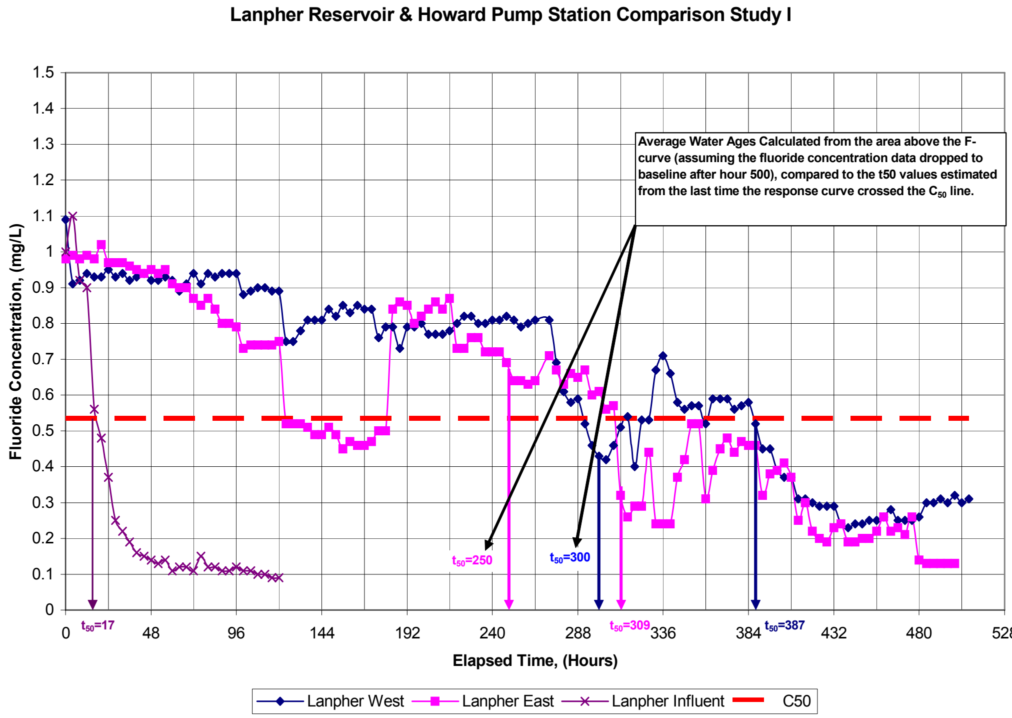

Figure 42. Lanpher Reservoir Phase I - T_{50} approximations.

The fluoride concentration verses time curve in Figure 42 actually crossed the T_{50} point multiple times. The final time that the concentration crossed the C_{50} line was theorized to be representative of the average exit water age based on the fact that all the other crossing points were well before the minimum age estimated by Equation 6. The corresponding minimum and maximum MRTs to the Equation 6 average water age estimates are 258 and 329 hours, from subtracting the influent T_{50} value (17 hours) from the average water age range of 275-346 hours. These MRTs are much larger than all of the estimated t_d listed in Table 11. Therefore, it is likely that one or both the average water ages were overestimated. Therefore, the MRT in the east cell was theorized to actually be somewhere between 150 and 200 hours, creating an even larger gab between the two cells. With the incomplete F-curves in Figure 42, it was impossible to determine what really happened. However, it was evident that the average water age from Phase

I to Phase II decreased by somewhere between 130.5 and 174.5 hours and it was also concluded from the MRTs and the TTHM formation that closing the effluent gate after Phase I improved the balance between the reservoir basins.

3.2.3.2 Lanpher Reservoir Mixing: The shape of the Lanpher Reservoir response curves during Phase I (Figure 42) and Phase II (Figure 41) were very different. The Phase I data points greatly fluctuated over time, whereas, the Phase II the curves have similar curvature, with minimal peaks and valleys. The results indicate there was significant short-circuiting and dead-zoning and/or sloshing of water within or between the two basins during Phase I. Then during Phase II, the water appeared to be mixing and moving through the reservoir with minimal short-circuiting, dead-zoning, and sloshing. The pumping schedule is believed to have contributed to the fluctuation in concentration with time. Referring back to Figure 40, steep valleys (new water passing through) in the Phase I response curves following periods of increased pumping rates were observed. This observed trend is also seen from the east basin response curve, but it seems that the increased pumping rate periods forced new water through the basin, followed by a sloshing effect and old water with a higher fluoride concentration exited. Even during Phase II, steeper increases of concentration were observed during high pumping rate periods. Since water depth measurements were not recorded hourly, it was not possible to determine if the fluctuations in concentration were due to fill/draw patterns. However, the variation between the effluent response curves between Phase I and II may be due to separating the Lanpher and Highland No. 2 pressure zones with the closing of the river-crossings. Section 3.2.5 further examines how the river-crossings may have influenced the Phase I and Phase II Lanpher effluent channel tracer response curves.

The hatch samples from the Lanpher Reservoir floating cover were evaluated to provide insight on what was happening inside of the reservoir during the two tracer study phases. Figure 43 is a plan view of Lanpher Reservoir with the hatch sample results from 11/17/2006 plotted spatially. These samples were taken 772 hours after the fluoride was turned off and 100 hours after the fluoride feed was resumed. Therefore, in Figure 43, fluoridated water had been entering the basin for approximately three days. The average concentration in the west and east basins on 11/17/2006 were 0.31 mg/L and 0.43 mg/L respectively. There was minimal variation of concentrations within the basins and there were no hatch points that consistently had higher or lower concentrations than the others, when compared to the results form the different hatch sampling days. The Lanpher Reservoir hatch sample results from 11/14/2006, 11/21/2006, and 11/28/2006 are included in Appendix F (Figures 124, 125, & 126). Therefore, the Phase II hatch sampling results indicate sufficiently that water was mixing through the reservoir. No dead-zones or short-circuiting were apparent at the hatch locations. However, samples were only collected at 15 foot depths, so it is possible that dead-zones and/or short-circuiting were present but were not observed from the hatch sampling points.

Figure 43. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/17/2006.

The hatch sample concentrations from the four Phase II sampling day were average and plotted in Figure 44 with the fluoride concentration results from the two effluent channels. The hatch samples coincided fairly well to the effluent curves during Phase II. Since the concentration at the effluent curves were lower than the average hatch sample (except on 11/28/06), it added confidence to the notion that there was minimal short-circuiting and dead-zoning during Phase II.

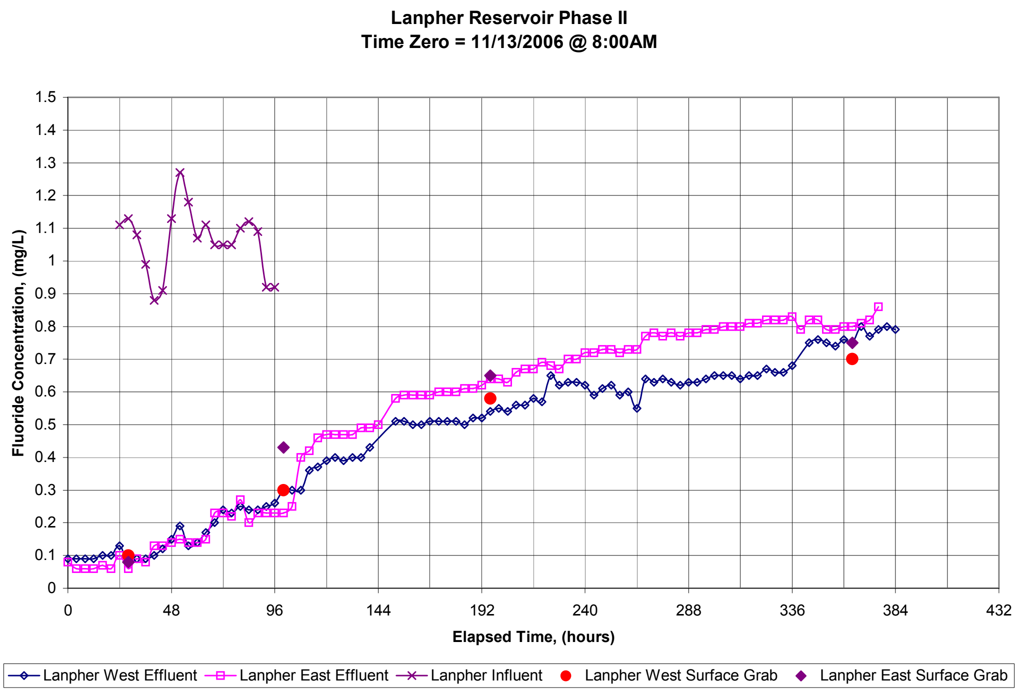

Figure 44. Lanpher Reservoir effluent channel and floating cover grab sample fluoride concentrations.

Hatch sampling over Lanpher Reservoir was only conducted once during Phase I on 10/27/2006 (268 after the fluoride was turned off). The resulting concentrations from the different hatches are displayed in Figure 45. The concentration average from the west basin was approximated to be 0.42 mg/L on the west and 0.28 mg/L on the east after receiving water with baseline fluoride concentrations for approximately 10 days. Since all grab samples from both sides were well below the C_{50} value of 0.535 mg/L of fluoride at this time, it was theorized that the effluent concentrations would also be less than C_{50}. However, the results were contradictory. The averaged hatch sample results from 10/27/2006 were plotted on the concentration verses time graph with the influent and effluent Lanpher Reservoir fluoride response curves (Figure 46). The grab samples over the surface of the reservoir were nearly 0.4 mg/L lower than the concentration at the effluent. At first it was thought that one of the sets of data had to be in error, however, there is reason to believe that the river-crossings may have been the cause of the offset of results. See Section 3.2.5 for further discussion on the effect of the river-crossings. All of the average data points from the west and east basins are listed in Table 12. The difference in average concentration between the two basins during Phase II were all lower than the Phase I averages, again leading to the conclusions that closing the effluent gate to the east cell helped balance the basins.

Figure 45. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 10/27/2006.

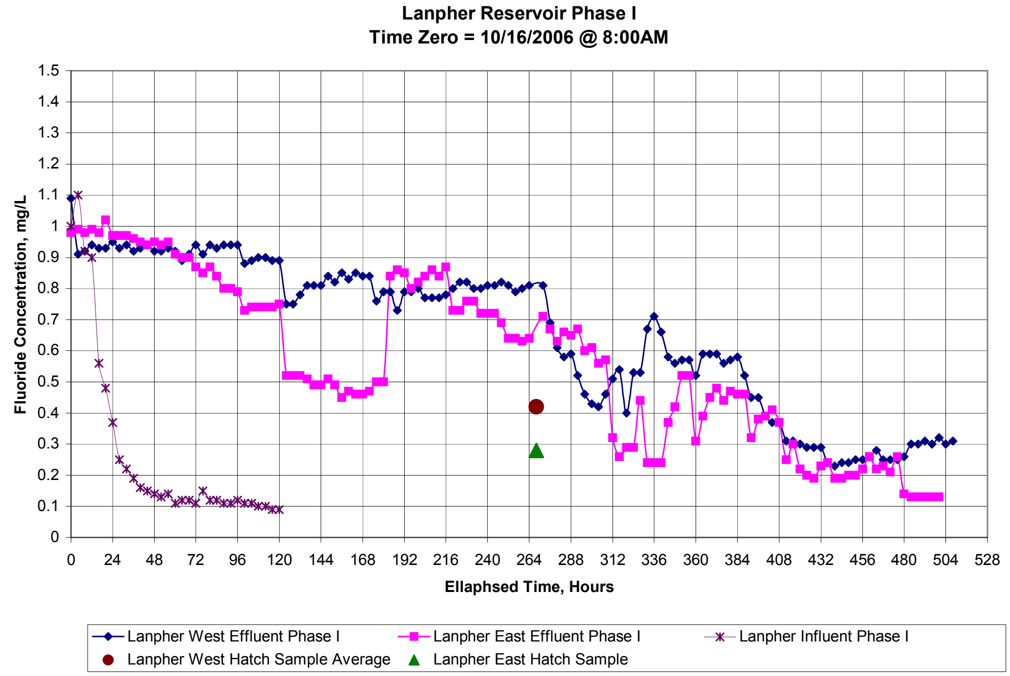

Figure 46. Lanpher Reservoir Phase I average hatch sample results from the west and east basins compared to the effluent channel data.

Table 12. Lanpher Reservoir comparison of the balance between the two cells

Hatch Sampling Date	West Basin Hatch Fluoride Concentration Average	East Basin Hatch Fluoride Concentration Average	Difference Between Cells
	mg/L	mg/L	%
Phase I - 10/27/2006	0.418	0.277	33.7%
Phase II - 11/14/2006	0.101	0.083	17.8%
Phase II - 11/17/2006	0.307	0.430	28.5%
Phase II - 11/21/2006	0.586	0.648	9.6%
Phase II - 11/28/2006	0.700	0.756	7.4%

3.2.4 Herron Hill Reservoir

Herron Hill Reservoir was added to the sampling plan as an intermediate sampling point to aid in calibrating the PWSA hydraulic model. It is an intermediate point because it is a secondary storage facility that receives water pumped from both Highland No. 1 Reservoir and directly from the AWTP through Bruecken Pump Station. It is a small reservoir with a capacity of 14 MG at a depth of 22-feet. Samples were collected from the influent and effluent of the reservoir. The resulting fluoride concentrations were plotted again time in Figure 47 along with the concentrations from Bruecken Pump Station and Highland No. 1 Reservoir. Water enters the system through Bruecken Pump Station within a 24-hour period and is pumped either to Highland No. 1 Reservoir, Herron Hill Reservoir, or directly to service lines in the distribution system. From Figure 47 it is apparent that Herron Hill Reservoir is receiving a mixture of source water from Bruecken Pump Station and Highland No. 1 Reservoir, because the influent response curve to Herron Hill Reservoir is between the Highland No. 1 Reservoir effluent and Bruecken Pump Station curves. Sufficient data from not collected at the influent of Herron Hill Reservoir during Phase I to evaluate the shape of the response curve. However, in Phase II, the response curve had a steep increasing slope between hours 672 and 696. It is thought that during this period, more water was pumped directly to Herron Hill Reservoir, then as the slope of the concentration response curve decreased there was more water contribution from Highland No. 1 Reservoir. The response curve from the fluoride tracer was typically seen at the effluent of Herron Hill Reservoir before the effluent of Highland No. 1 Reservoir and the distance between the Herron Hill influent and effluent curves suggests that water turns over quickly in the reservoir.

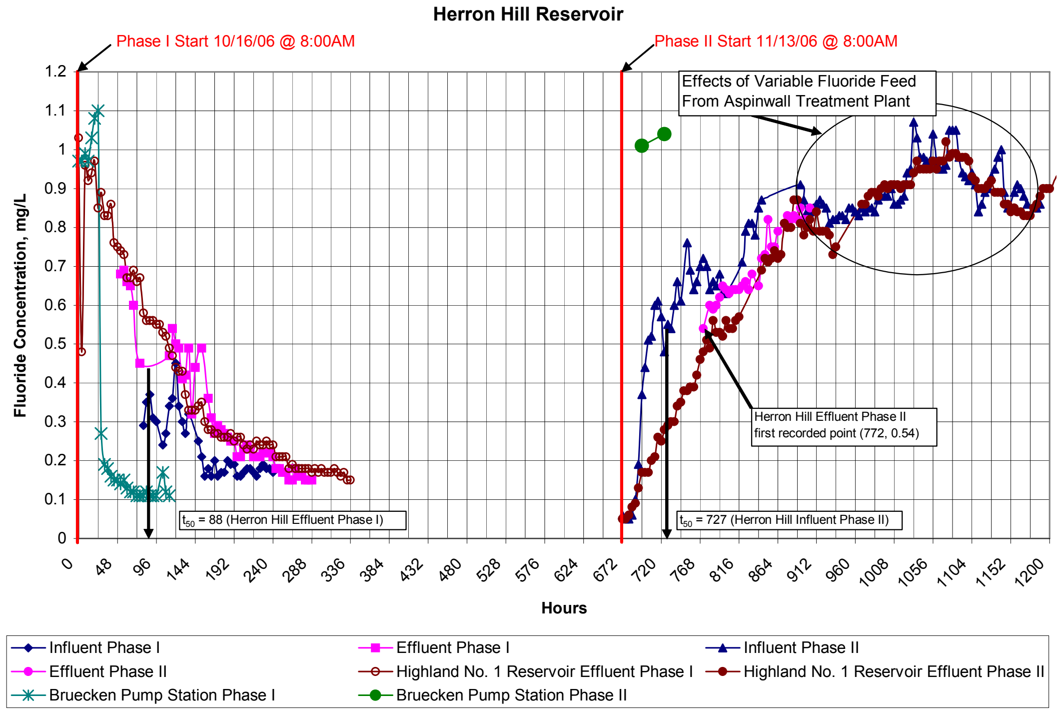

Figure 47. Herron Hill Reservoir influent and effluent response curves (Phase I & Phase II).

To estimate the water aging effects of Herron Hill Reservoir, the water ages of the influent and effluent were estimated from the C_{50} value of 0.535 mg/L of fluoride on Figure 47. During Phase I, sufficient data from not collected at the influent and during Phase II, sufficient data were not collected from the effluent to determine the MRT in the reservoir. However, the water age of the influent water was estimated to be between 96 and 117 hour (4.0 to 4.9 days) during Phase I. There was some fluctuation between hours 96 and 117 and no data were collected between 0 and 72-hours. Without the complete response curve, the area above the F-curve could not be calculated (Equation 7) to verify the average water age entering Herron Hill Reservoir. During Phase II, the first effluent datum point collected was at hour 772 (100 hours, 4.2 days, after the fluoride feed was resumed) with a fluoride concentration of 0.54 mg/L. This concentration corresponds with the C_{50} value of 0.535 mg/L and is within the age range of values determined from Phase I. Therefore, there was minimal change in Herron Hill effluent water ages between Phase I and Phase II. The influent average water age was also determined from Figure 47 to be 727 hours (55 hours, 2.3 days, after the fluoride feed was resumed). This age was confirmed by finding the area above the F-curve to point (892, 0.91) where the concentration of fluoride began to fluctuate due to the inconsistent fluoride feed at the AWTP. Therefore, assuming that the first point of the Herron Hill effluent curve is representative of the T_{50} value, then the MRT in Herron Hill Reservoir was estimated to be 45-hours (1.9 days). Since the average water parcel spends less than two days in Herron Hill Reservoir, it was determined that this intermediate reservoir is not a significant source of water quality degradation. The age of water exiting Herron Hill Reservoir is dependent on the age of water exiting Highland No. 1 Reservoir. Therefore, decreasing the age of the source water from Highland No. 1 Reservoir would decrease the water age exiting Herron Hill Reservoir. The Highland No. 1 Reservoir effluent age may be decreased either by lowering surface water levels or by moving more water through the Highland No. 1 Reservoir by increasing the capacity of the membrane plant at the effluent of Highland No. 1 Reservoir. Otherwise, to decrease the MRT in Herron Hill Reservoir from two to one day, either the capacity would have to be cut in half or the pumping rate would need to be doubled. Therefore, it is best to improve the operation of Highland No. 1 Reservoir because it is over six times the size Herron Hill Reservoir.

3.2.5 Effects of Highland No. 2 and Lanpher Reservoir Supersystem Separation

During Phase I the Highland No. 2 and the Lanpher Reservoir Supersystems were interconnected. The three river-crossings, which connect the two supersystems, were opened allowing water to flow back and forth based on demand and pressure. Figure 48 is a graph of the hourly rate of pumping and the elevation of the surface water in both the Lanpher and Highland No. 2 Reservoirs during Phases I and II. Hourly surface elevating data were available for Highland No. 2 Reservoir, however, for Lanpher Reservoir only one reading was collected daily shown by dots in Figure 48. Therefore, Figure 48 only shows the diurnal changes in surface elevation for Highland No. 2 Reservoir. The surface elevation of Highland No. 2 Reservoir and Lanpher Reservoir were kept at approximately the same elevation throughout the study to attempt to provide equal pressure on either side of the river-crossings. During Phase I, the surface water elevation in Lanpher Reservoir peaked at hour 175 (7.29 days), then the recorded elevation began to steadily decrease. Since the Lanpher water level data were collected at the same time every day, it is a good approximation of the overall trend of the elevation changes, even through the diurnal variations were not recorded. The peak in water elevation in Lanpher Reservoir was onset by an increased pumping rate, followed by decreased pumping. Therefore, Figure 48 also shows how the surface water elevations changed in response to the hourly pumping rate.

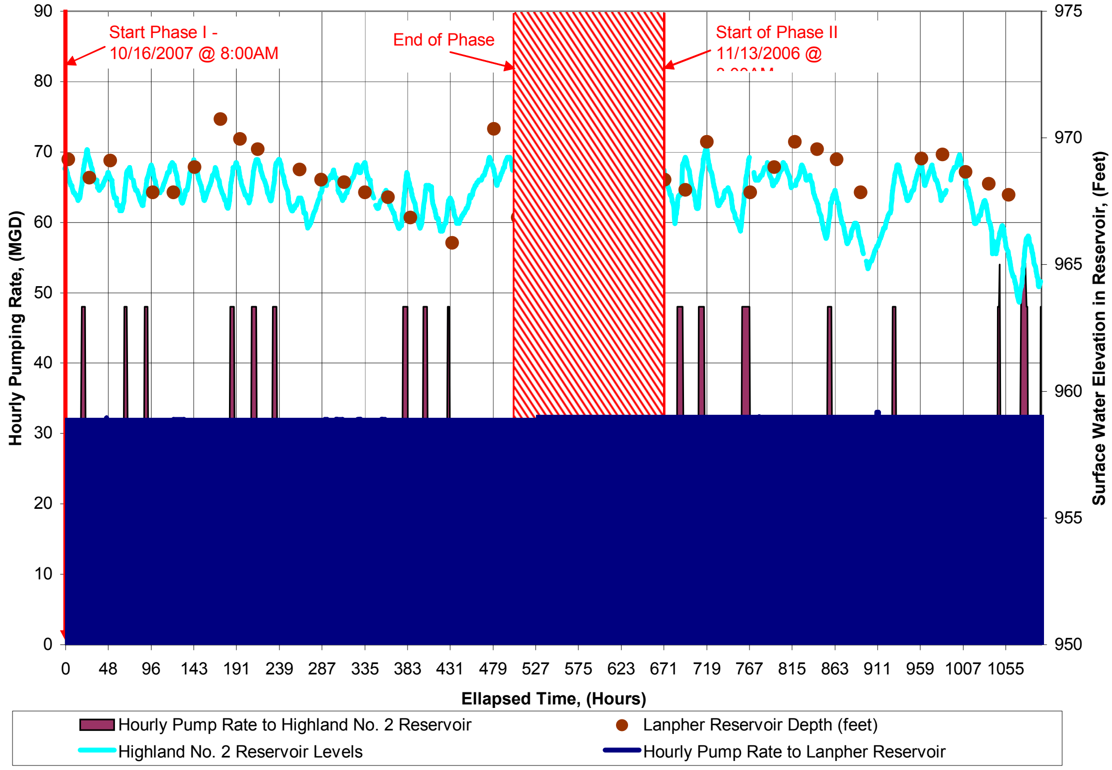

Figure 48. Lanpher and Highland No. 2 Reservoirs daily pumping rates and water levels.

During the filling period in Lanpher Reservoir, between hours 122 and 175, the surface elevation increased quickly, but the diurnal variation of levels in Highland No. 2 Reservoir stayed fairly constant. This time period corresponds to the steep drop in concentrations observed in the Lanpher Reservoir east basin effluent. It was also the first time since the start of the study where the surface elevation of Lanpher Reservoir was observed to be apparently higher than the elevations at Highland No. 2 Reservoir. In Figure 49, it is also evident that the fluoride concentration leaving Highland No. 2 Reservoir steadied out around hour 124, when the east Lanpher Reservoir basin sustained the sharp decline in fluoride concentration. Therefore, it is theorized that the higher water surface elevation in Lanpher Reservoir increased the pressure provided from Lanpher Reservoir, moving more through the Lanpher Supersystem and causing short-circuit (explaining the significant decrease in fluoride concentration at Lanpher Reservoir).

Once the surface elevation in Lanpher Reservoir began to fall, the pressure provided by or the demand from the Lanpher Reservoir to the system decreased and there was less flow rate through Lanpher Reservoir. The decreased flow rate and decrease head may have stopped the short circuiting and allowed old dead zoning water to circulate through Lanpher Reservoir. It is also a possibility that old water from the west basin was allowed to flow over to the east basin raising the fluoride concentrations back up to 0.8 mg/L. Then an old pocket of water may have been sloshing around the effluent channels near the sampler suction line, explaining why average concentration in both of the reservoirs effluent channels were observed to be much higher than the average concentrations from the hatch grab samples.

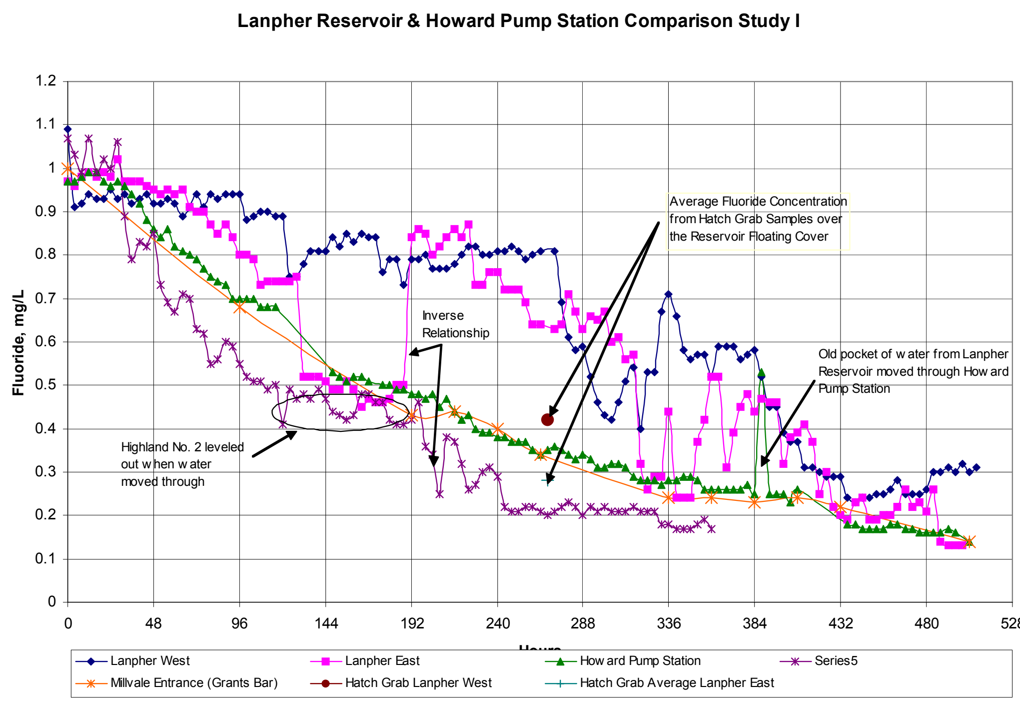

Figure 49. Lanpher Reservoir Phase I data comparison to hatch grab samples, Highland No. 2 Reservoir, Millvale, and Howard Pump Station

To further evaluate what happened during Phase I to cause the fluoride concentration to vary greatly in Lanpher Reservoir, the sampling locations downstream from Lanpher Reservoir were evaluated. Samples collected from the entrance point to Millvale Boro, Howard Pumping Station, Lanpher Reservoir basins floating covers, and Highland No. 2 Reservoir effluent were plotted along with the Lanpher Reservoir effluents fluoride response curves in Figure 49. The effluent curves of Highland No. 2 and Lanpher Reservoirs mark the entry point of water to the Highland No. 2 and Lanpher Supersystems, respectively. Both the Highland No. 2 and the Lanpher Reservoir response curves were included in Figure 49 because the two supersystems were combined during Phase I by the three river-crossings, so water from Lanpher Reservoir may have entered the Highland No. 2 Supersystem and visa versa. Since Millvale Boro and Howard Pump Station are downstream from Lanpher Reservoir, their tracer response curves should have had the same general response shape to the right of the Lanpher Reservoir curves. However, in Figure 49 the decreased fluoride concentrations were observed at both Howard Pump Station and Millvale Boro before the change at the effluents of Lanpher Reservoir, meaning the water at these two downstream sites was younger than the water exiting Lanpher Reservoir. The great fluctuations in fluoride concentration recorded at the Lanpher Reservoir effluents were also not observed downstream. Furthermore, when the surface of Lanpher Reservoir was sampled, all of the grab samples showed that the average concentration in the reservoir was close to the concentrations observed down stream with the west basin a bit above and the east a bit below, since the east basin turns over more quickly as discussed in Section 3.2.3. When compared to the Highland No. 2 Reservoir and Lanpher Reservoir effluent fluoride response curves, the Millvale Boro and Howard Pump Station curves are between the two. Therefore, a logical conclusion is that Millvale Boro and Howard Pump Station were not receiving all their water directly from Lanpher Reservoir. During Phase II, after the river-crossings were closed and fluctuations in fluoride concentrations were not observed at the Lanpher Reservoir effluents. The fluoride concentration data from the two Lanpher Reservoir effluents and floating cover, Millvale Boro, Howard Pump Station, and Highland No. 2 Reservoir were plotted against elapsed time in Figure 50. Again, the change in fluoride concentration was observed at Highland No. 2 Reservoir before Lanpher Reservoir, but Millvale Boro and Howard Pump Station data coincides closely to the Lanpher Reservoir effluents. There were still a few areas where the fluoride response reached Millvale Boro and Howard Pump Station before the Lanpher Reservoir effluents. For example, between hours 72 and 96 or 120 and 144 the concentrations at the downstream locations are higher than one or both of the Lanpher Reservoir effluent channels. Therefore, it is theorized that some newer water is getting to Millvale Boro and Howard Pump Station via bypassing Lanpher Reservoir.

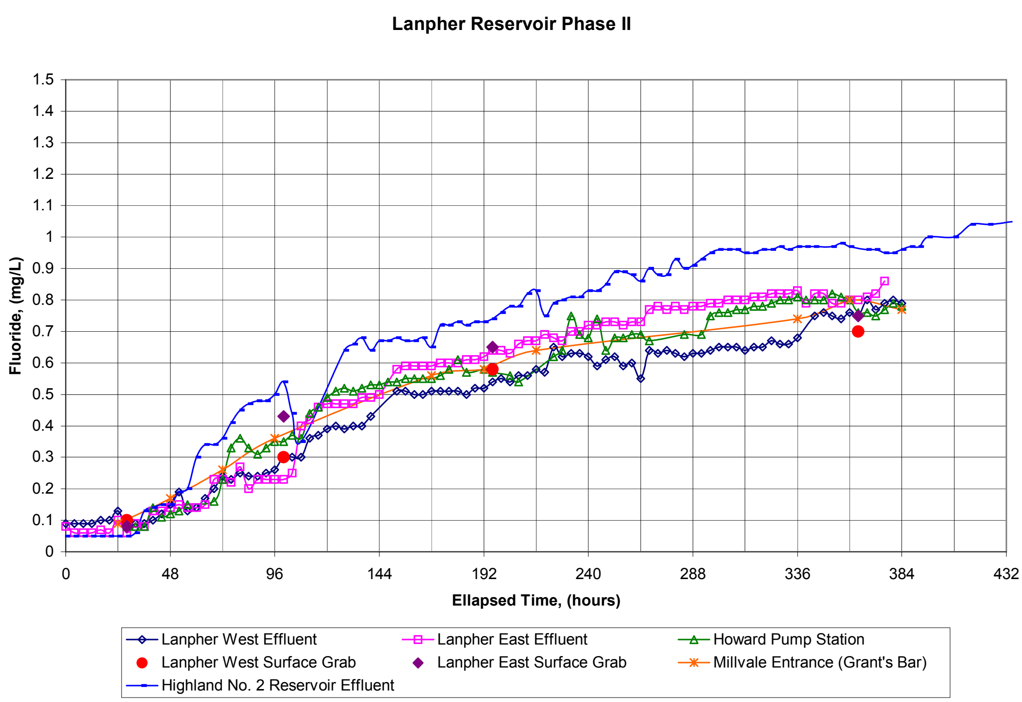

Figure 50. Lanpher Reservoir Phase II - Comparison of grab sample concentrations in the reservoir and concentrations after the reservoir.

During Phase I, water from the Highland No. 2 Supersystem was theorized to have been servicing the Lanpher Supersystem, therefore, decreasing the demand from Lanpher Reservoir. The decrease demand or bypassing of Lanpher Reservoir was theorized to be the cause of increased water ages in Lanpher Reservoir and the compartmentalization (where old and new water was not mixing before exiting). It is known that the amount of water level fluctuations (fill/draw cycles) in each reservoir changes the age of the water and water flows from high to low pressure, therefore, the difference in operation of Highland No. 2 and Lanpher Reservoir influences the age of water in the distribution system. Closing the river-crossings from Phase I to Phase II separated the districts served by Lanpher and Highland No. 2 Reservoir and appears to have balanced water ages between the two systems, as well as, allowing for better control of disinfectant residual. However, keeping the river crossings closed limits the ability of PWSA to provide water to different parts of the system during emergencies. To assure that the valves may be opened for emergency water demand between the two systems, a valve exercising program should be implemented.

4.0 SUMMARY AND CONCLUSIONS

The PWSA fluoride tracer study data was determined to be very useful in analyzing the PWSA drinking water distribution system. Average water ages, MRTs, and mixing characteristics were estimated from the concentration versus time response curves. The samples collected from the surface of the three primary reservoirs were also found to be valuable in evaluating the mixing regime within these large storage facilities. TTHM concentrations were plotted against the calculated water ages to evaluate water quality at each of the sampling sites. Also, conducting a step-down tracer study (Phase I) directly followed by a step-up tracer study (Phase II) added confidence to the water ages calculated during Phase I and allowed for the analysis of the effects of closing the river-crossings and closing the effluent sluice gate by 50 percent to the east Lanpher Reservoir Basin. From the tracer study data results, potential operational changes and facility improvements were identified to decrease water age and improve water quality form the Stage 2 DBPR.

From the water age estimations, it was found that 80 percent of the sampling site during Phase I and 67 percent of the sampling site during Phase II had water ages classified as "long" [AWWA and EES, 2002], with water ages greater than three days. The improvement of water age between Phase I and II was theorized to be due to the operational changes of closing the river-crossings and lowering the east Lanpher Reservoir Basin effluent sluice gate, although it may have been due to diurnal or temporal variations within the distribution system. For the purpose of this study, the T_{50} value was found to be a good approximation of the average water age. However, diffusion of tracer molecules was evident at the end of the exponentially shaped tracer response curves. There was a “tailing” effect, where the rate of change of concentration with time decreased. This is a security concern because it means that if a contaminant is introduced into the PWSA distribution system, low concentrations of the contaminant will still be present in the system at times that are more than twice the T_{50} values.

The oldest water was located at the Reserve Twp. sampling sites. The Phase I and II T_{50} values in Reserve Twp. were consistently greater than 320 hours (13.3 days), the age at the entry point to Reserve Twp. The sampling site prior to Reserve Twp. was Howard Pumping Station with a water age of 146 hours (6 days). Three sites in the PWSA distribution system that received water from Brashear Tanks or Allentown Tanks also had water ages over 300 hours (12.5 days). Therefore, water entering the Reserve Twp. has already aged significantly in the PWSA distribution system. It was estimated that within Reserve Twp., water ages by only three days.

As expected, all of the primary reservoirs had evidence of dead-zoning and short-circuiting. However, from the shape of the fluoride response curves and data collected over the reservoir, Highland No. 1 Reservoir was found to be mixing rather well, whereas, more dead-zoning and short-circuiting was observed in Highland No. 2 Reservoir. The baffles in Highland No. 2 Reservoir encourage plug flow, but are likely the cause of the stagnant zones [AWWA and EES, 2002]. A dead-zone was identified in Highland No. 2 Reservoir and was likely due to the configuration of the baffles, which limit the ability of the turbulent jet to mix the reservoir. The Lanpher Reservoir Phase I and Phase II results were contradictory results, however, Phase II portrayed the reservoir as mixing sufficiently. From evaluating response curves downstream of

Lanpher Reservoir, it is theorized that water maybe bypassing Lanpher Reservoir, resulting in increased water aging and TTHM formation within the Lanpher Reservoir. Mixing in the reservoirs was attributed to the turbulent jet entry and the variation in water depth and pumping schedules. Increasing pumping during the nights and weekend, when pumping rates are low, appears to be contributing to storage facility mixing.

The two cells in Highland No. 1 and Lanpher Reservoir were found to be imbalanced with the east (smaller) cells turning over more quickly. For Lanpher Reservoir, the Phase II results showed improved balance between the cells, which was attributed to closing the east basin effluent sluice gate by 50 percent after Phase I. Since the Highland No. 1 Reservoir is connected by a spillway, mixing between the cells was anticipated. However, results from both phases showed that the Highland No. 1 Reservoir is operating as two independent cells.

Sediment in Highland No. 1 Reservoir may be encouraging mixing. The locations of the excess sediment are near the abandoned outlets and there is concern that removing the sediment may reopen dead-zones. The sediment should be removed because it decreases disinfectant residual, provides precursors for DBP formation, increases backwashing frequency at the membrane plant, and lowers the aesthetic appeal of the Highland No. 1 Reservoir.

Herron Hill Reservoir was determined to be an insignificant source of water quality degradation. The age of water exiting Herron Hill Reservoir is dependent of the percentage and age of water received directly form the plant and Highland No. 1 Reservoir. Herron Hill Reservoir is small and has a quick turn over, therefore, focus should be placed on reducing the water age from Highland No. 1 Reservoir.

The TTHM samples were used to evaluate the water quality deterioration with time. Although the formation of DBPs is dependant on multiple factors, listed in Section 1.3.3, it was found that as water age increases, TTHM concentrations increase. Sampling sites off of Highland No. 2 Reservoir, Lanpher Reservoir, Brashear Tanks, Allentown Tanks, McNaugher Reservoir/Spring Hill Tanks, Squirrel Hill Tanks and in Millvale Boro had T_{50} values exceeding 144 hours (6 days) and had TTHM concentrations which were approaching or greater than the MCL. The highest TTHM concentrations were in Reserve Twp., which is logical because it is at the farthest reach of the distribution system.

Closing the river-crossings allowed PWSA to increase control the Highland No. 2 and Lanpher Supersystem disinfectant residual by preventing water from changing directions and flowing back and fourth between the supersystems. Closing the river-crossings also appeared to have balanced the T_{50} values from the outlets of the Lanpher and Highland No. 2 Reservoirs

From the resulting data, the following distribution system operational approaches and facility improvements were identified as potential modes for the reduction of water age and improvement of water quality:

- Lowering tank elevations in the three primary reservoirs will decreased surplus storage and may increase turn over in the storage facilities. Also, lowering the tank elevations of some of the secondary storage facilities or taken one of the Brashear Tanks and/or Spring Hill Tanks out of service may improve water age at the far reaches of the distribution system and in Reserve Twp [Brandt, Clement et al., 2004];

- Moving more water (increase turnover) through Highland No. 1 Reservoir by increasing the capacity of the membrane plant;

- Altering water level variations and pump schedules [Brandt, Clement et al., 2004]; using modeling to in determining operational procedures to optimize age within, around, and at far reaches of the distribution system [Teefy, 1996];

- Increasing the influent momentum and mixing length during fill periods may increase mixing in reservoirs [Mahmood, Pimblett et al., 2005];

- Cleaning the primary reservoirs routinely and keeping contaminated water off the floating reservoir covers [AWWA and EES, 2002];

- Altering configuration of storage facilities to improve security and to minimize short-circuiting and dead-zoning. Facilities with a common inlet and outlet should be adjusted to assure that mixing is not just taking place near the inlet/outlet structure. Baffles or separate inlet and outlet may improve mixing conditions [Brandt, Clement et al., 2004]. Extending the outlets in Highland No. 1 Reservoir may decrease the potential for intentional contamination;

- Altering pressure network boundaries or installing time varying valves for flow control may allow more water to move through areas of the system [Brandt, Clement et al., 2004]. Opening up the pressure boundaries in the Lanpher Reservoir Supersystem, allowing the secondary storage facilities tanks to service the areas along the river (instead of flow directly from Lanpher Reservoir) may increase turnover in the Brashear, McNaugher Reservoir, and Spring Hill storage facilities by allowing water to flow through the looping system. However, more pumping would be required;

- Continuing to monitor the Lanpher Reservoir Basins effluent channels TTHM concentrations will allow the effluent sluice gate to be further adjusted to balance the water age in the basins;

- Adjusting the east effluent gate of the Highland No. 1 Reservoir basin may provide the same improvement of water age balance which was achieved at Lanpher Reservoir;

- Adding flow meters to the influent and effluents of the reservoirs will allow for the verification of exactly how much flow is moving through the storage facilities;

- Developing a manual and/or automated flushing and valve exercising program will move old water through the system and help clean out the distribution system to reduce DBP formation [Brandt, Clement et al., 2004];

Implementing operational changes to the PWSA distribution system will allow PWSA to decrease water age and thereby reduce DBP formation to meet the Stage 2 DBPR. Further modeling work and tracer studies may be useful in determining which one, or combination of distribution system operational changes that PWSA should implement.

5.0 RECOMMENDATIONS FOR FUTURE STUDIES

The PWSA distribution system is very complex with many components that are not fully understood. The fluoride tracer study conducted for this research has provided insight into the water age, mixing, and flow patterns within parts of the distribution system. However, there are still many unknowns to be studied and there are multiple technologies and operational strategies that may be utilized to improve the PWSA distribution system including:

- ➢ A System Optimization Study may be completed to determine how to operate the PWSA distribution system to provide quality water in a cost effective manner. Components of the System Optimization Study may include:
    - Using the AwwaRF Managing Distribution Retention Time to Improve Water Quality-Phase II Guidance Manual [Brandt, Powell et al., 2006] which includes a spreadsheet for calculating the turnover and retention time in storage tanks;
    - Using the PWSA existing hydraulic modeling to determine the amount of water level variation needed in the storage facilities. As discussed in the SCCRWA case study [Teefy, 1996] , decreasing the amount of fluctuation in water levels increases the age of water in and around the storage facility, but there is less spread of old water through the system. Whereas, if water level fluctuations are increased, the water age decreases in and around the storage facility and there is an increase of old water spread through the system. Therefore, a balance must be found to determine how the water levels should be fluctuated;

- Using the PWSA hydraulic modeling to determine the effects of change of pressure district boundaries, the effects of tanking a Brashear and/or Spring Hill Tank, and the effects of lowering the maximum operating water level in some of the storage facilities;

- Further developing the PWSA hydraulic model to perform water quality analysis to evaluated the effects have having the river-crossing open or closed on maintaining chlorine residual, in addition to a hydraulic analysis looking at how the river-crossings increase or decrease water age. If the river-crossings are reopened in the future, the PWSA hydraulic model may be used to determine optimum operational procedure from the Highland No. 2 and Lanpher Reservoirs to assure that more storage facilities are being utilized. The solution may be somewhere in between. The orientation of river-crossings may need to be changed to opened or closed based on how the system is operating.

- Complete a further analysis of TTHM formation within the distribution system, including the optimization of the chlorine booster stations;

- Further evaluating the balance of the Lanpher and Highland No. 1 Reservoir basins. TTHM samples should be collected from the effluent and the effluent gates should be adjusted accordingly;

- Further analyzing Highland No. 2 Reservoir to see if baffles should be removed. Mixing conditions are preferred since it is easier to achieve mixing than plug flow conditions [Kirmeyer, Friedman et al., 2005];

- Evaluating if increased turbulent jet entry, different inlet and outlet orientation, or a mechanical mixing source is needed to increase mixing in storage facilities;

- Develop a reservoir cleaning and inspection program [AWWA and EES, 2002]. Prior to cleaning highland No. 1 Reservoir, complete a full hydraulic analysis to see if removing sediment will increase dead-zoning and short circuiting. Also, review if reopening the abandoned outlets would improved mixing in Highland

No. 1 Reservoir and reduce sediment accumulation in these areas or if the outlets should be moved into the center of the reservoir for security purposes;

- Gaining a better understand of the existing capacity of the primary reservoirs is needed for modeling and water quality purposes. If the reservoirs are going to continue operating "as is", then sediment volume estimates should be determined, as described in Section 3.2.1.1.

➢ Running additional tracer studies or developing a model, such as a compartment model, for each reservoir instead of using the assumption that they are CSTRs, to improve the representation of storage facility behavior. A one, two, or three compartment model, discussed by Clark et al. [Clark, Abdesaken et al., 1996], can be developed to accounts for different mixing zones. For example, a three compartment model can account for short-circuiting zones between the inlet and outlet and the dead-zones, which invalidate the CSTR assumption.

➢ Using GIS software to conduct further analysis of the fluoride samples that were collected over the surface of the three primary reservoirs for mixing regimes.

➢ Developing CFD models and conduct study similar to Mahmood et al. [2005] to evaluate how well water inside the storage facilities is being utilized.

APPENDIX A

FLUORIDE TRACER STUDY RESPONSE CURVES

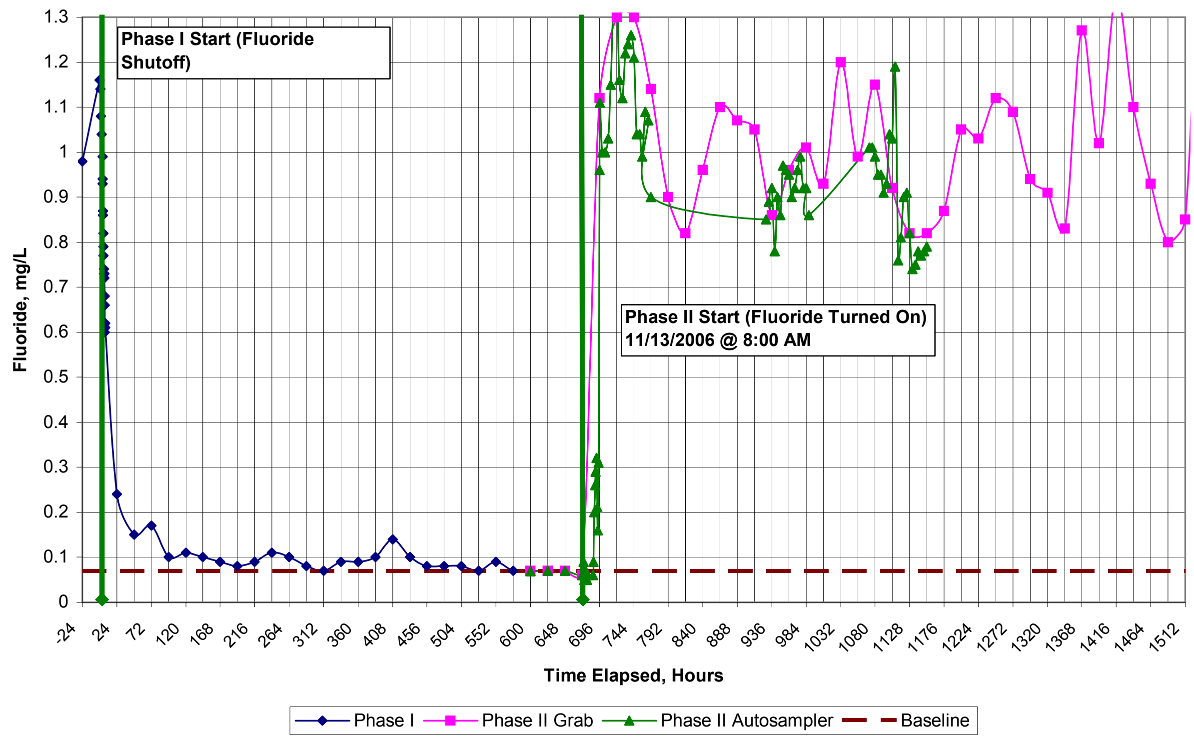

Figure 51. Site W01 - Clearwell tracer response curves.

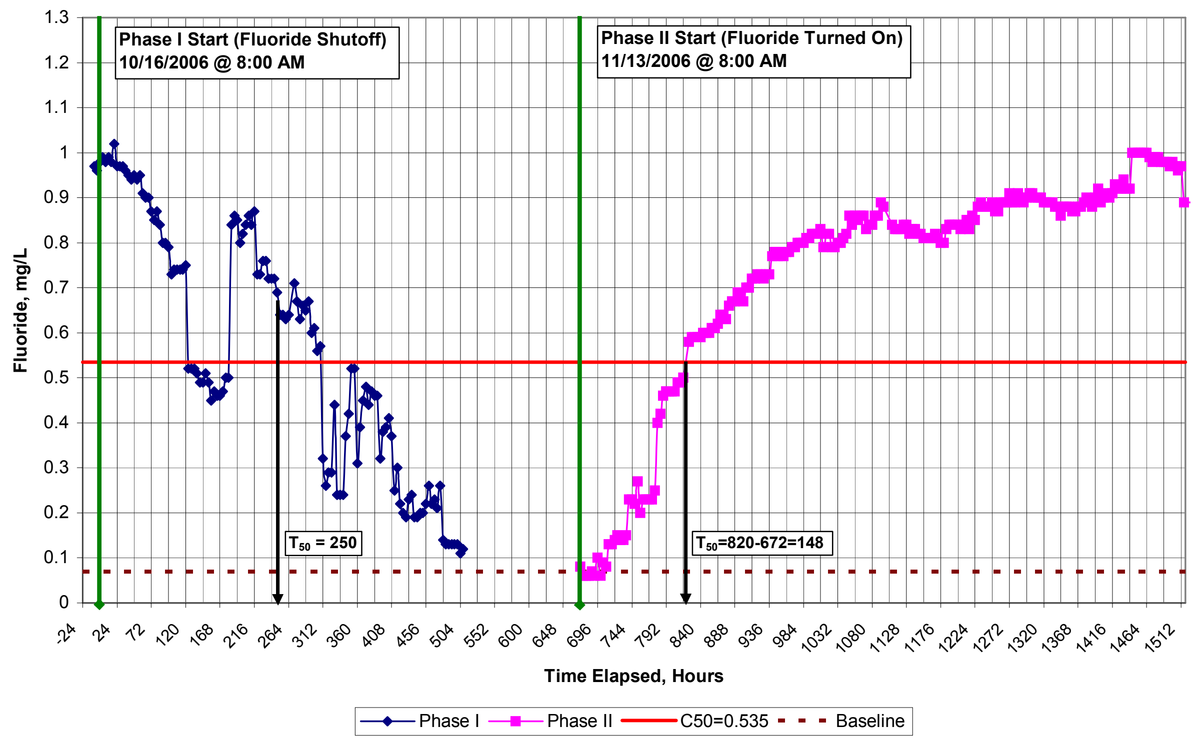

Figure 52. Site A01 - Lanpher Reservoir east effluent tracer response curves.

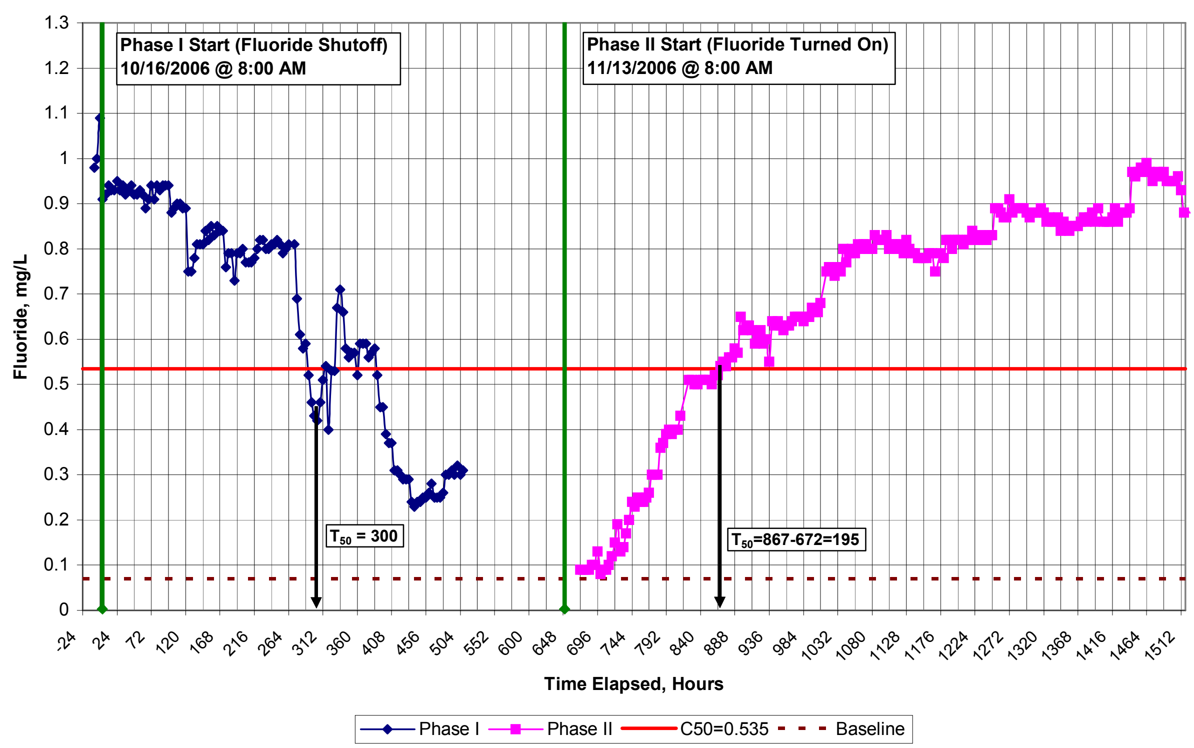

Figure 53. Site A02 - Lanpher Reservoir west effluent tracer response curves.

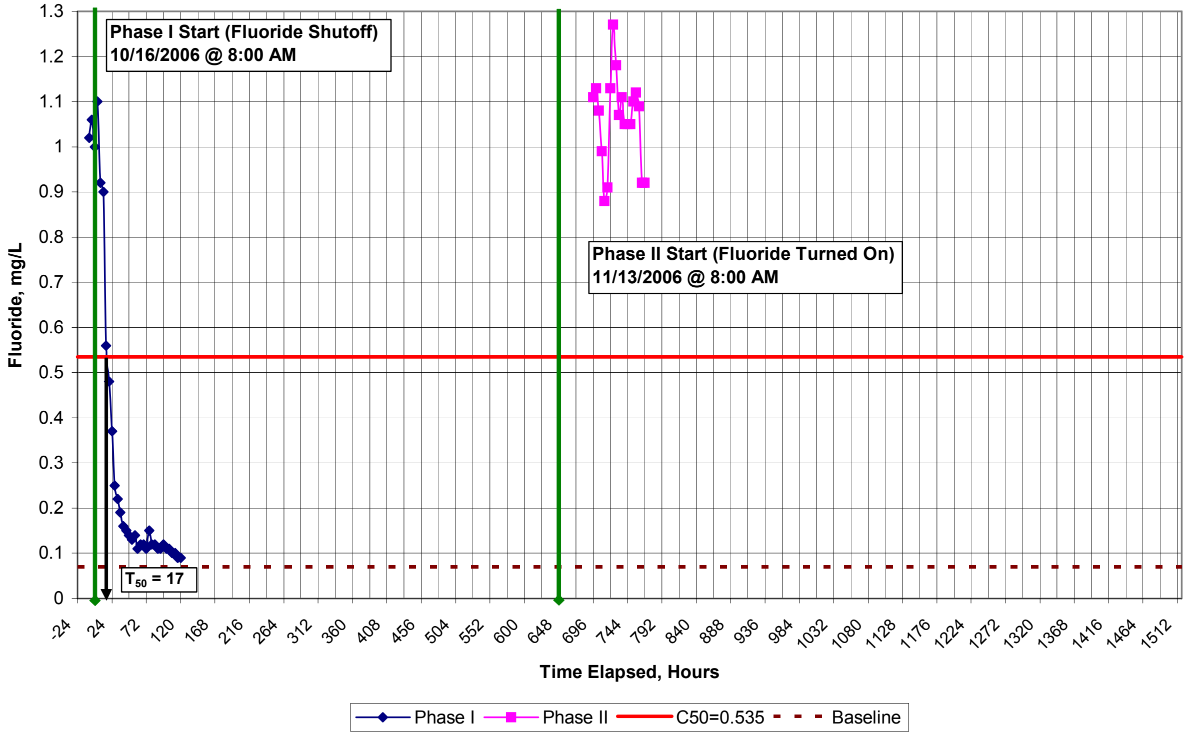

Figure 54. Site A03 - Lanpher Reservoir influent fluoride tracer response curves.

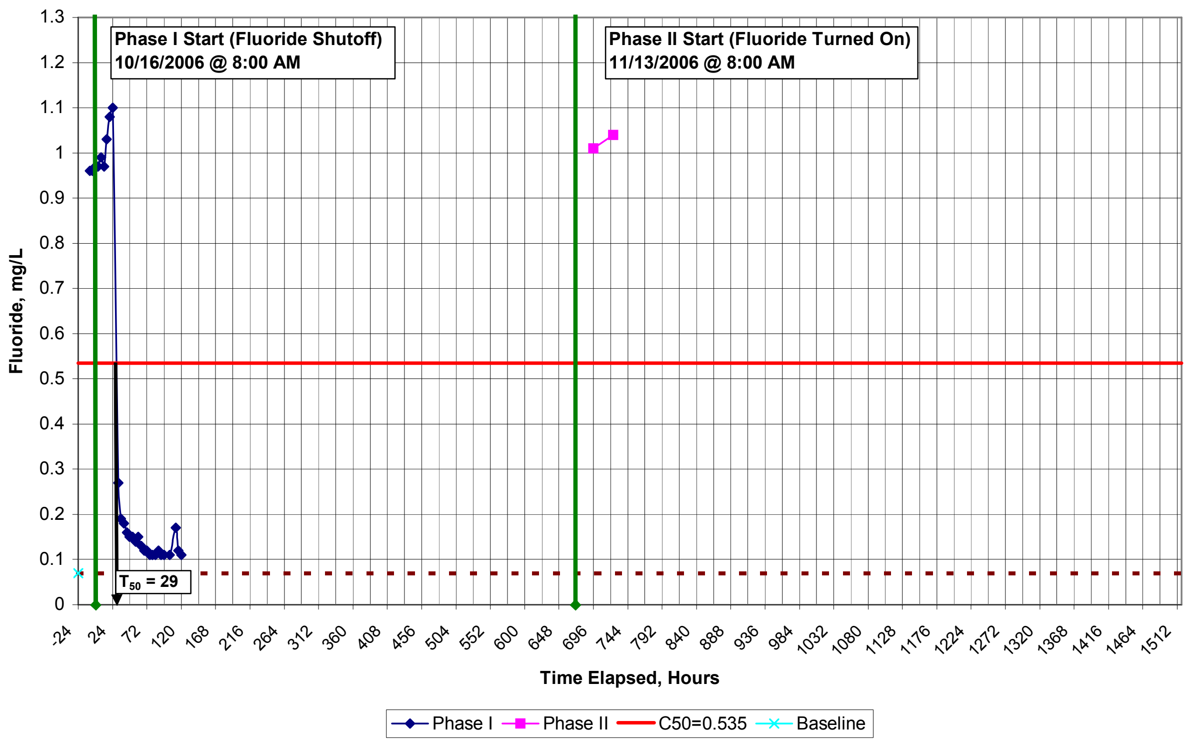

Figure 55. Site A04 - Bruecken Pump Station (Highland No. 1 Reservoir influent) tracer response curves.

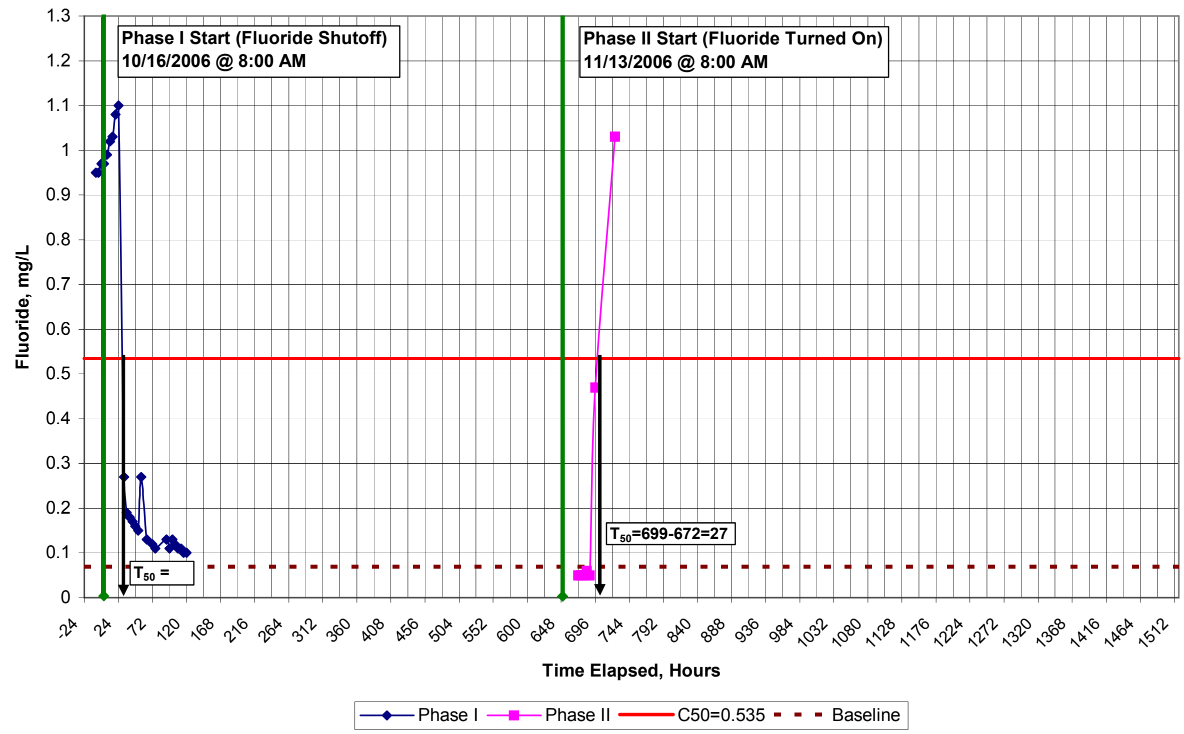

Figure 56. Site A05 - Bruecken Pump Station (Highland No. 2 Reservoir Influent) tracer response curves.

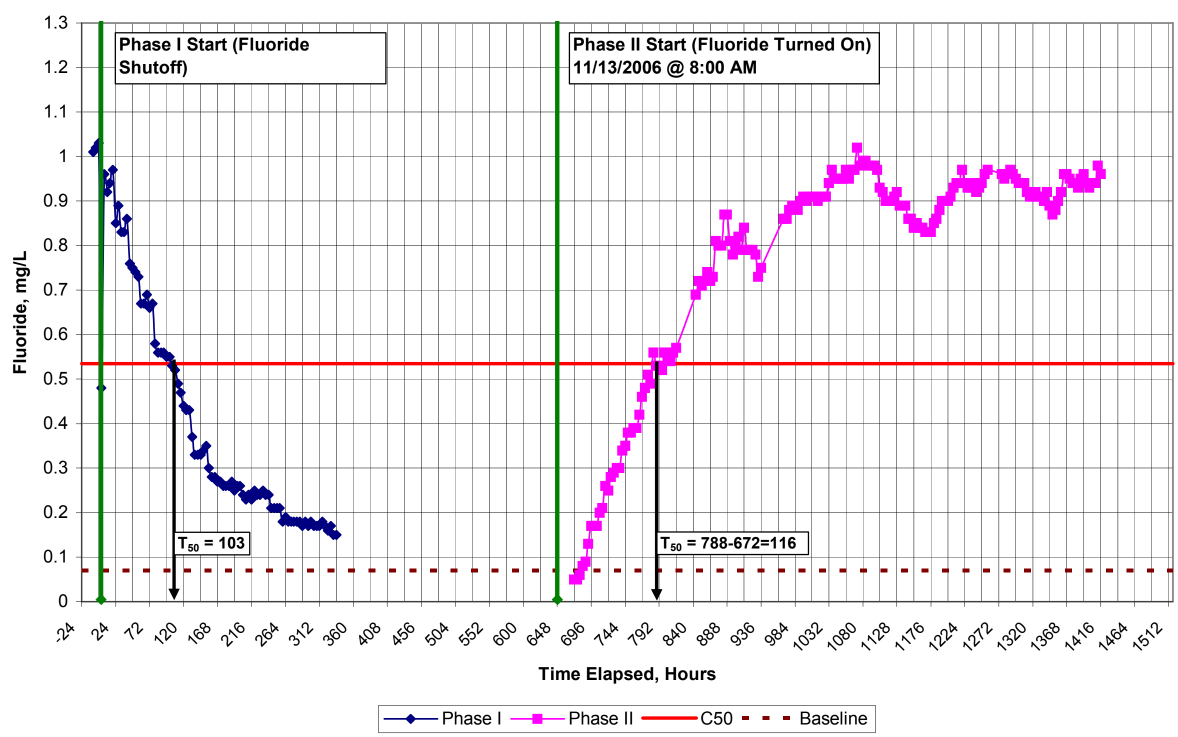

Figure 57. Site A06 - Highland No. 1 Reservoir tracer response curves.

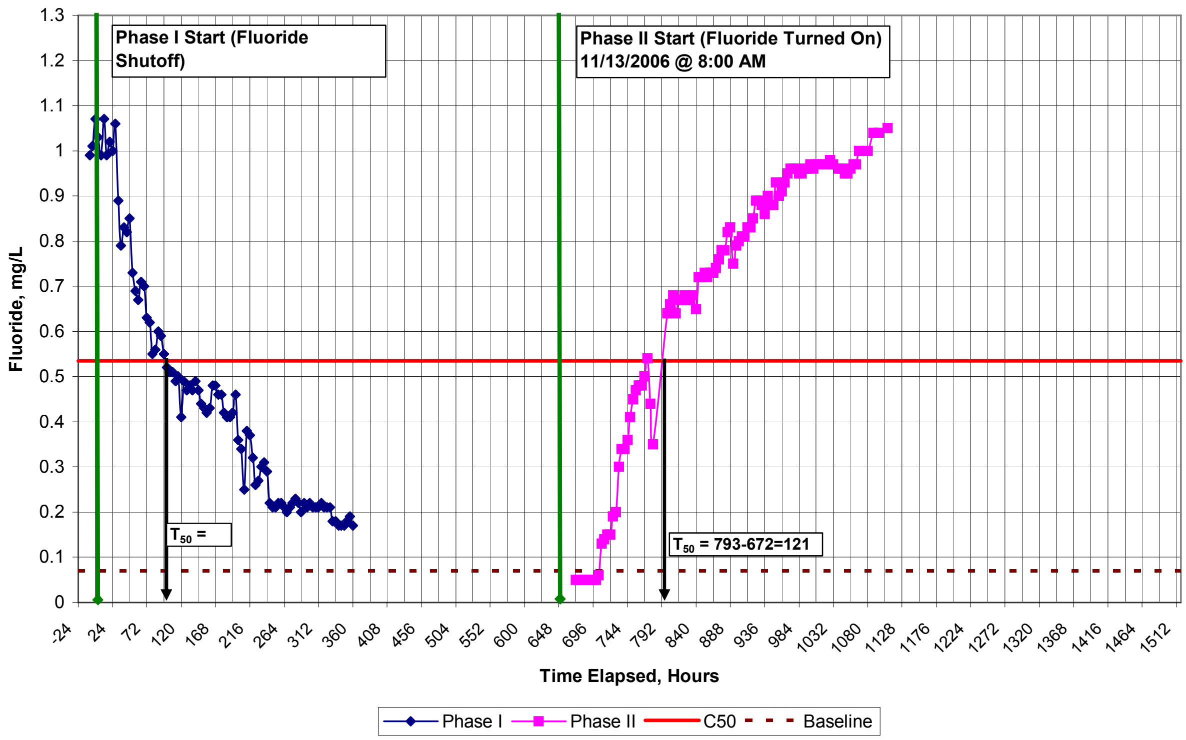

Figure 58. Site A07 - Highland No. 2 Reservoir effluent tracer response curves.

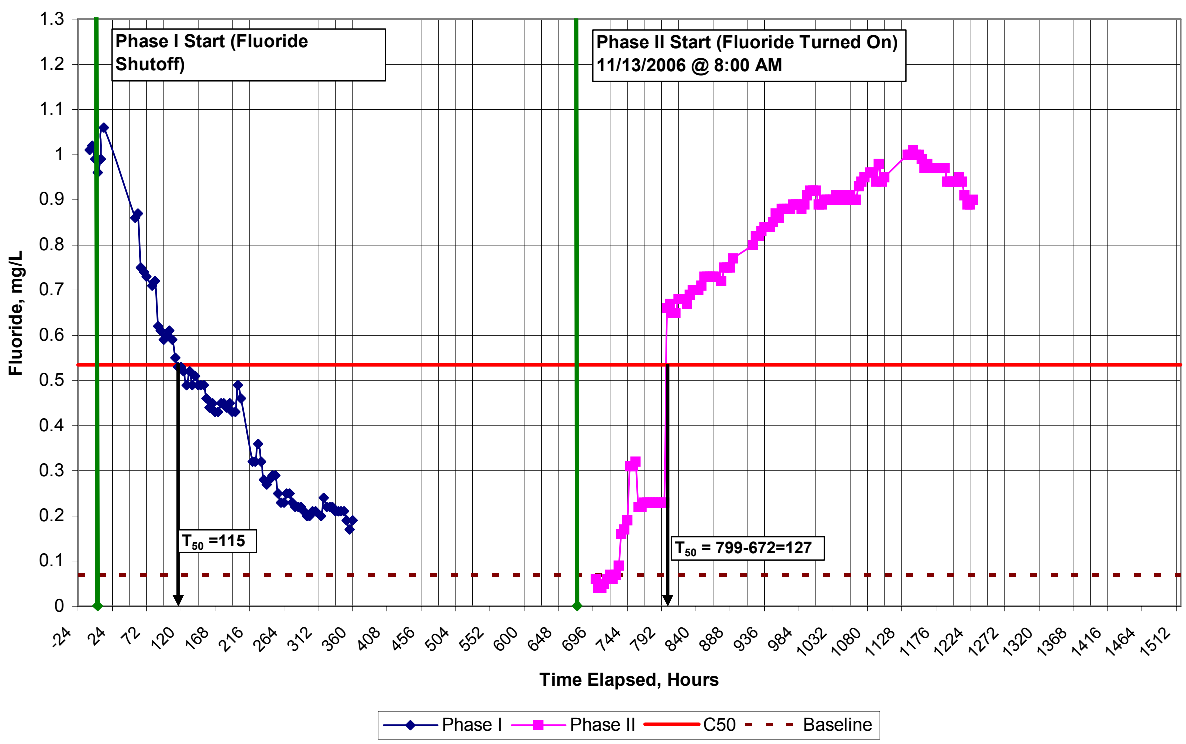

Figure 59. Site A09 - Mission Pump Station Tracer Response Curves

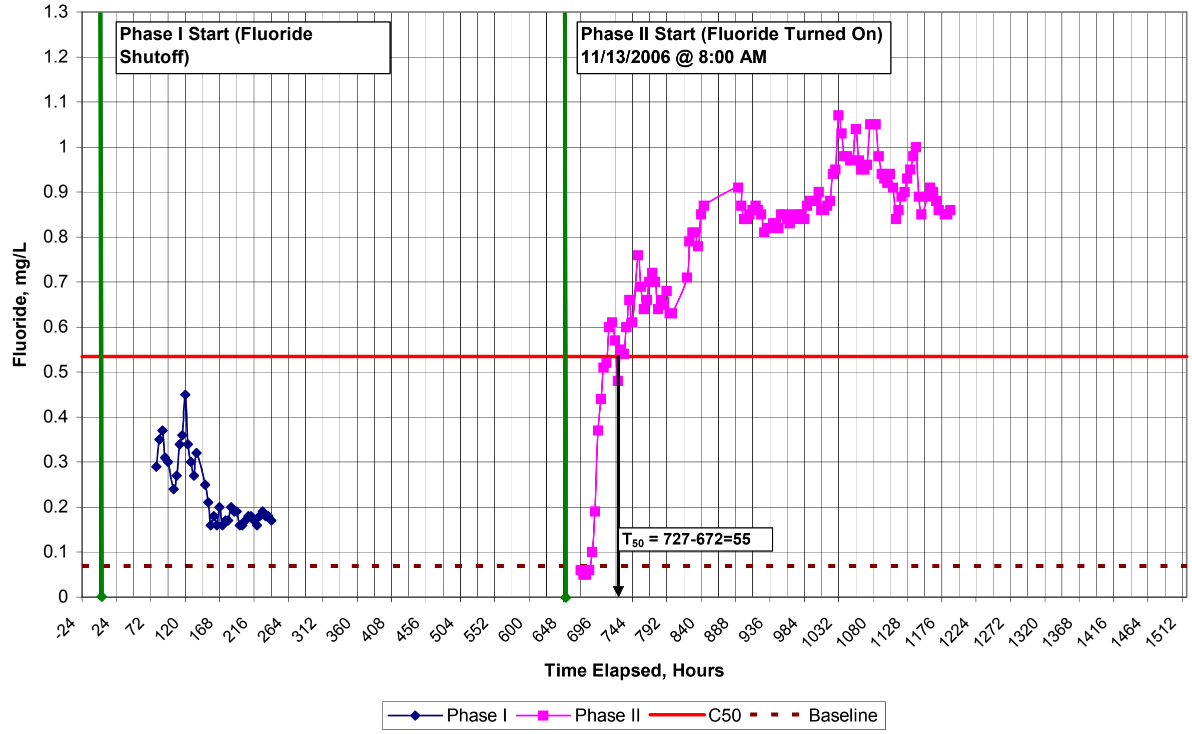

Figure 60. Site A10 - Herron Hill Reservoir influent tracer response curves.

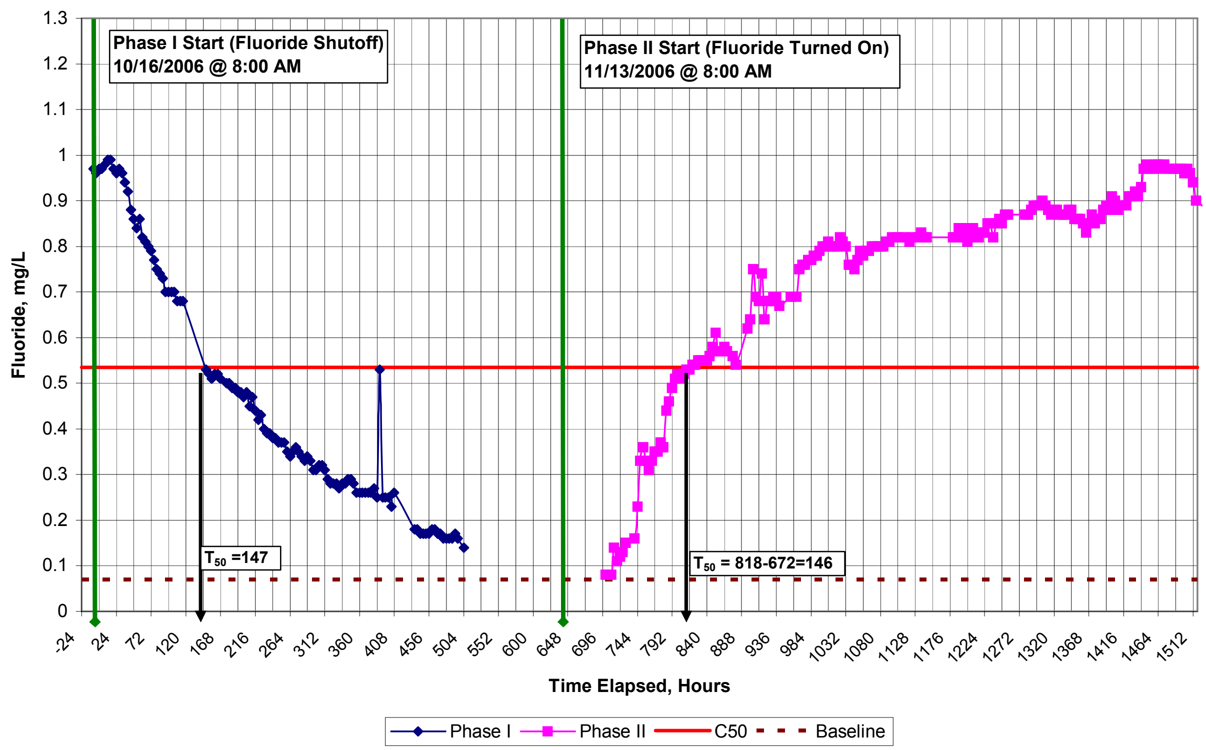

Figure 61. Site A08 - Howard Pump Station tracer response curves.

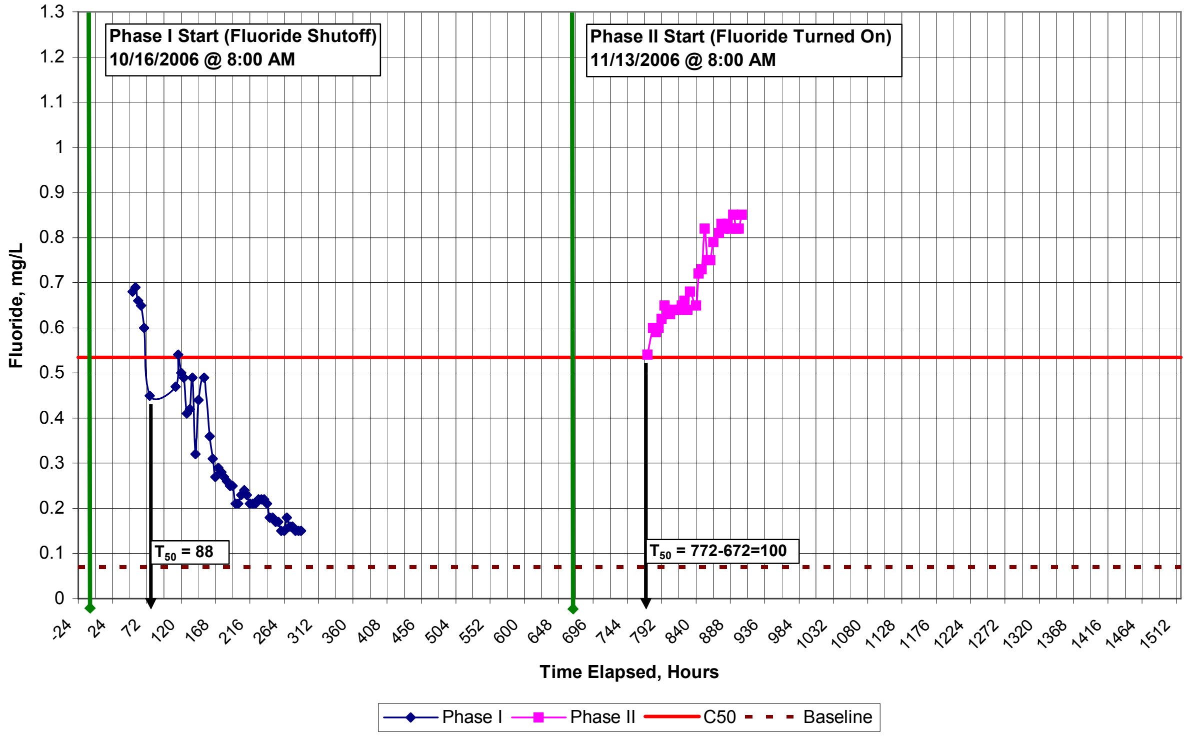

Figure 62. Site A11 - Herron Hill Reservoir effluent tracer response curves.

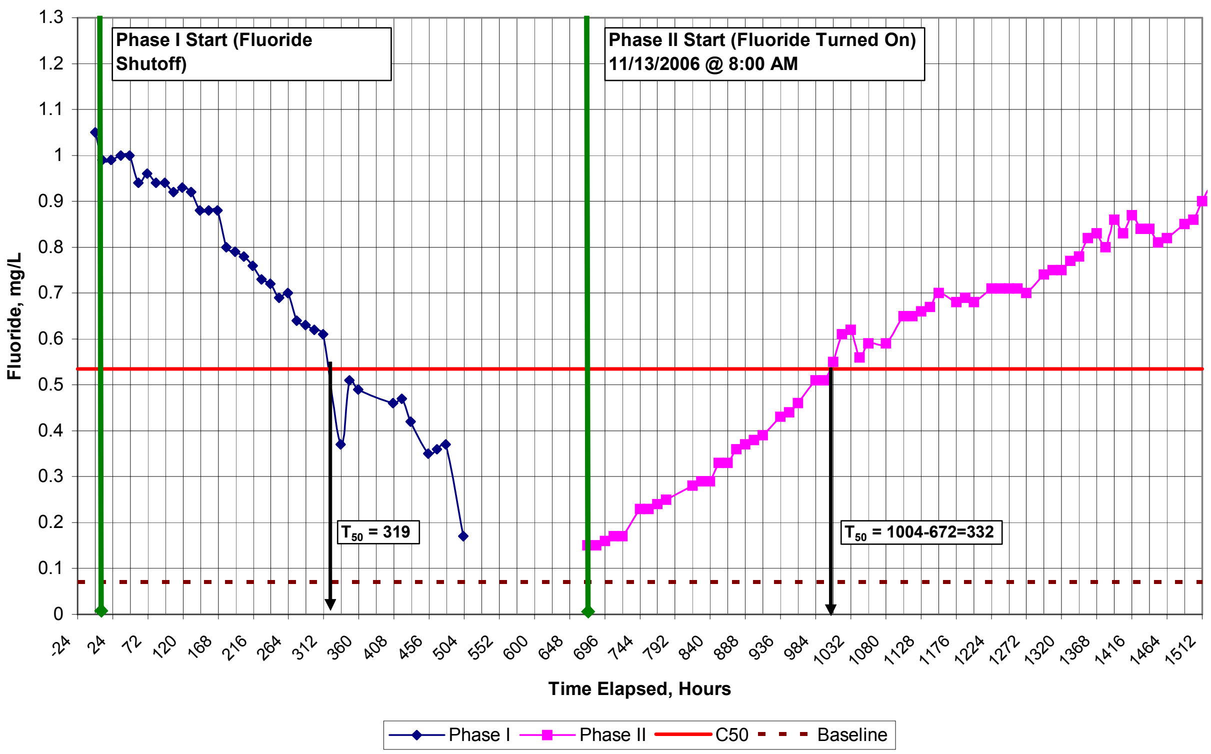

Figure 63. Site P01 - 27 Perryview Avenue tracer response curves.

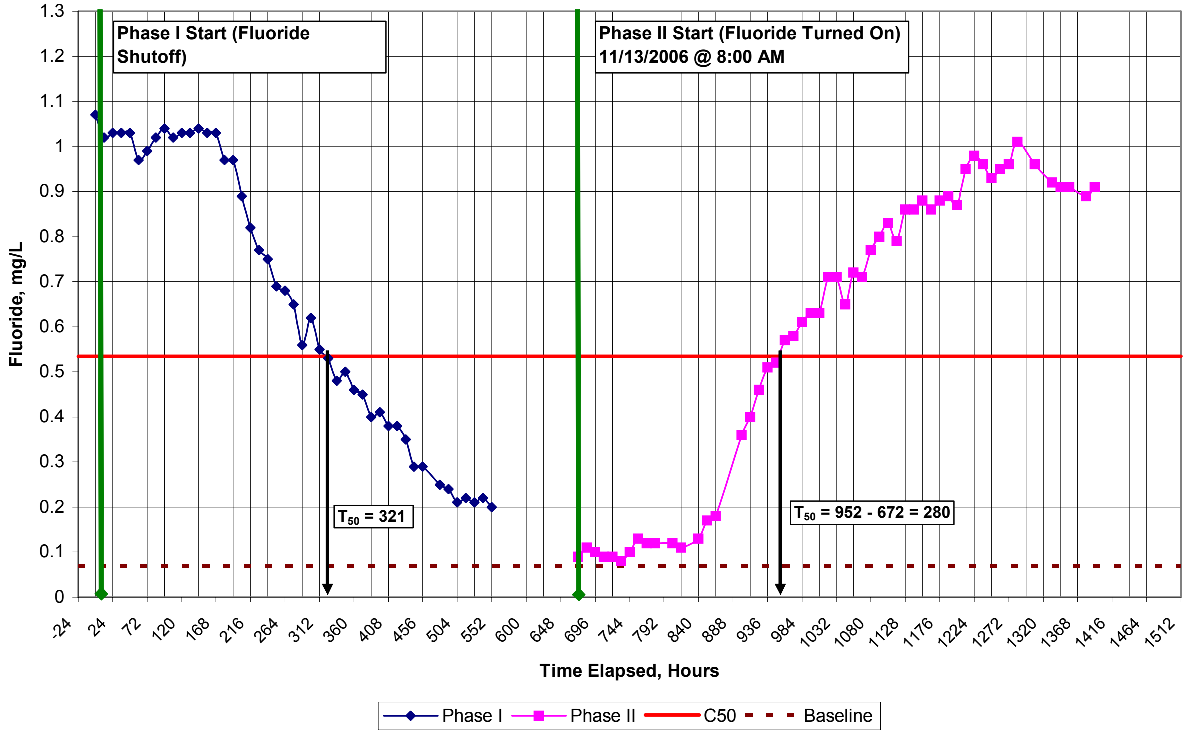

Figure 64. Site P02 - 3133 Brunot Avenue tracer response curves.

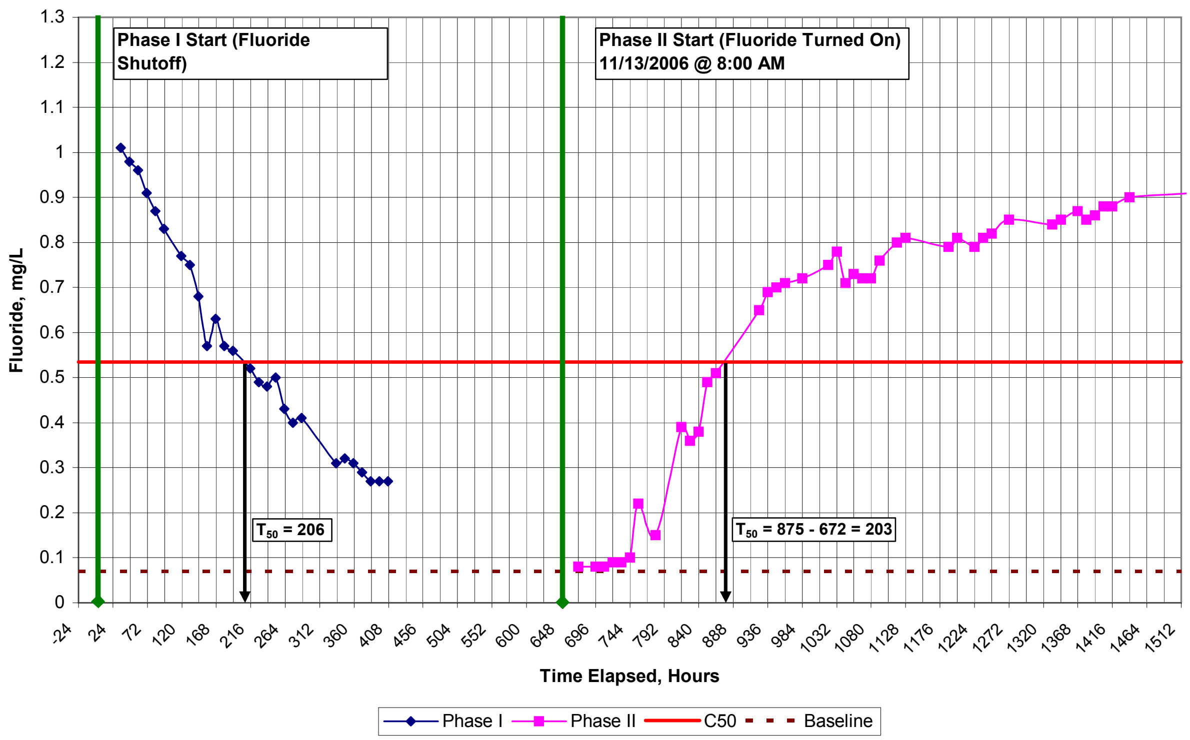

Figure 65. Site P03 - 1114 Colfax Street tracer response curves.

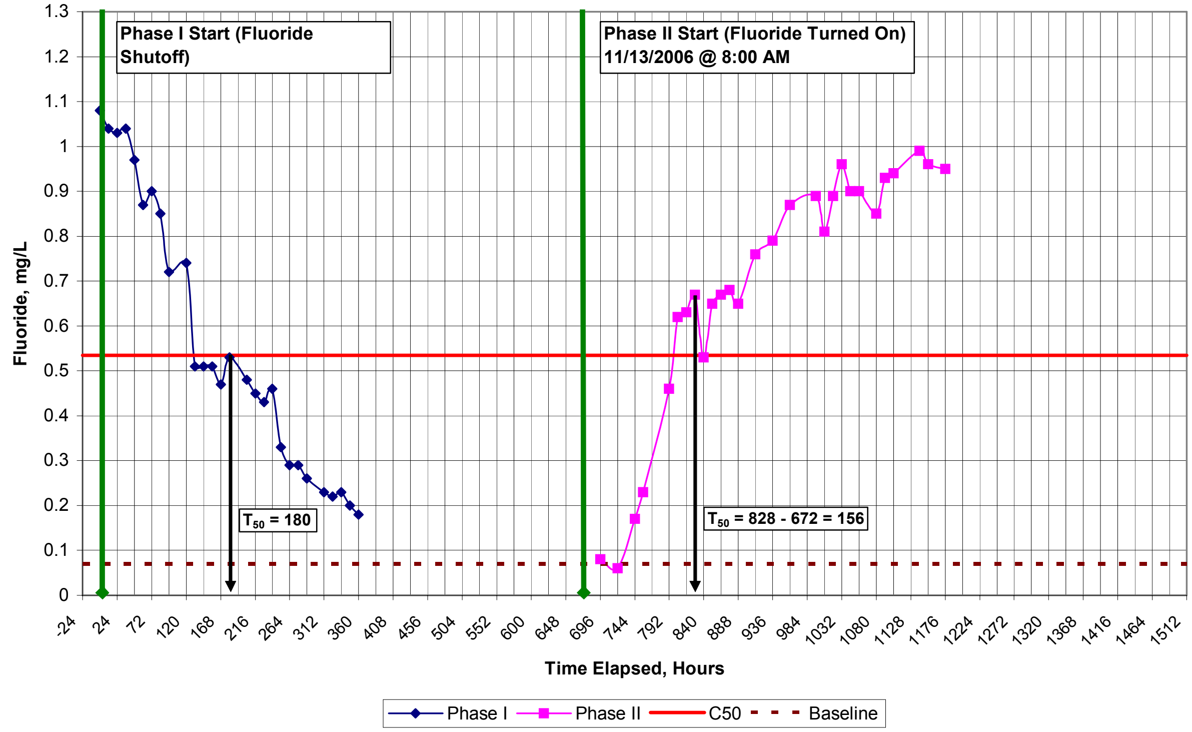

Figure 66. Site P04 - 6433 Forward Avenue tracer response curves.

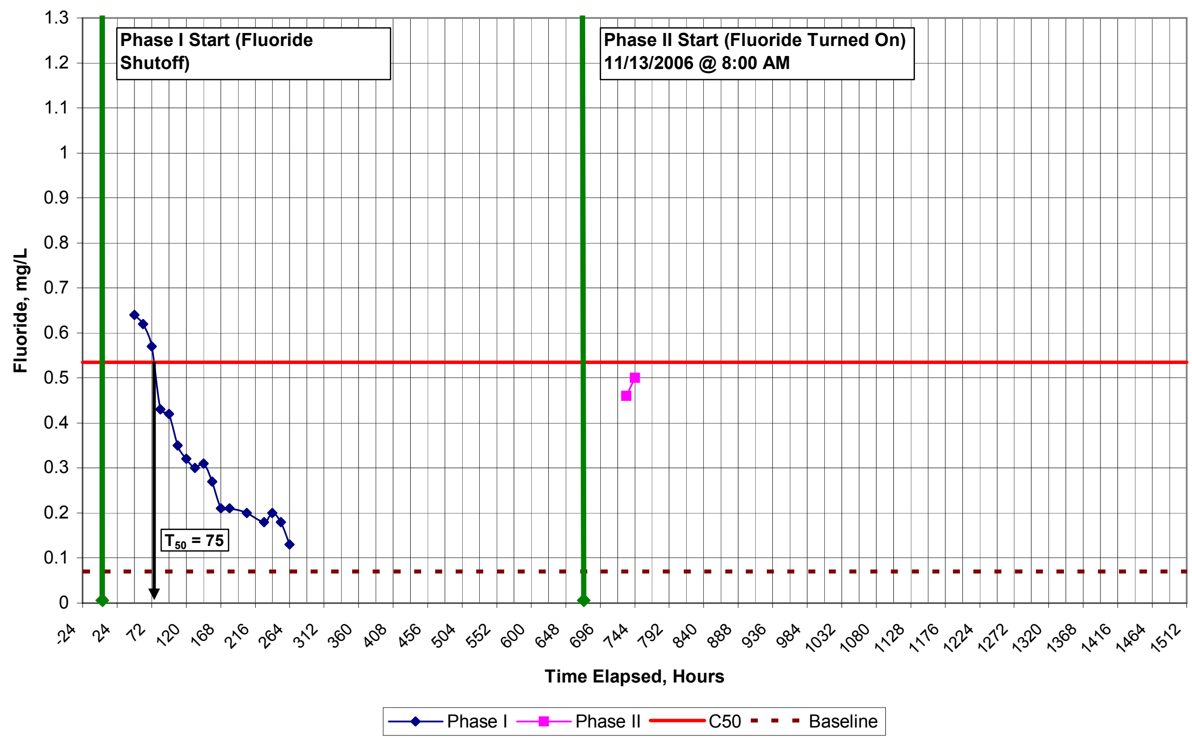

Figure 67. Site P05 - 5838 Darlington Road tracer response curves.

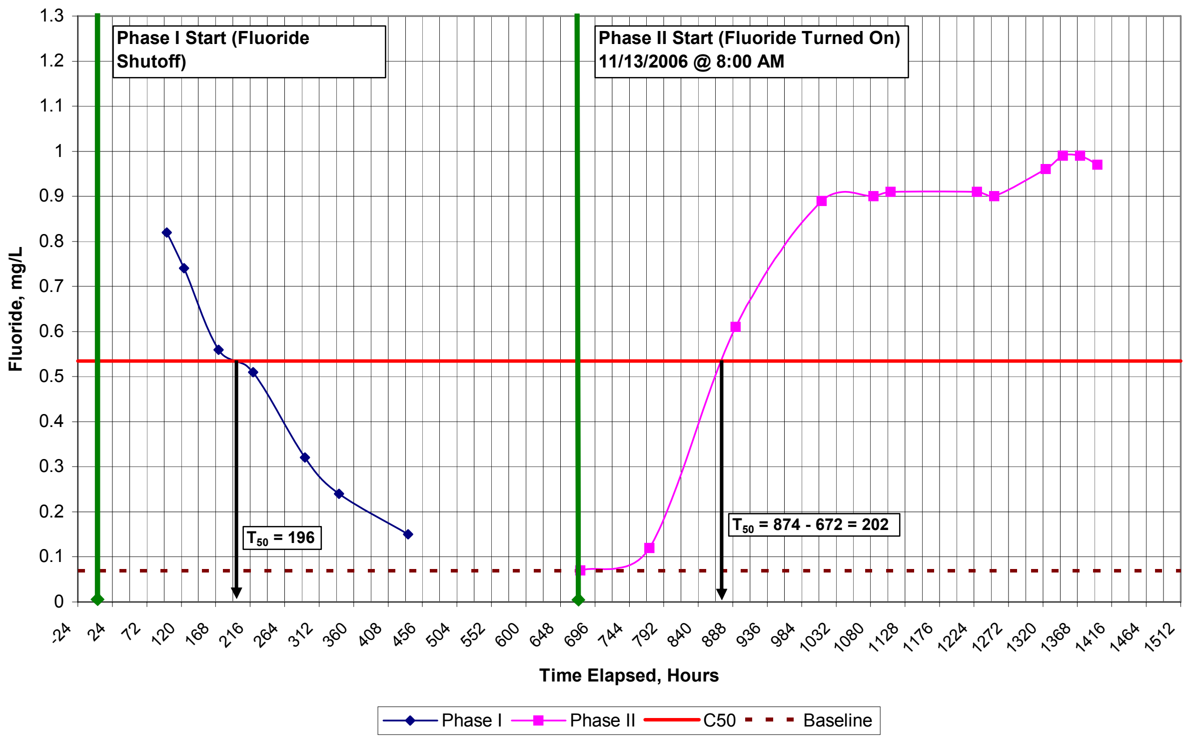

Figure 68. Site H01 - Hydrant 1(401 Well Street) tracer response curves.

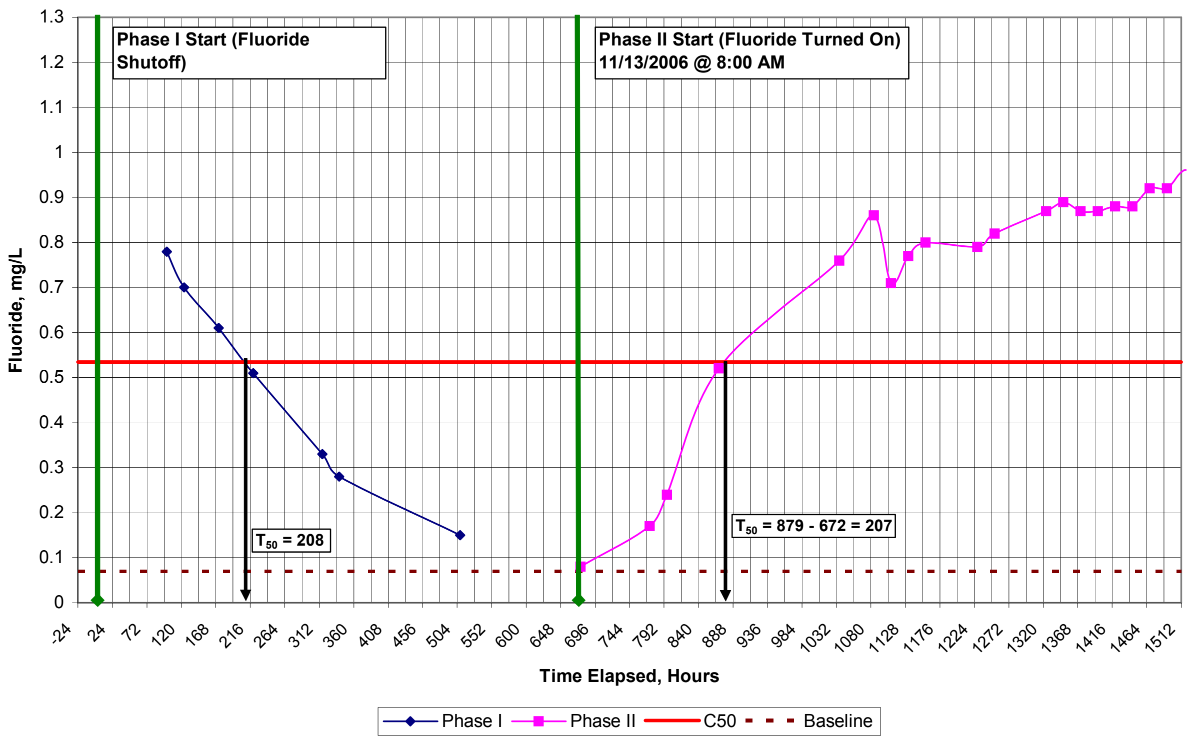

Figure 69. Site H02 - Hydrant 2 (1713 Brighton Road) tracer response curves.

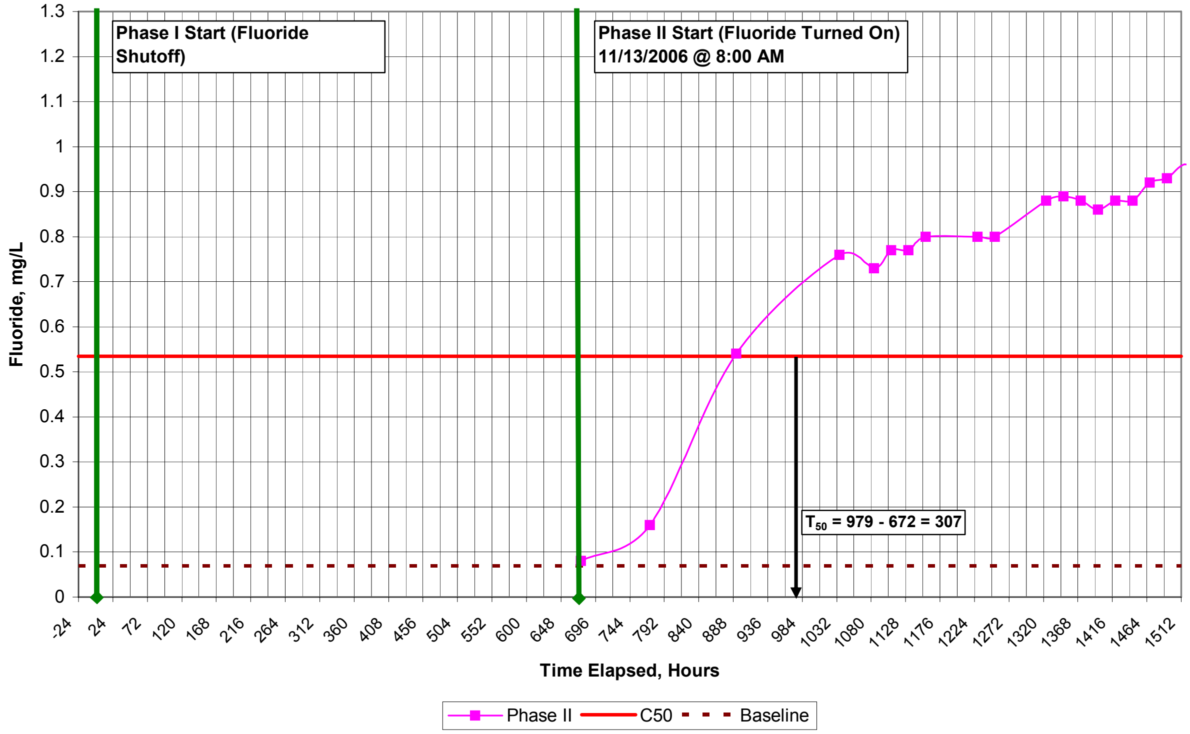

Figure 70. Site H03 - Hydrant 3 (Termon Avenue) tracer response curves.

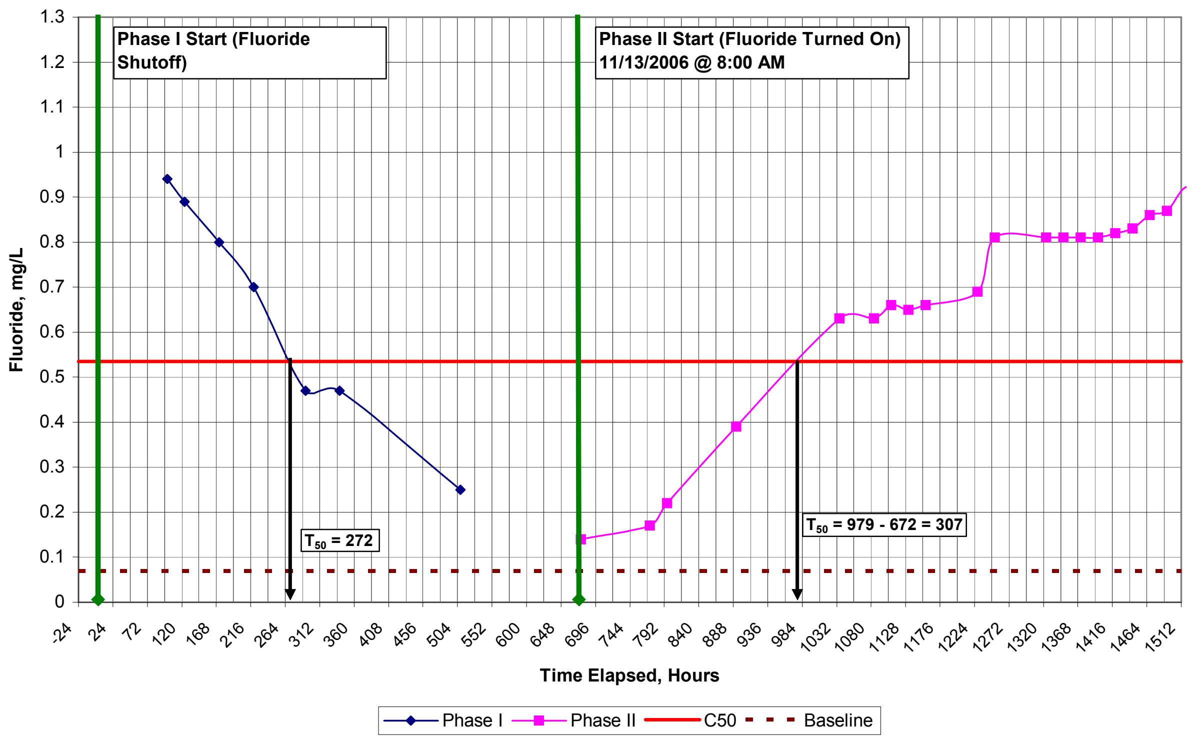

Figure 71. Site H04 - Hydrant 4 (4260 Evergreen Road) tracer response curves.

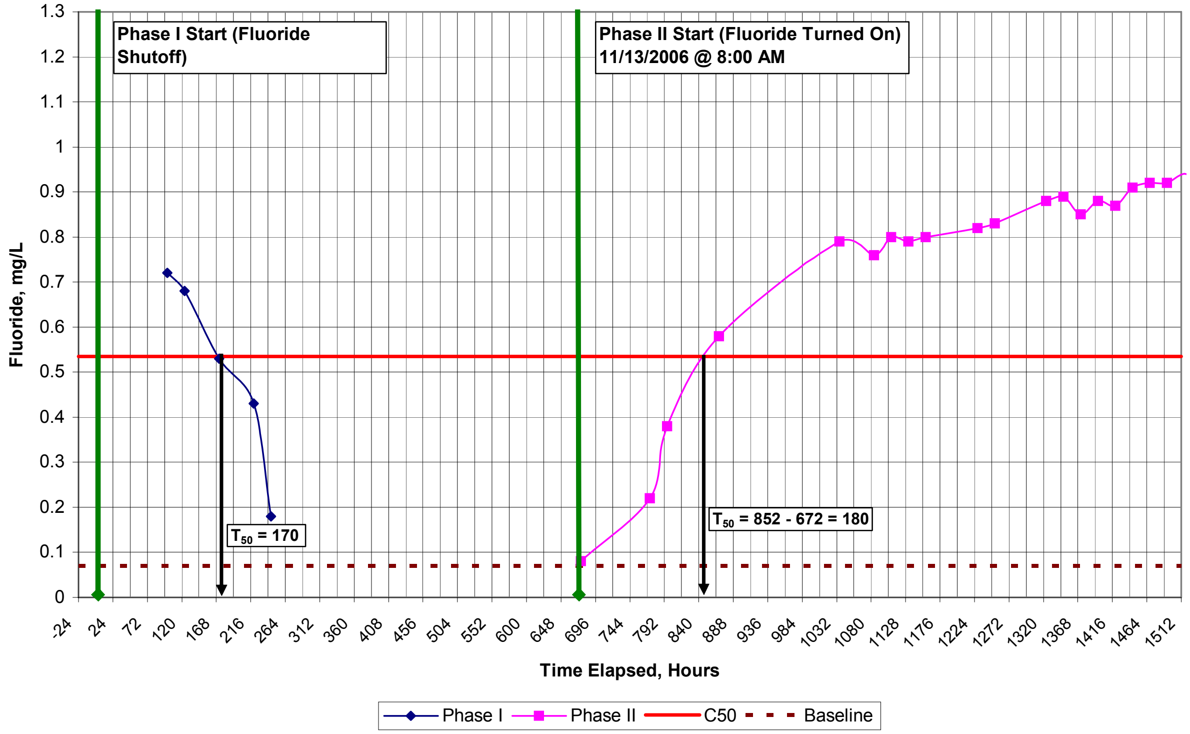

Figure 72. Site H05 - Hydrant 5 (Perrysville & Ivory Avenue) tracer response curves.

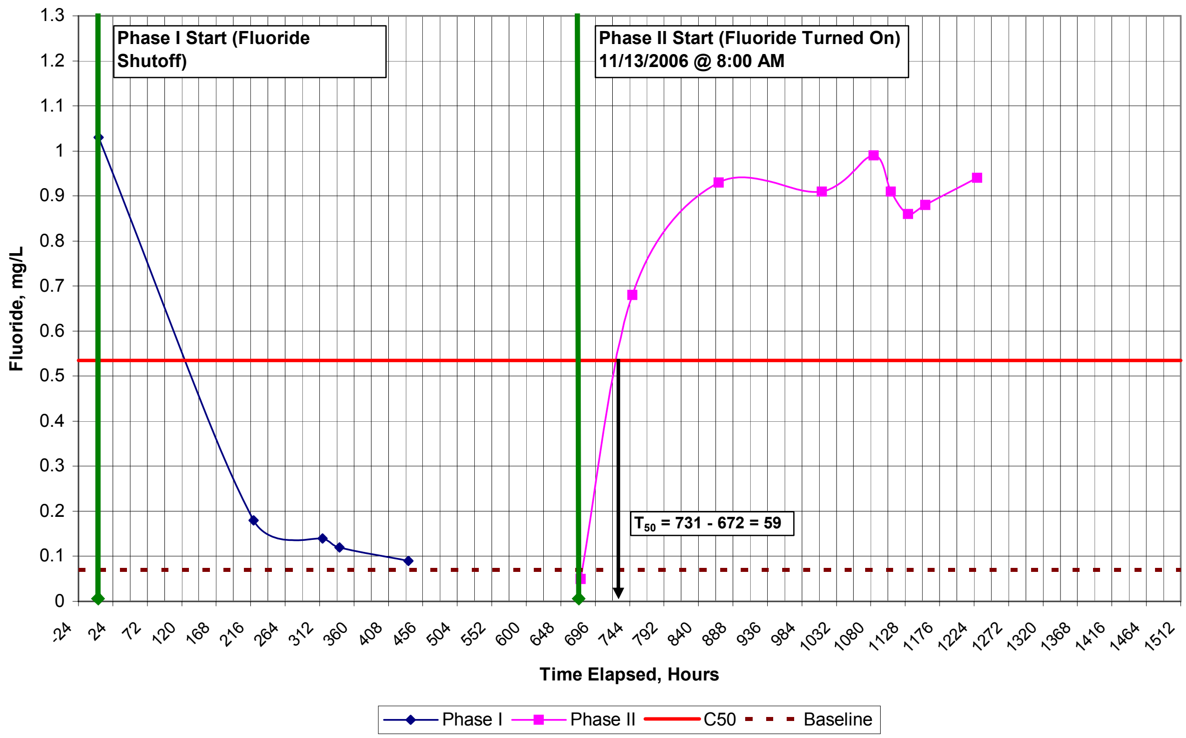

Figure 73. Site H06 - Hydrant 6 (Penn Ave., between 39th & 40th St.) tracer response curves.

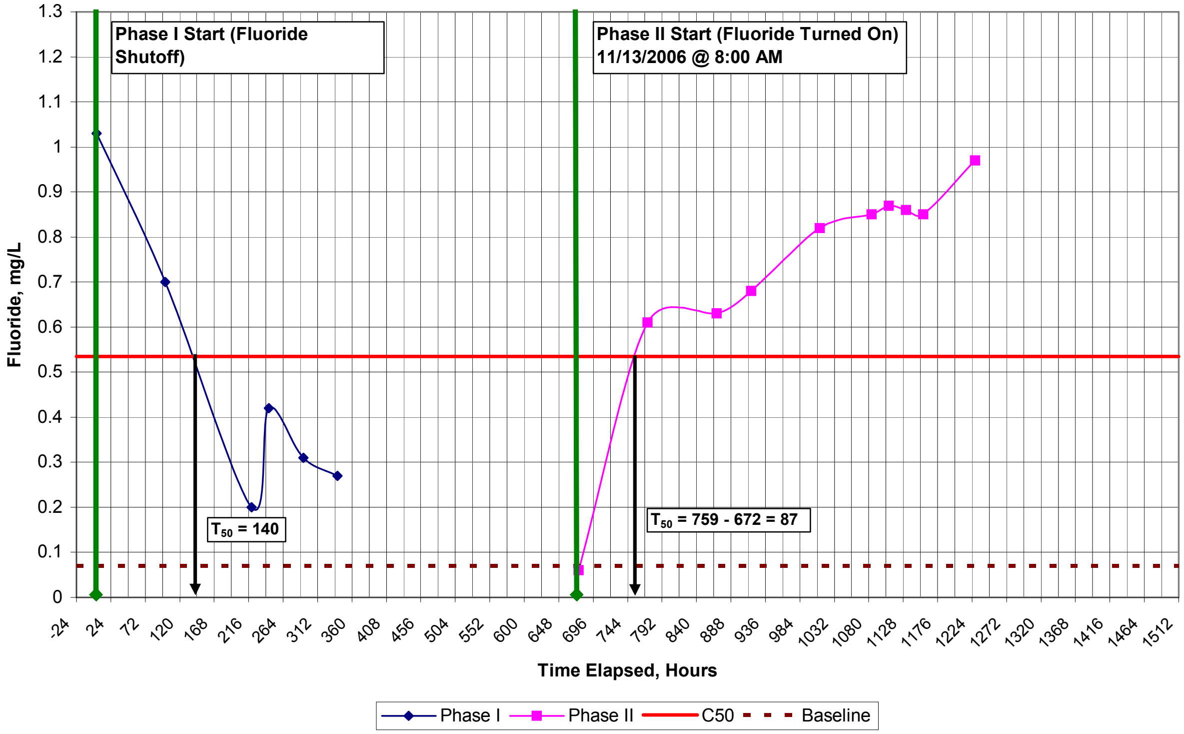

Figure 74. Site H07 - Hydrant 7 (Lincoln & Joshua Street) tracer response curves.

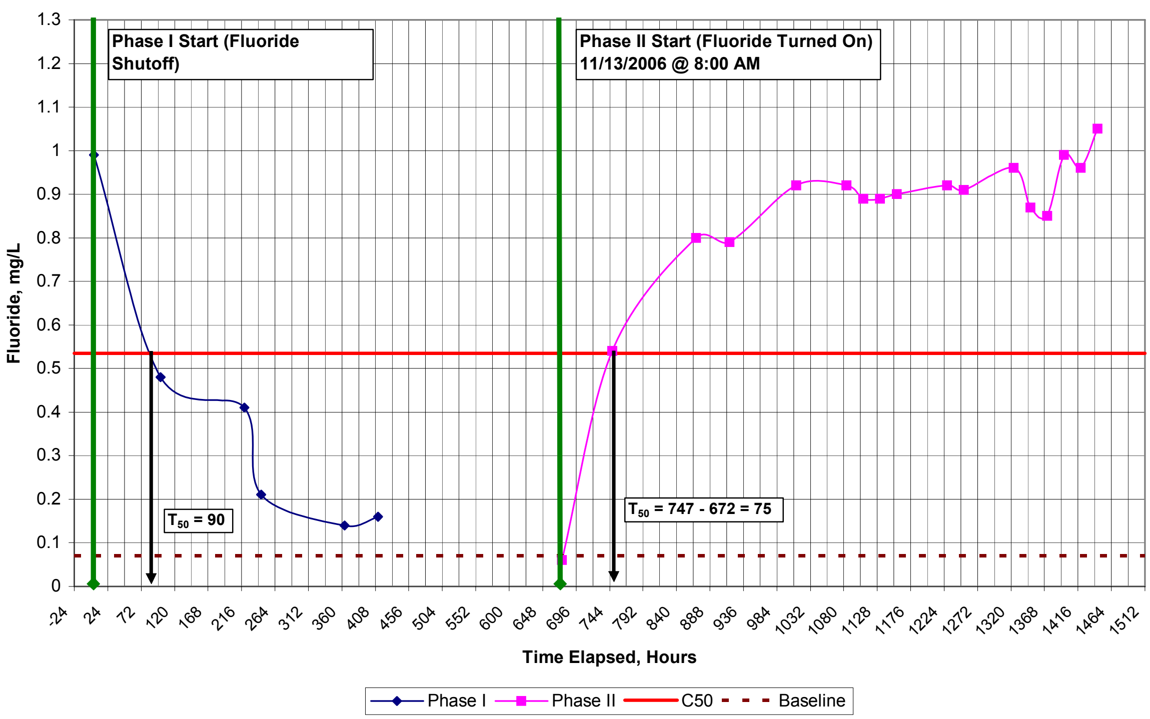

Figure 75. Site H08 - Hydrant 8 (Love St., first hydrant on left off Whipple St.) tracer response curves.

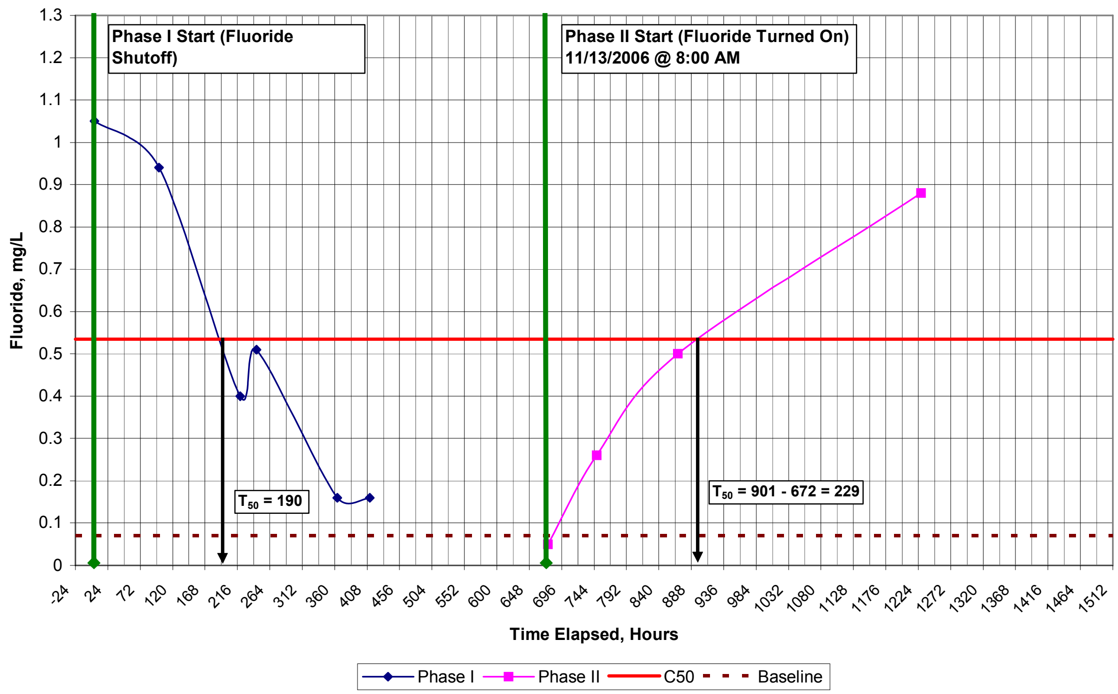

Figure 76. Site H09 - Hydrant 9 (Bigelow St. & Tesla St.) tracer response curves.

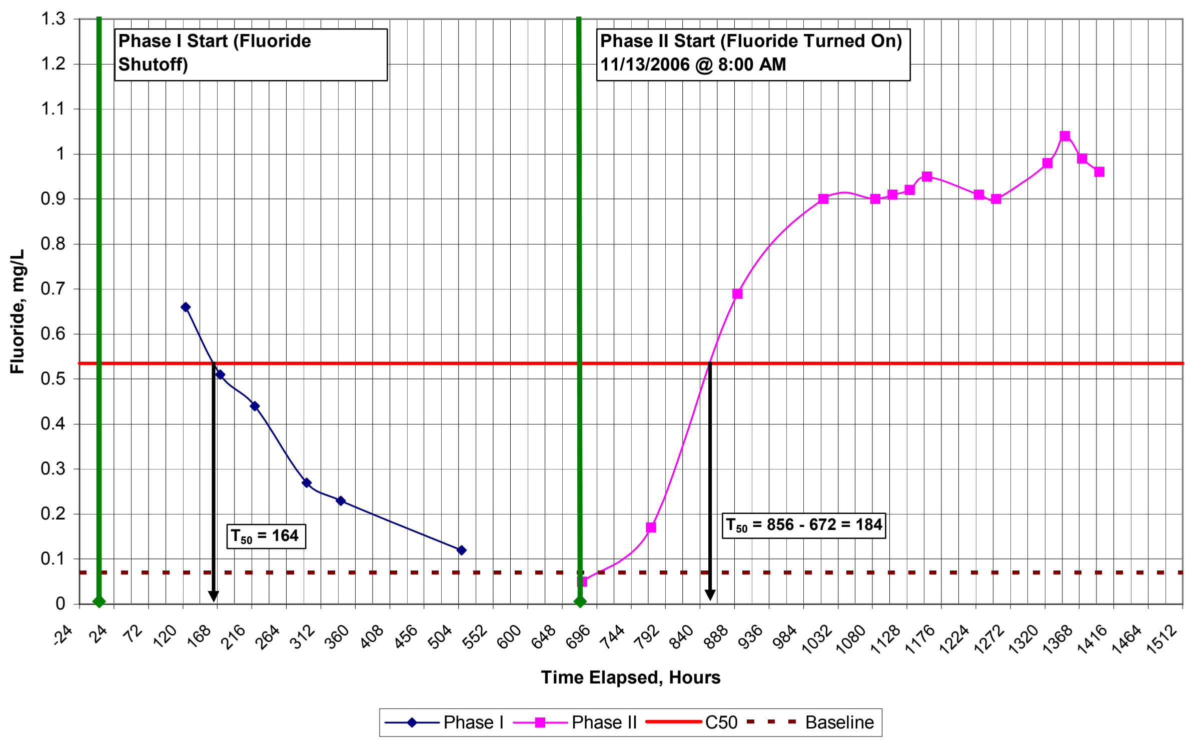

Figure 77. Site H10 - Hydrant 10 (Chartiers & Lorenz Street) tracer response curves.

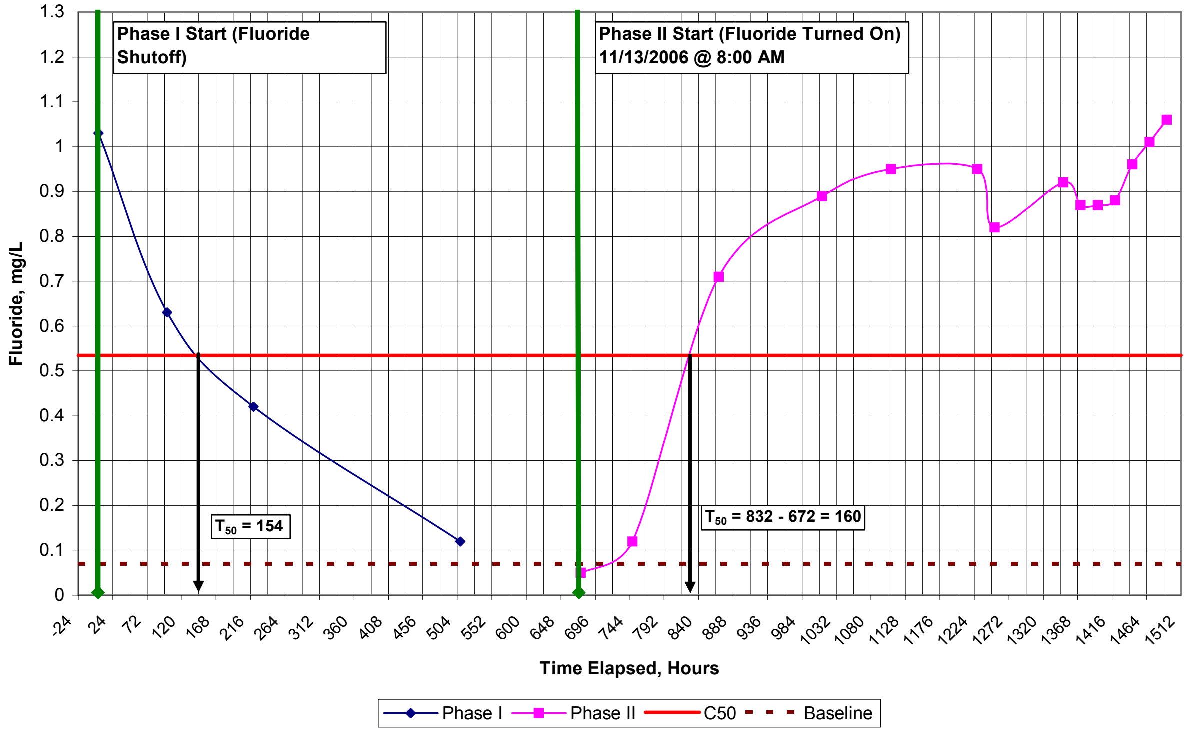

Figure 78. Site H11 - Hydrant 11 (Mon Warf Parking Lot) tracer response curves.

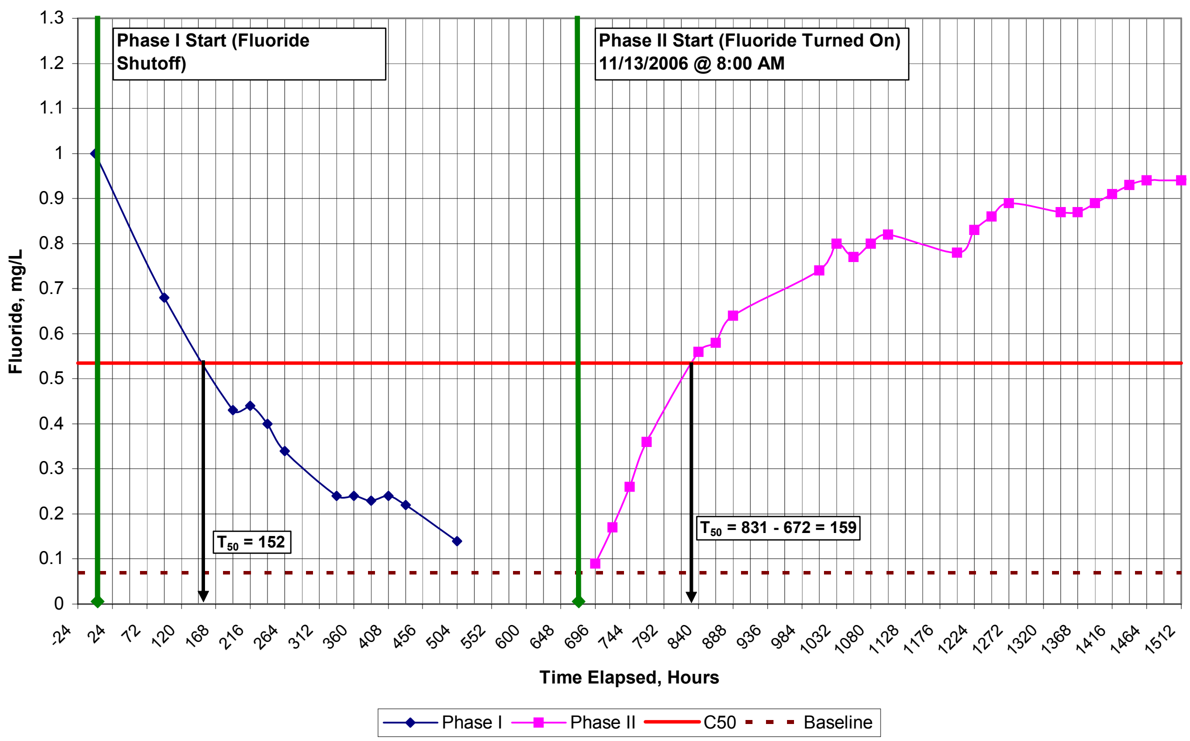

Figure 79. Site M01 - 114 Grant Avenue, Grant's Bar (Millvale) tracer response curves.

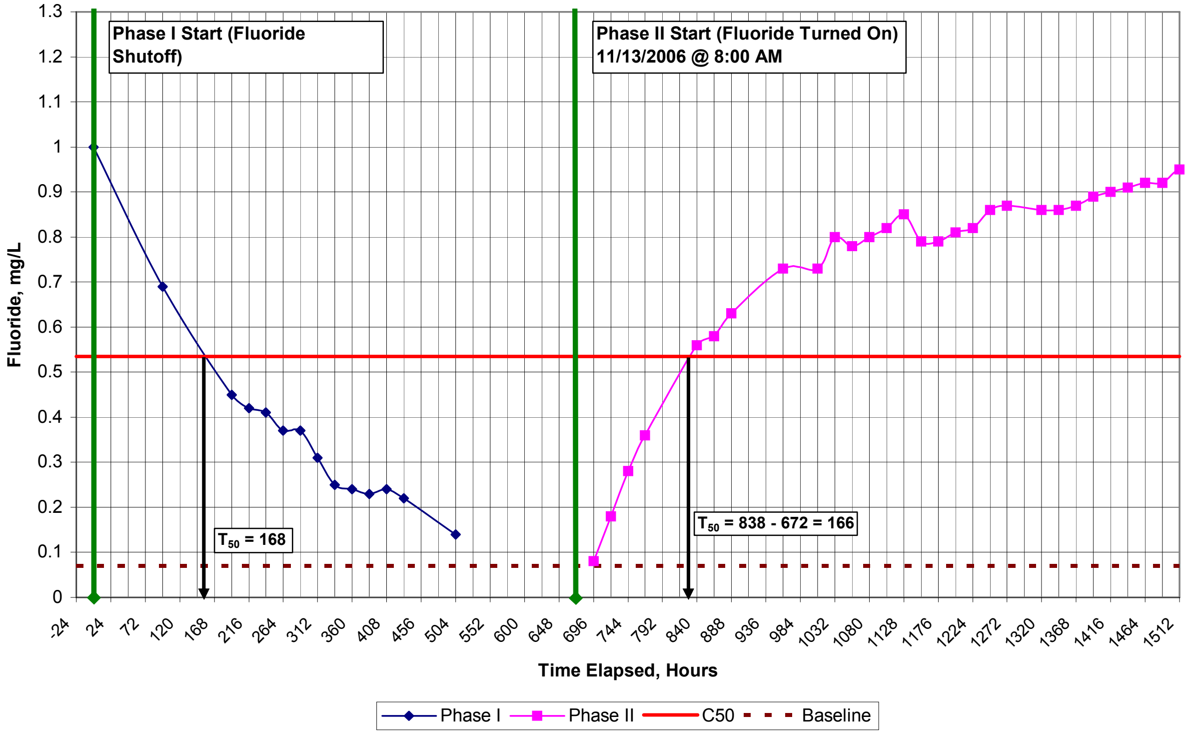

Figure 80. Site M02 - 1201 North Avenue, Hardees (Millvale) tracer response curves.

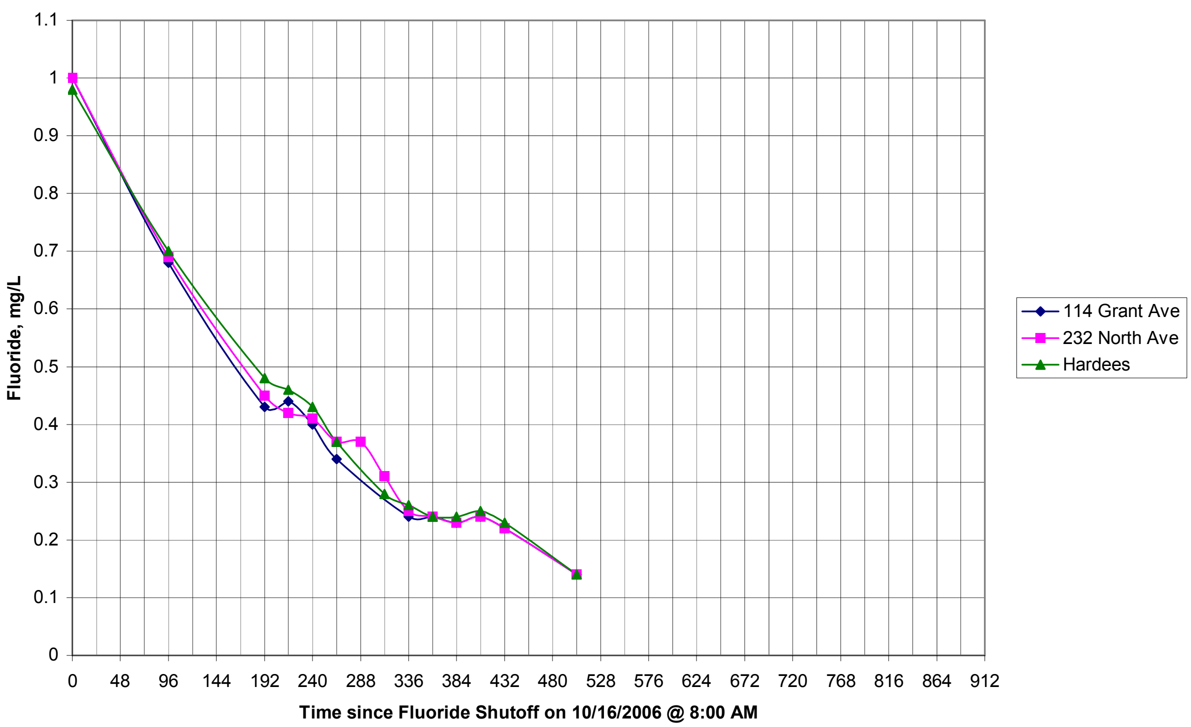

Figure 81. Millvale Sites M01, M02, M03 - Phase I tracer response curves comparison.

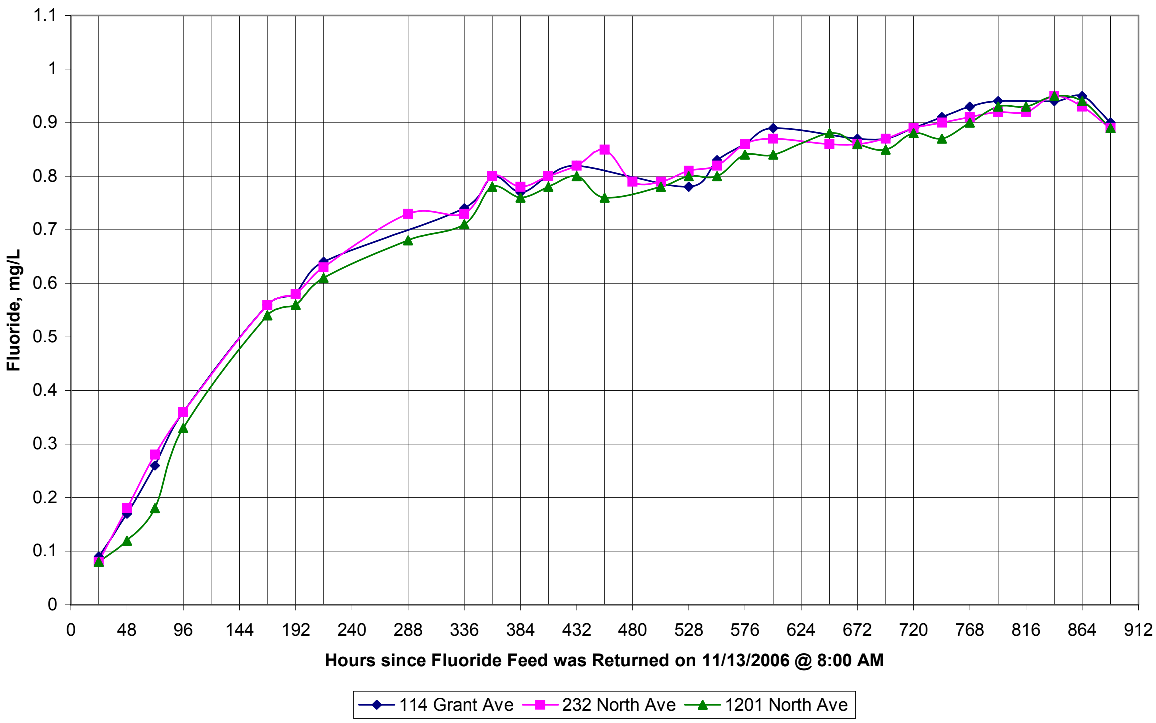

Figure 82. Millvale Sites M01, M02, M03 - Phase II tracer response curve comparison.

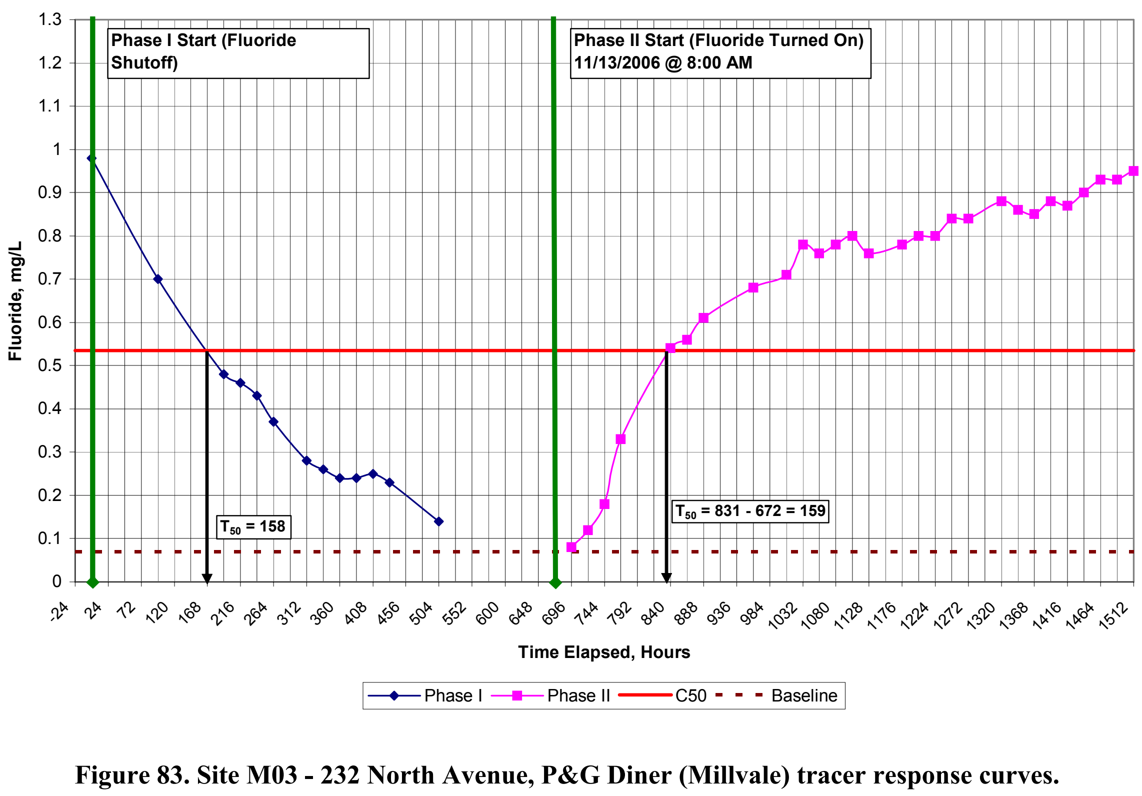

Figure 83. Site M03 - 232 North Avenue, P&G Diner (Millvale) tracer response curves.

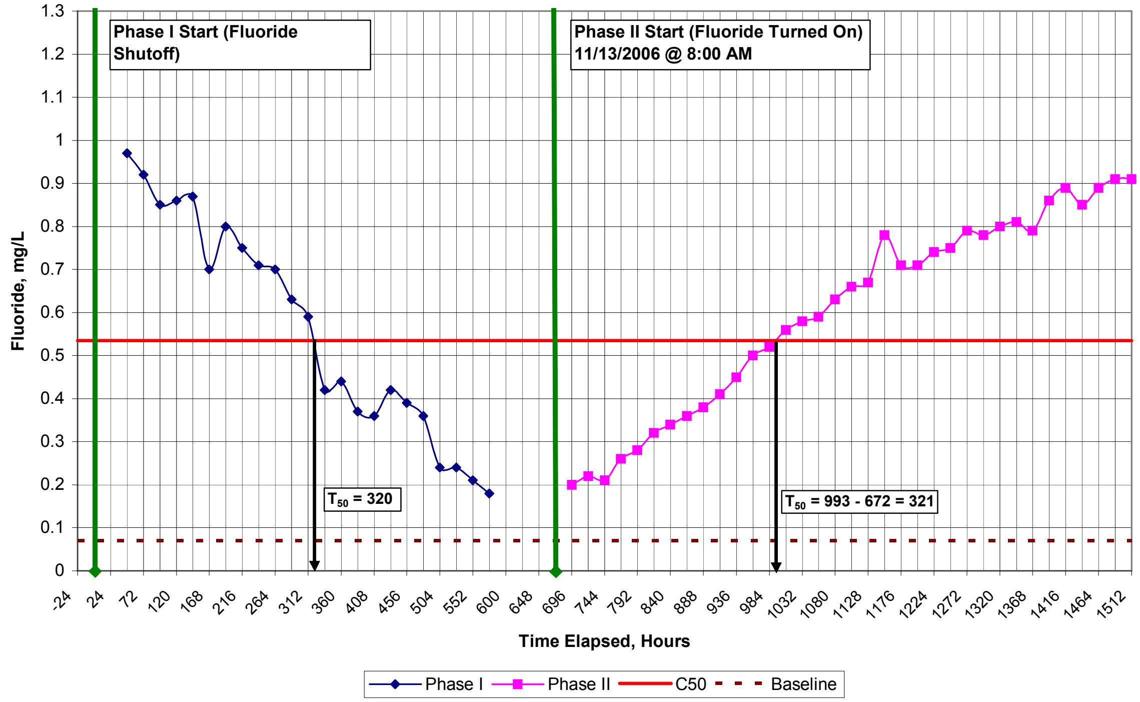

Figure 84. Site R01 - 4000 Mt Troy Road, cemetery (Reserve) tracer response curves.

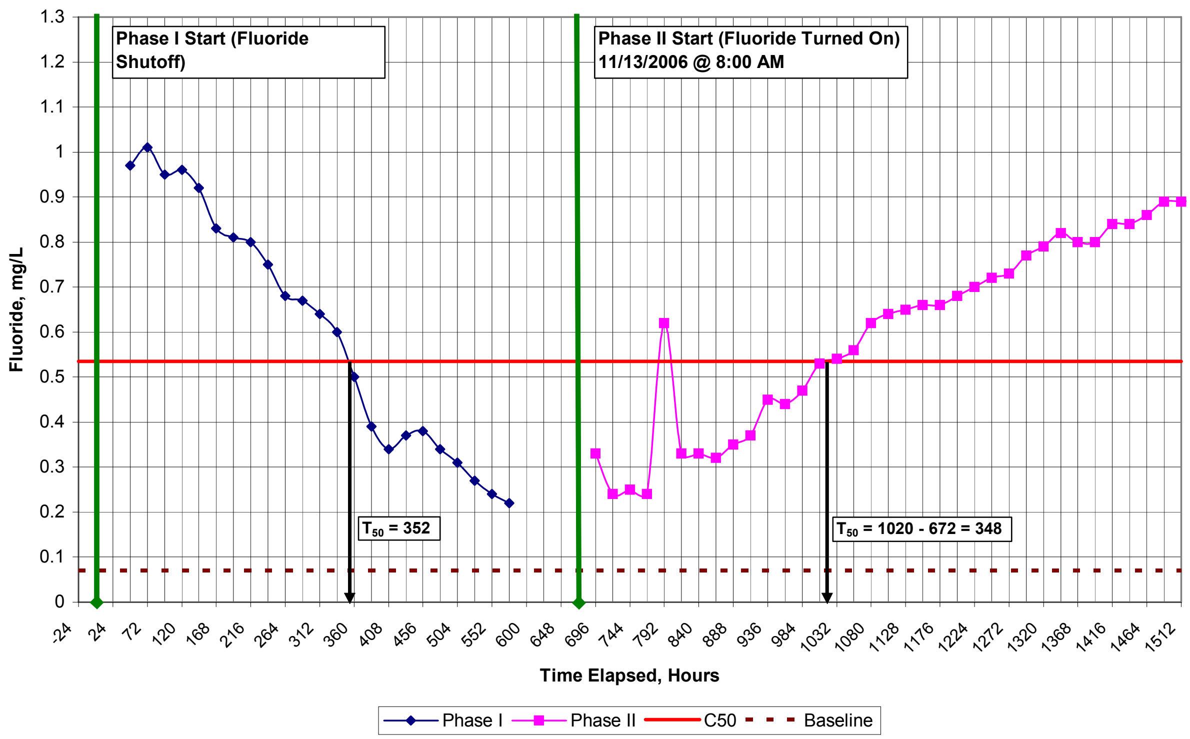

Figure 85. Site R02 - 116 Biscayne Terrace, fire station (Reserve) tracer response curves.

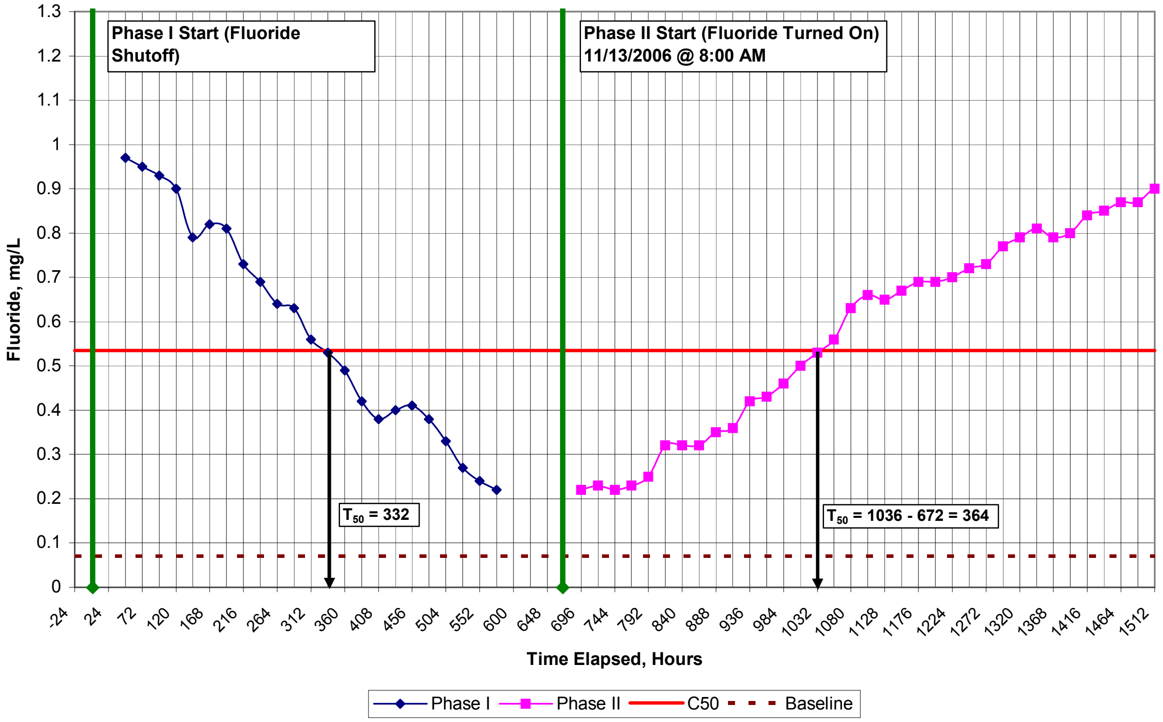

Figure 86. Site R03 - 33 Lonsdale Street, fire station (Reserve) tracer response curves.

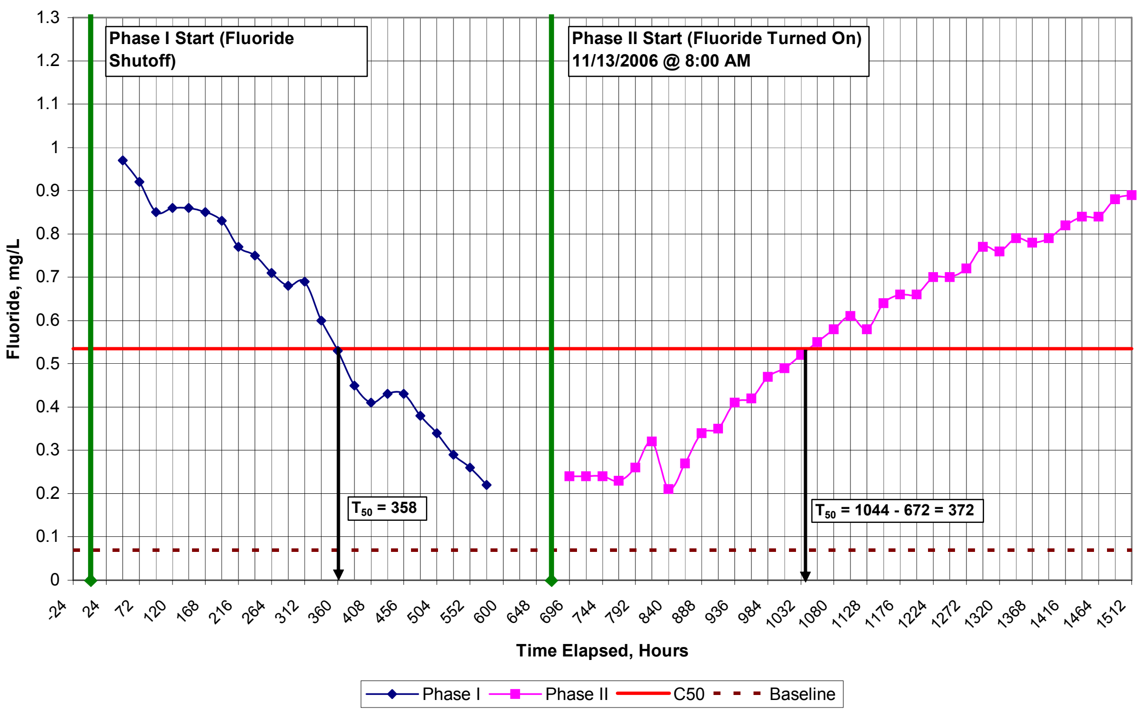

Figure 87. Site R04 - 2000 Mount Troy Road, bank (Reserve) tracer response curves.

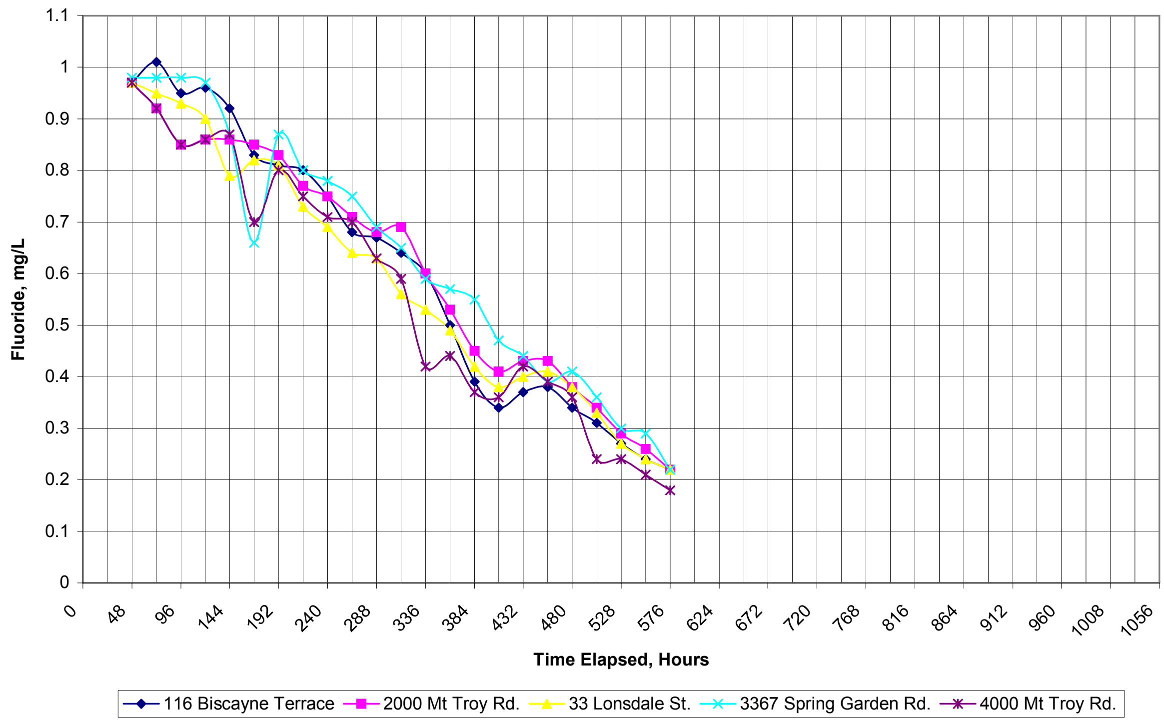

Figure 88. Reserve Sites R01 through R05 - Phase I tracer response curves comparison.

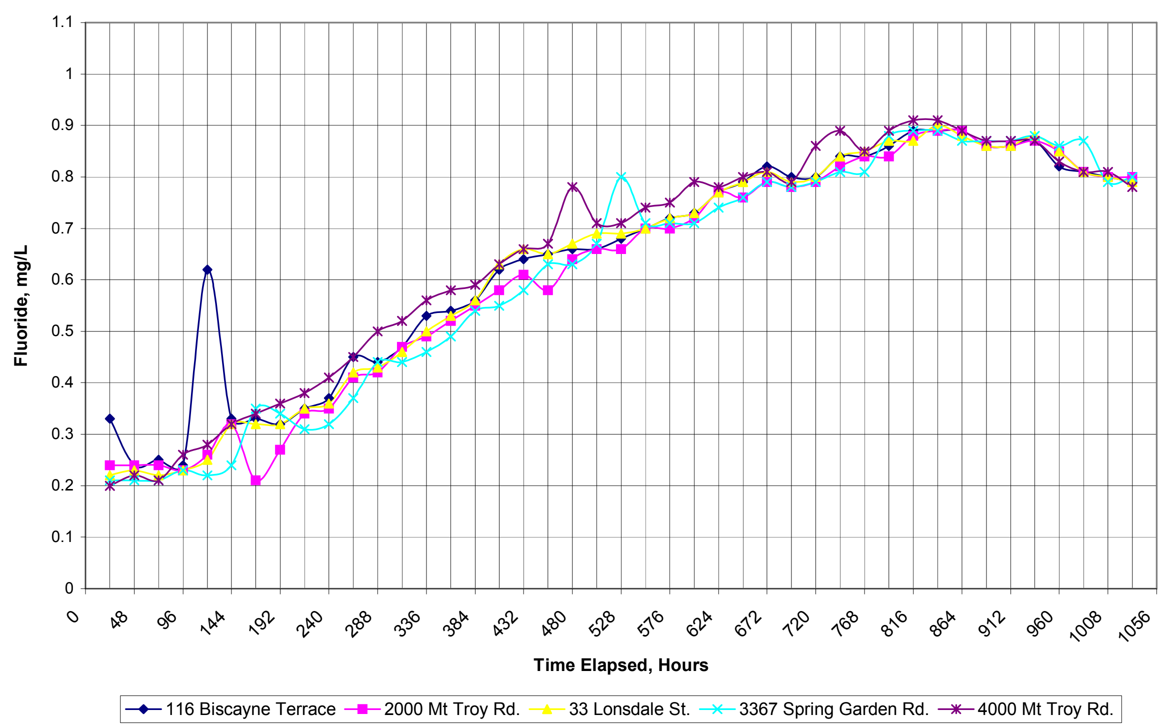

Figure 89. Reserve Sites R01 through R05 - Phase II tracer response curves comparison.

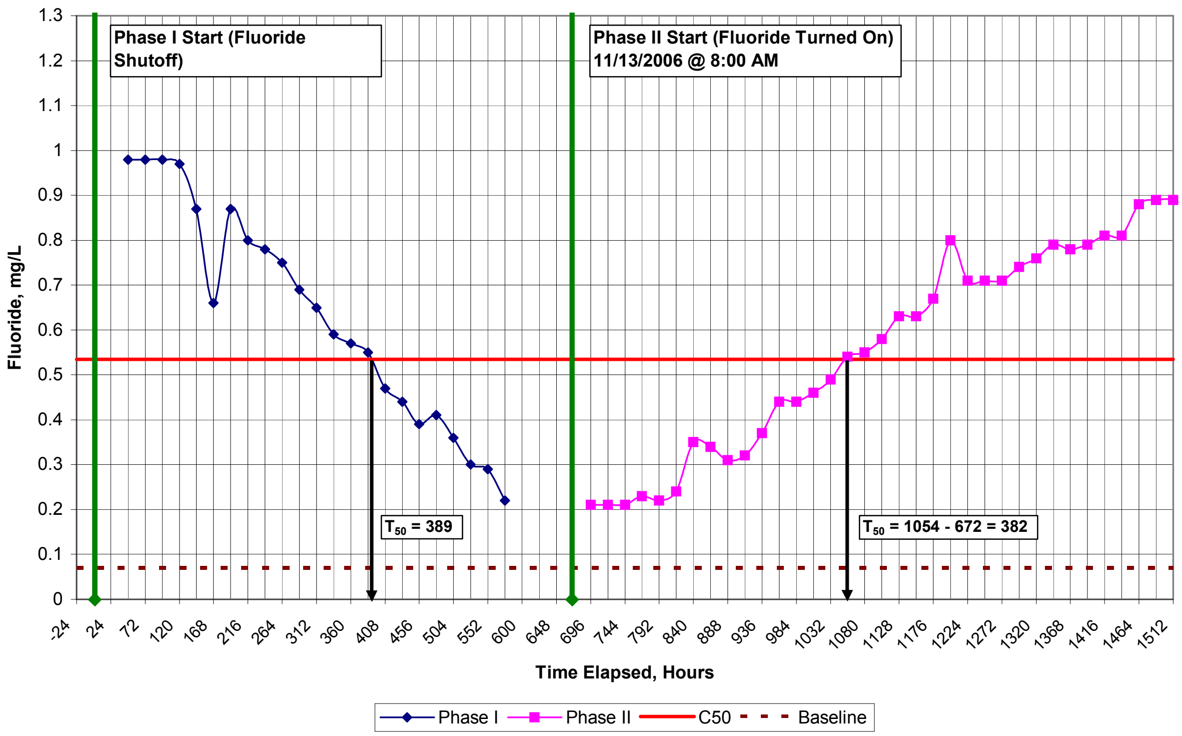

Figure 90. Site R05 - 3367 Spring Garden Road (Reserve) tracer response curves.

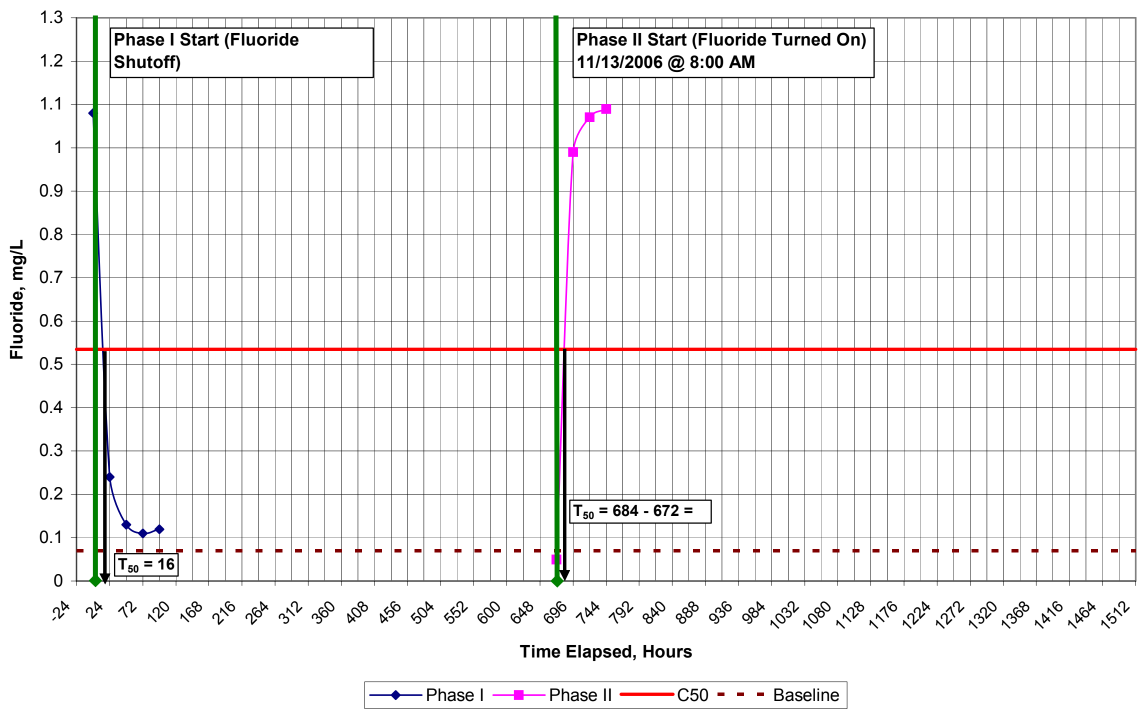

Figure 91. Site F01 - Feed @ Rockwood Valve Station (Fox Chapel) tracer response curves.

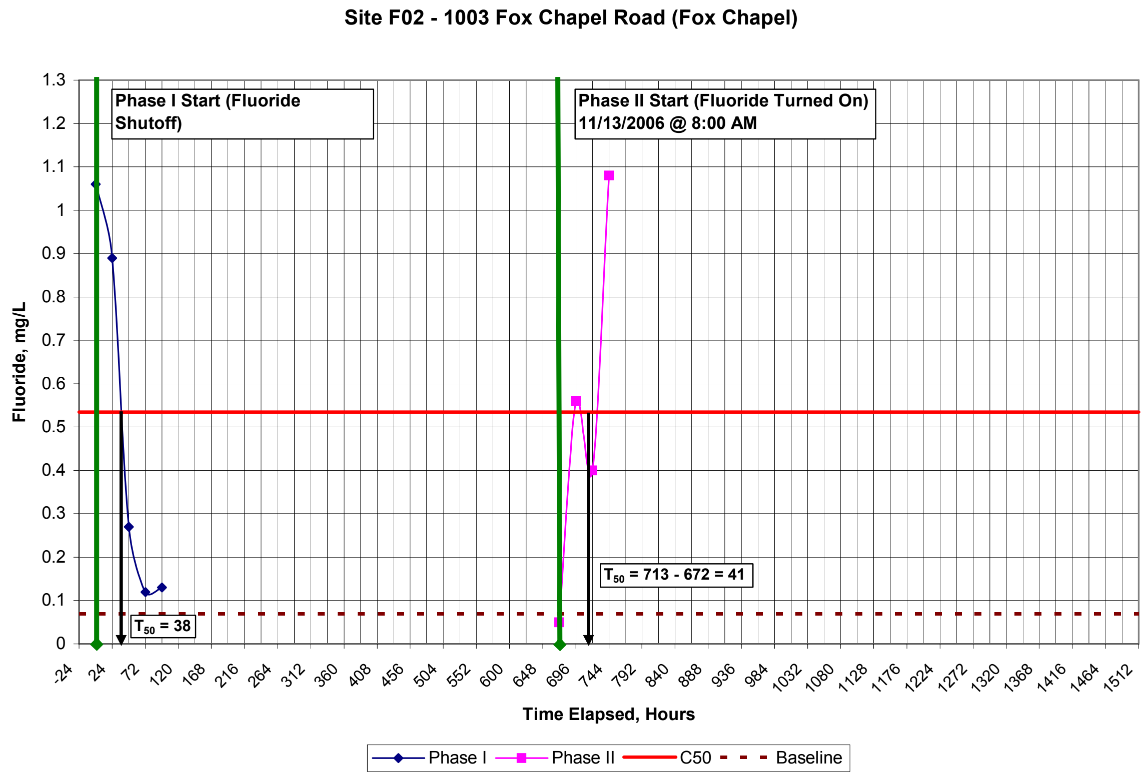

Figure 92. Site F02 - 1003 Fox Chapel Road (Fox Chapel) tracer response curves.

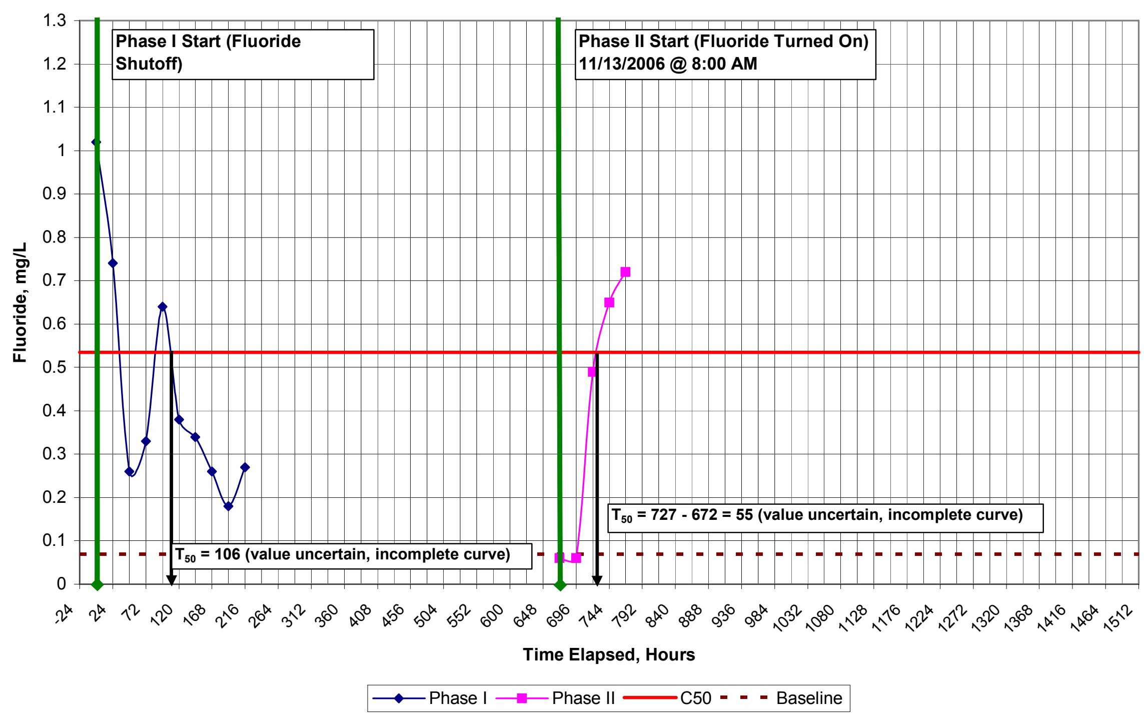

Figure 93. Site F03 - 280 Kappa Drive (Fox Chapel) tracer response curves.

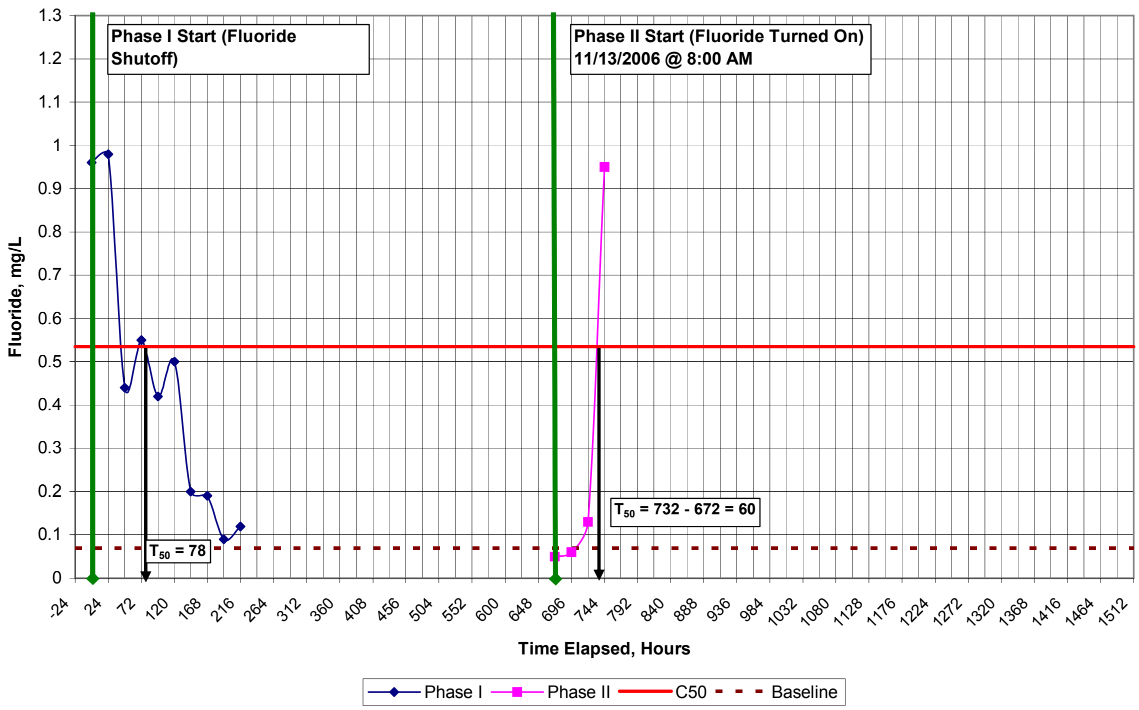

Figure 94. Site F04 - Hampton Twp. Interconnect (Fox Chapel) tracer response curves.

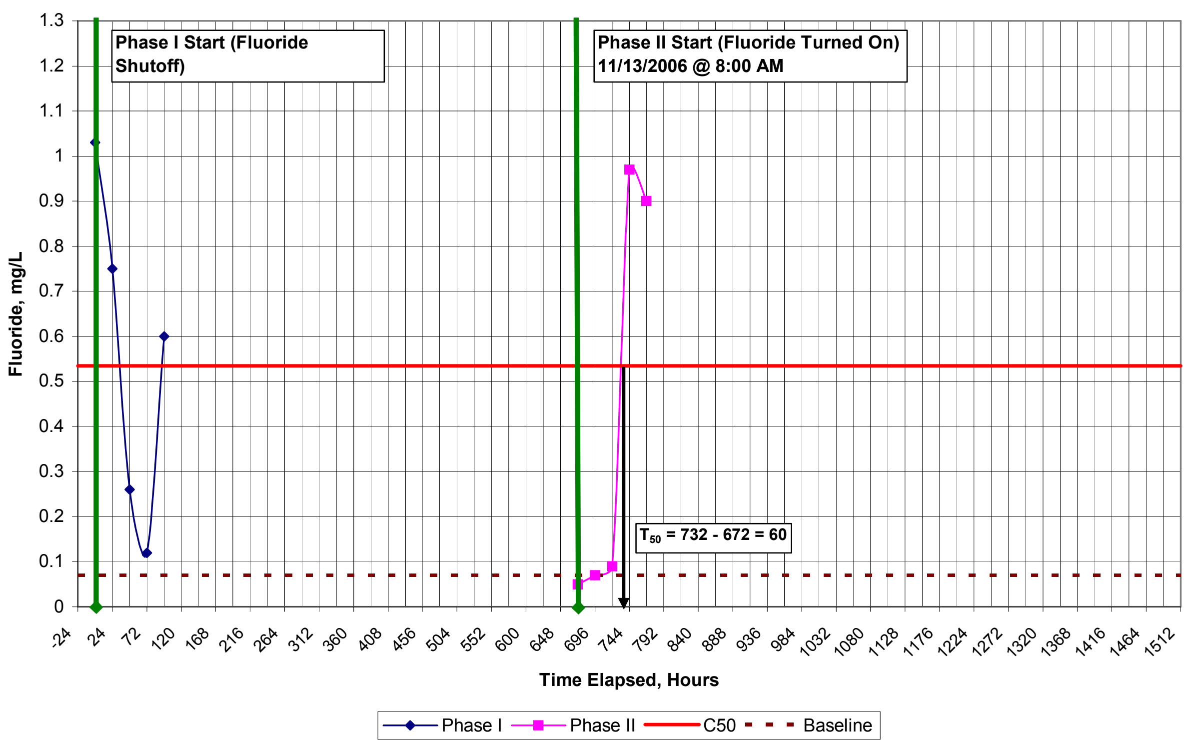

Figure 95. Site F05 - Blawnox Boro Interconnect (Fox Chapel) tracer response curves.

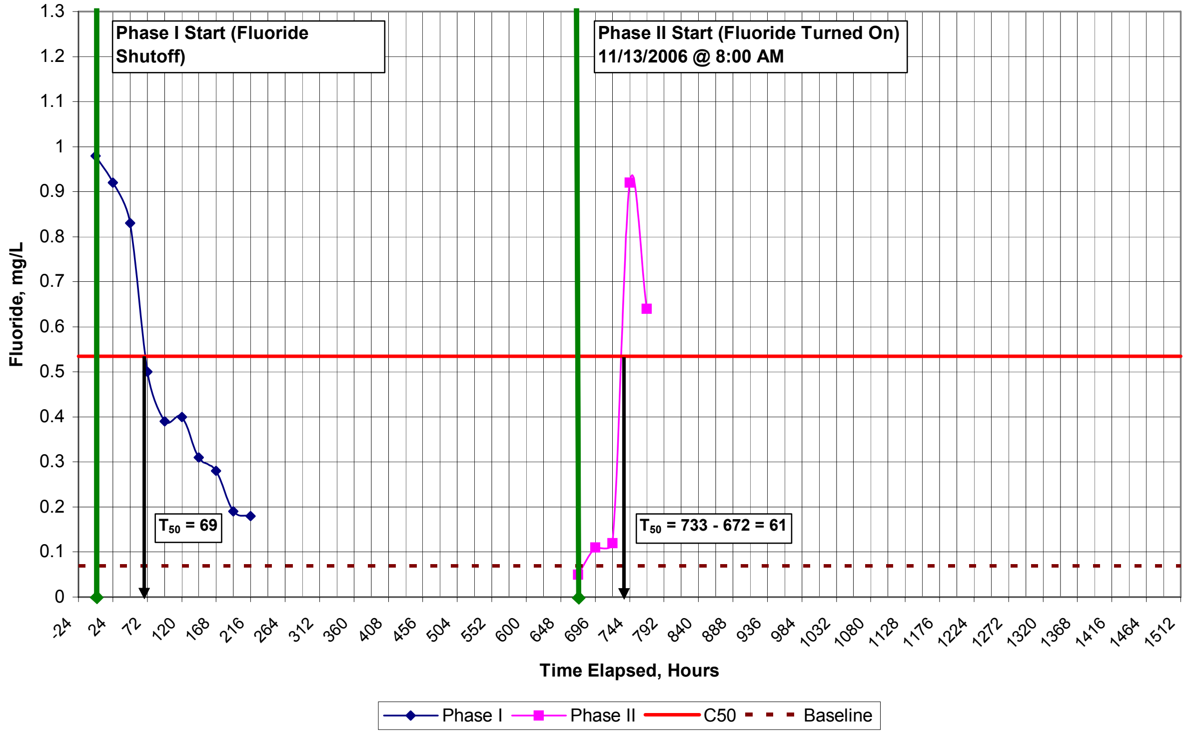

Figure 96. Site F06 - 928 Field Club Road (Fox Chapel) tracer response curves.

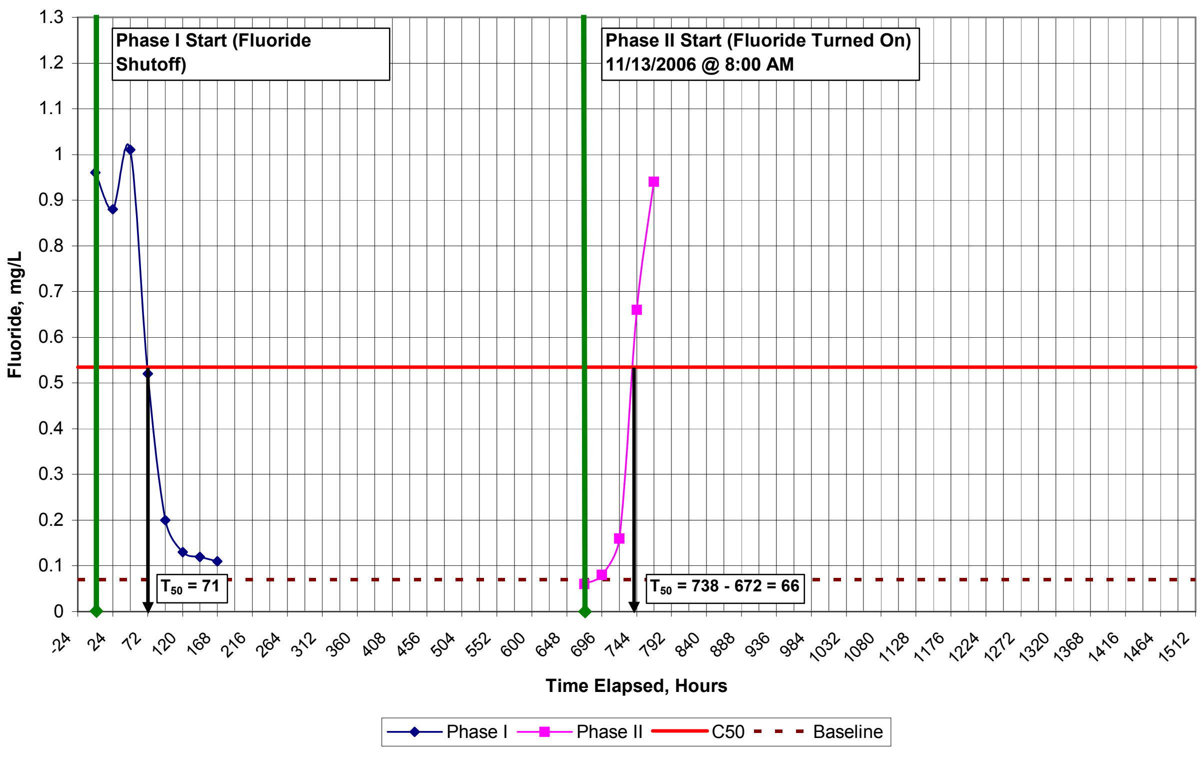

Figure 97. Site F07 - 341 Kittanning Pike (Fox Chapel) tracer response curves.

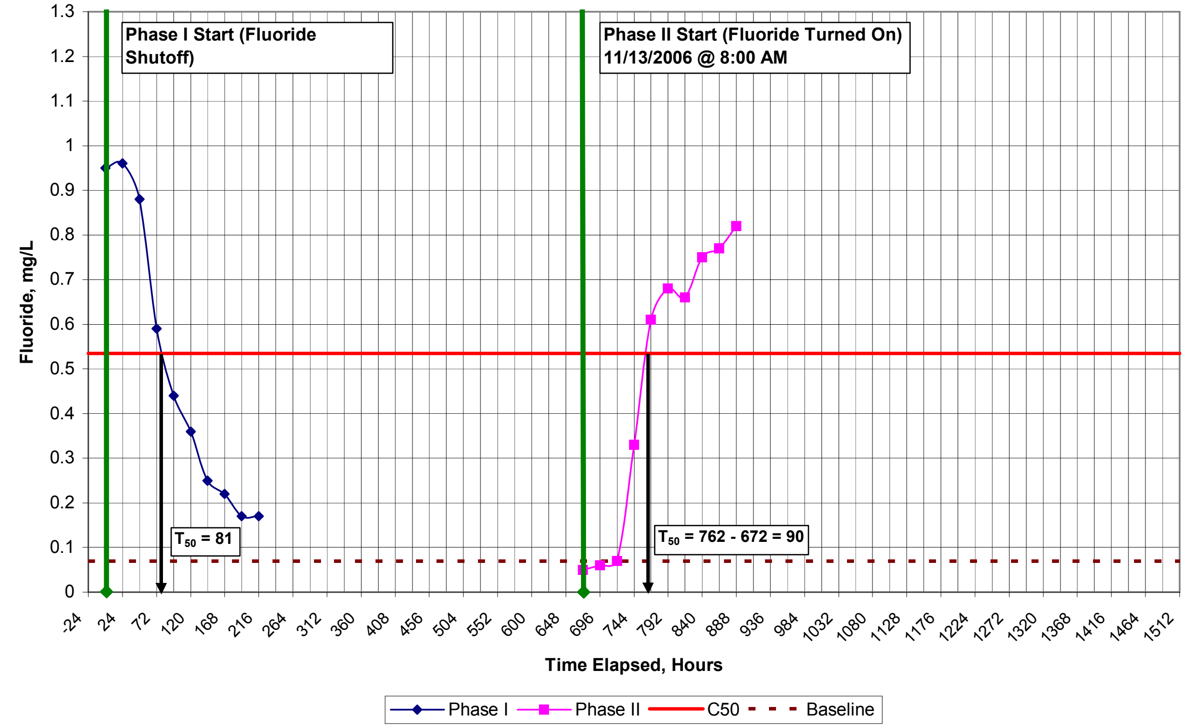

Figure 98. Site F08 - 503 Guys Run Road (Fox Chapel) tracer response curves.

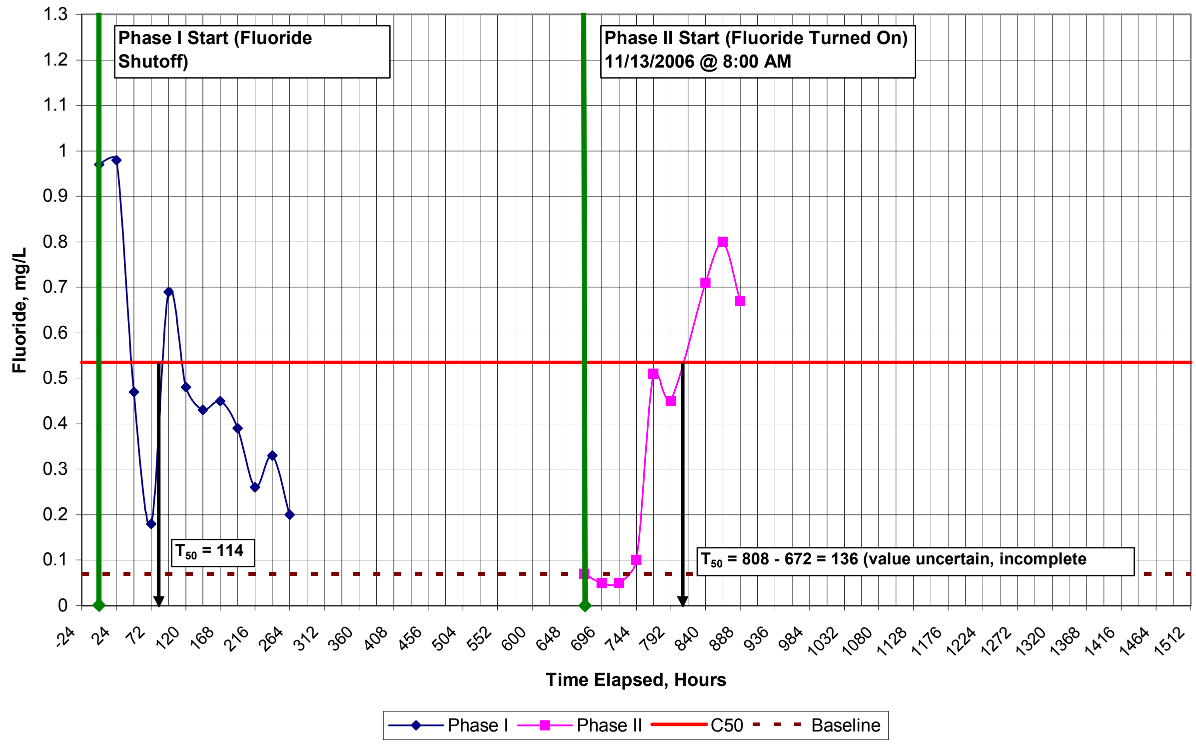

Figure 99. Site F09 - 3563 Harts Run Road (Fox Chapel) tracer response curves.

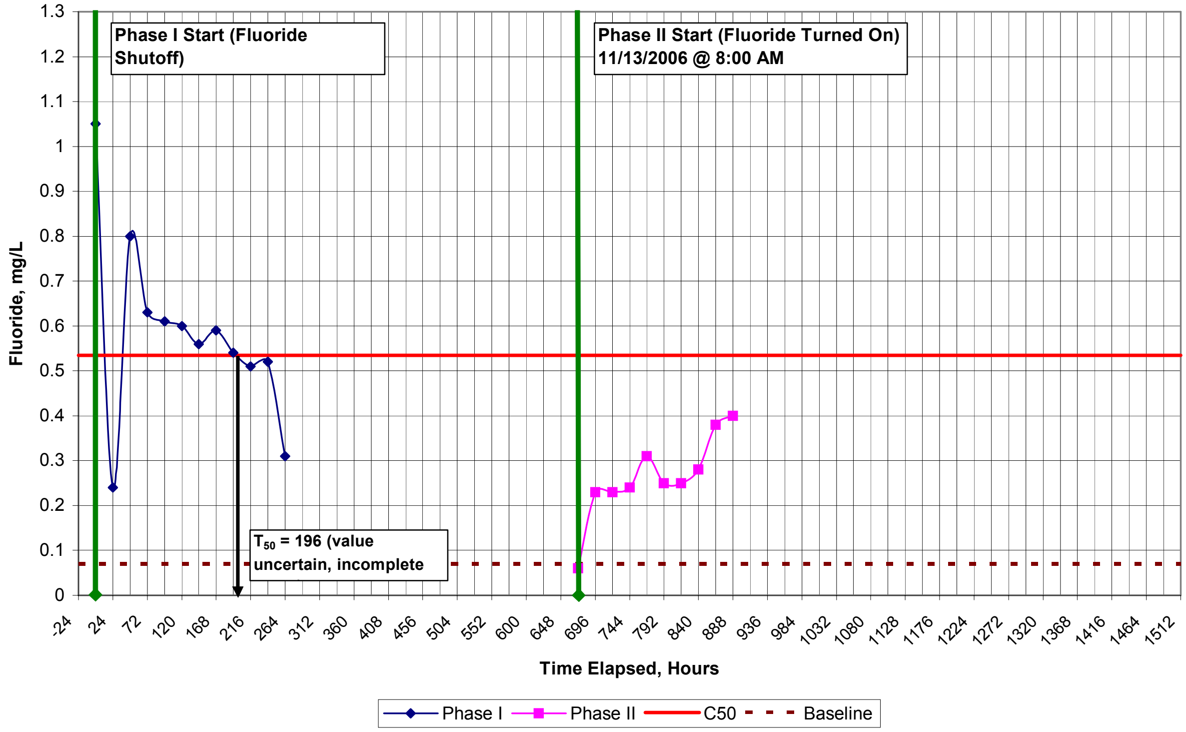

Figure 100. Site F10 - 502 Guyasuta Road (Fox Chapel) tracer response curves.

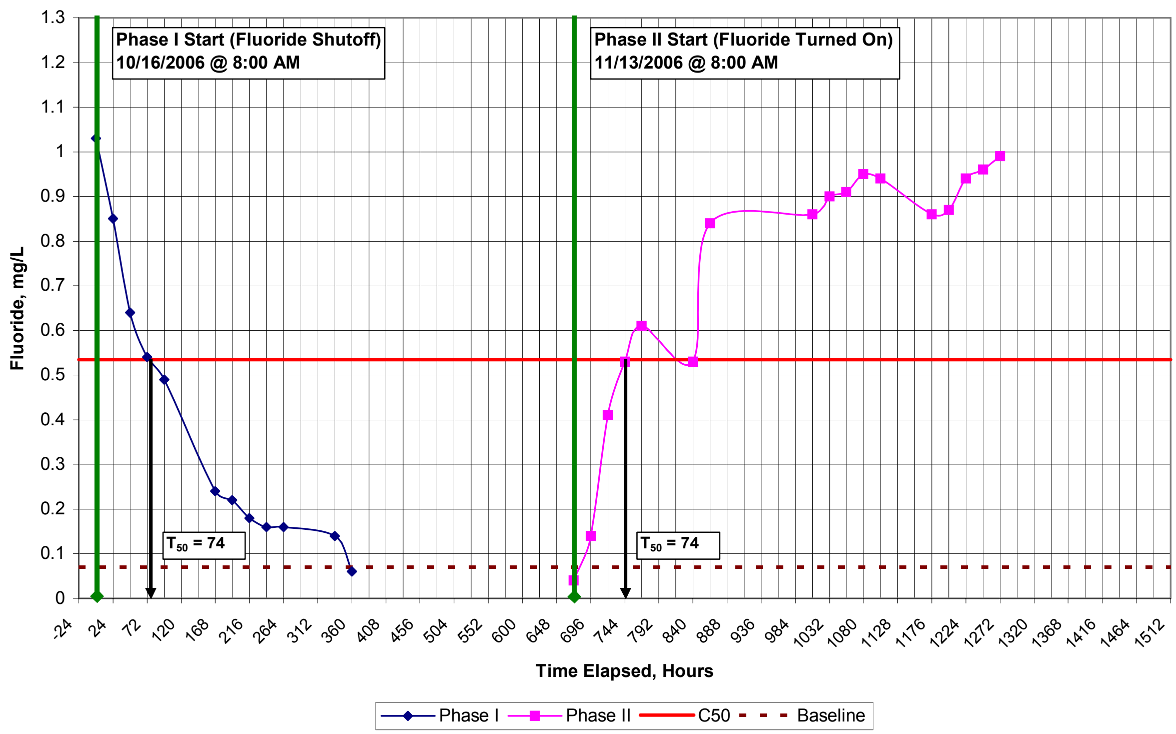

Figure 101. Site C01 - Baker Hall (CMU) tracer response curves.

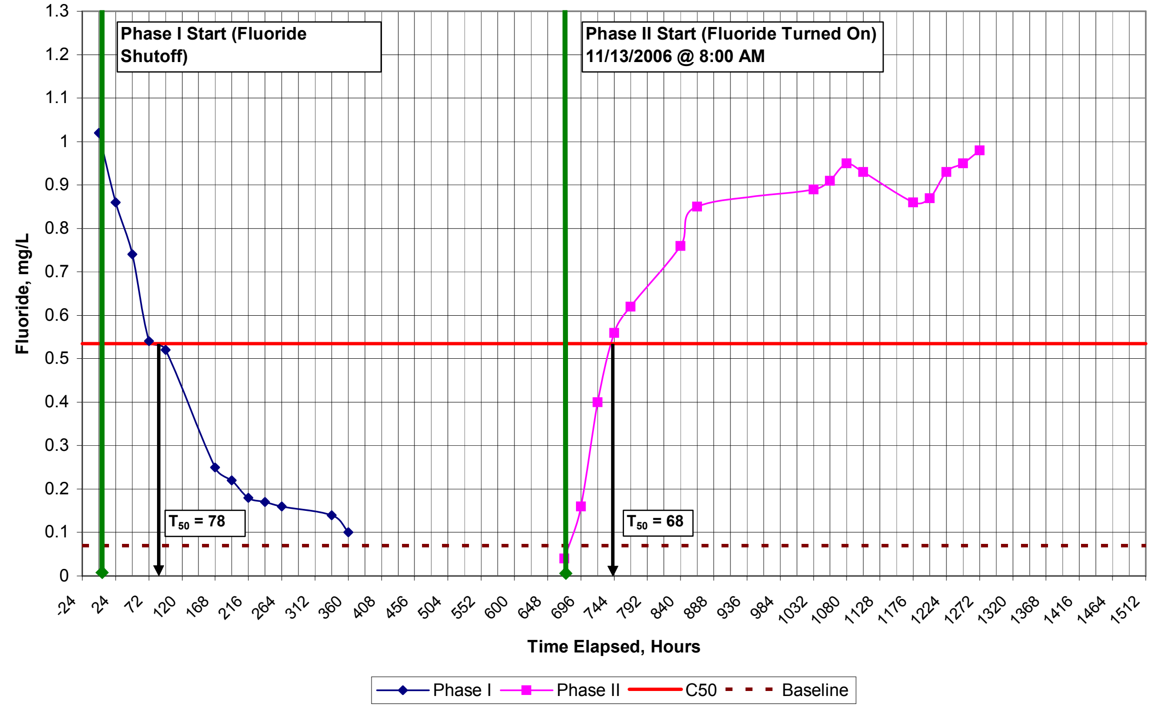

Figure 102. Site C02 - Hunt Library (CMU) tracer response curves.

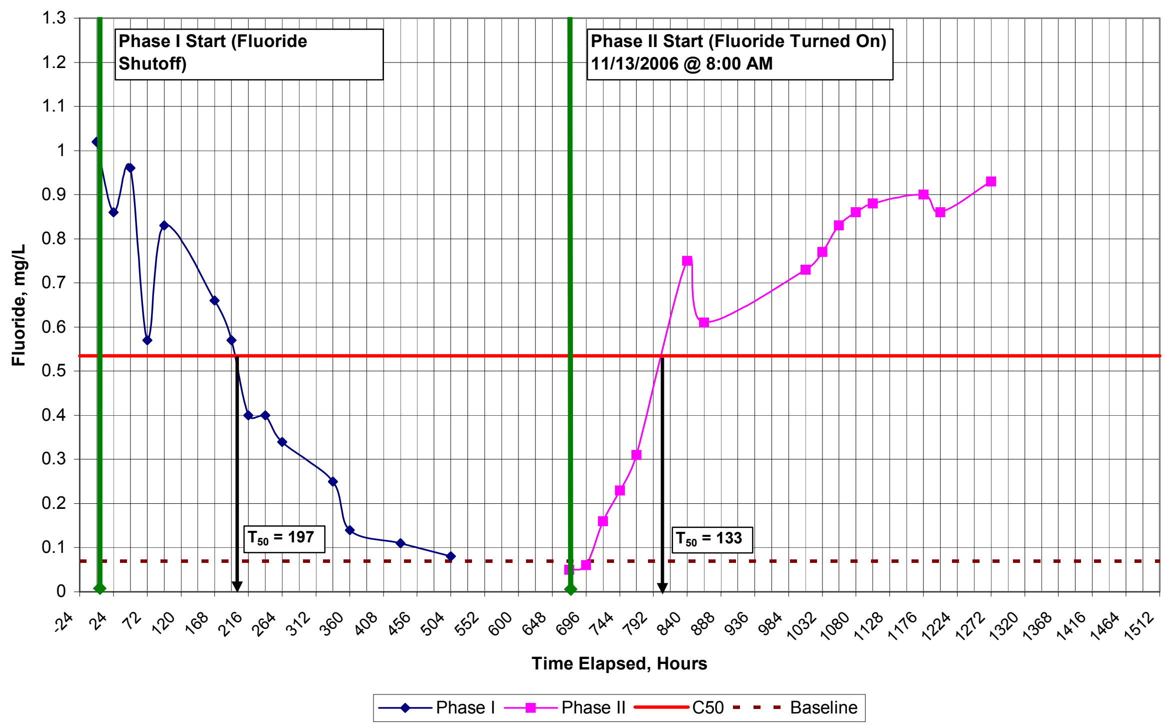

Figure 103. Site C03 - Porter Hall (CMU) tracer response curves.

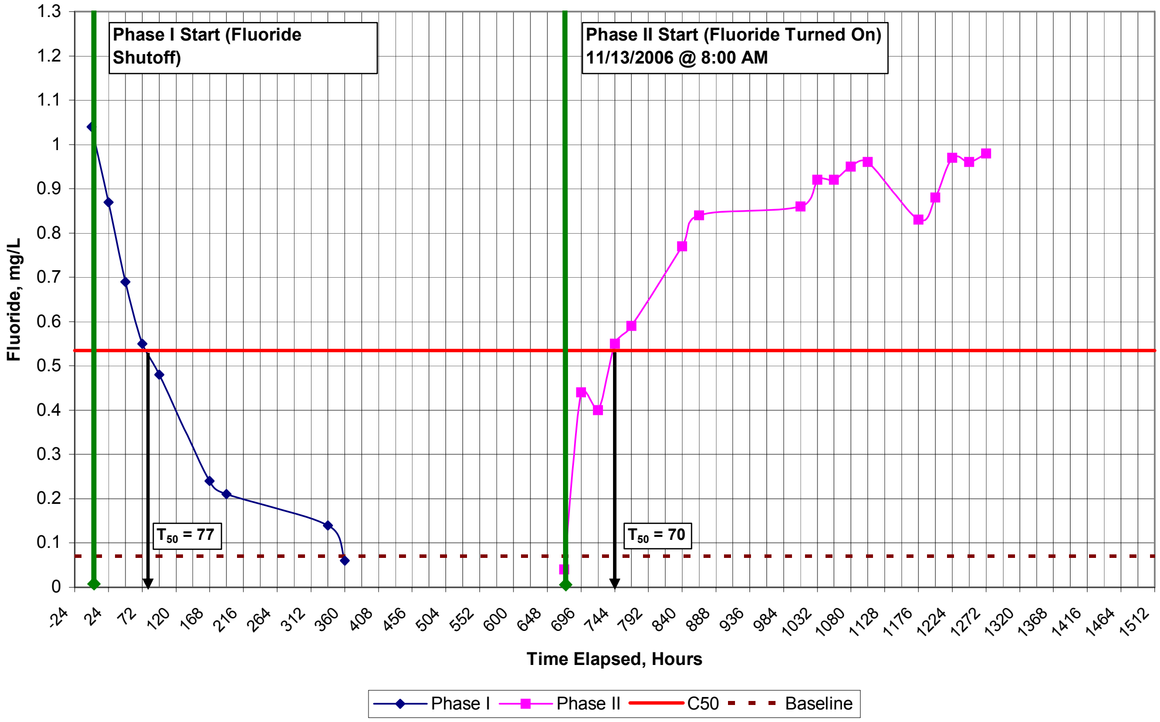

Figure 104. Site C04 - Purnell Hall (CMU) tracer response curves.

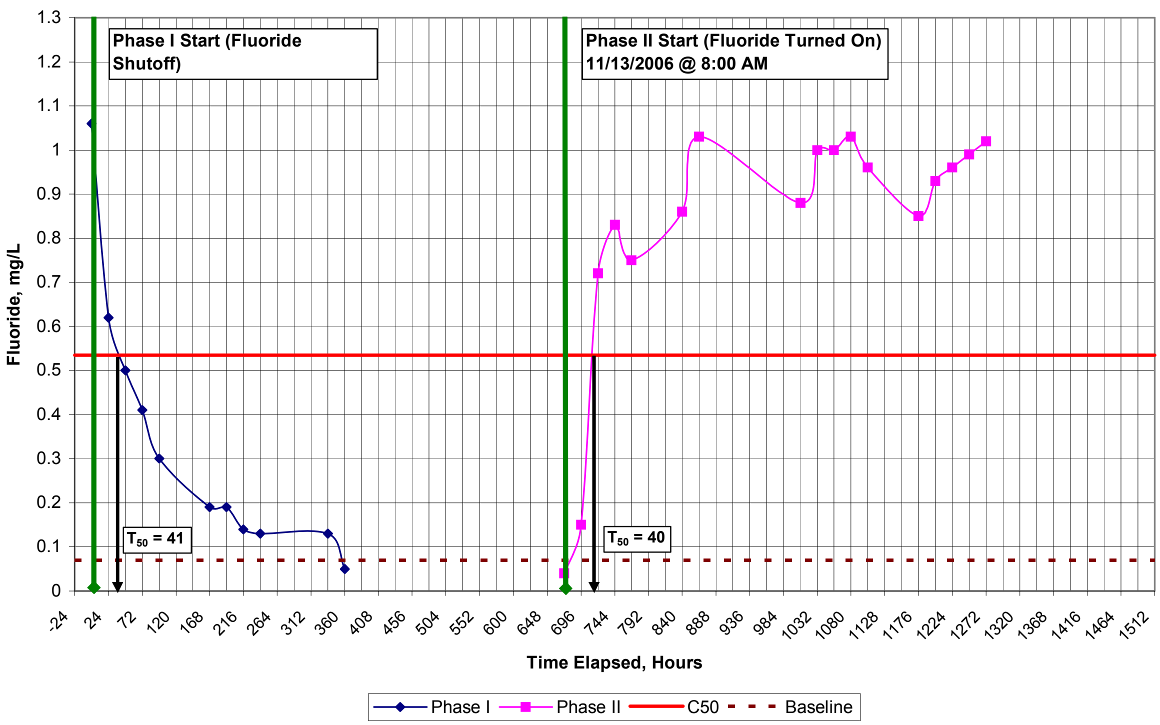

Figure 105. Site C05 - Robert's Hall (CMU) tracer response curves.

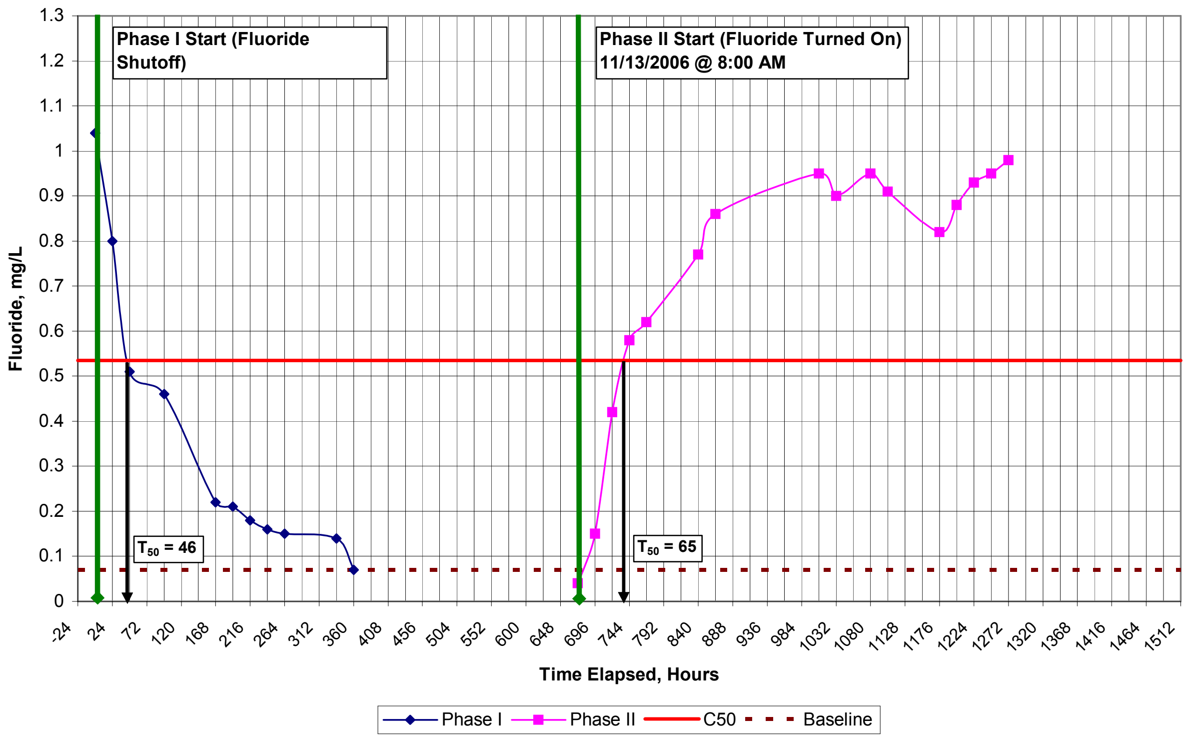

Figure 106. Site C06 - Tepper School (CMU) tracer response curves.

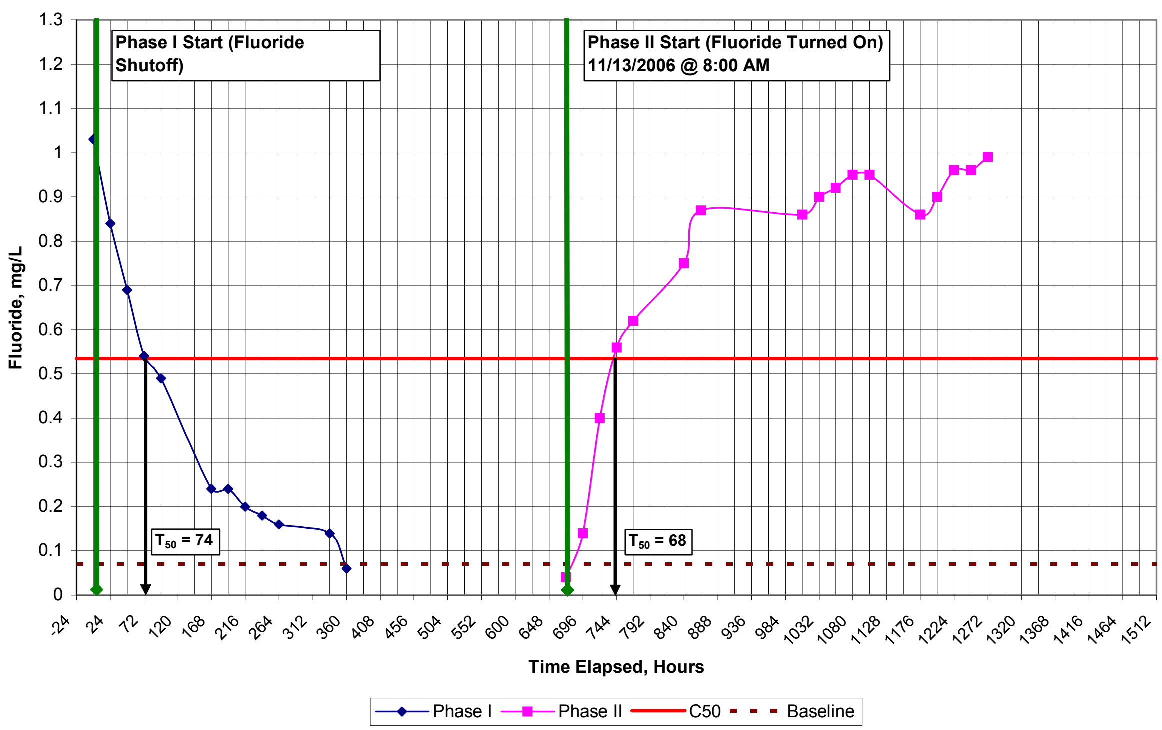

Figure 107. Site C07 - University Center (CMU) tracer response curves.

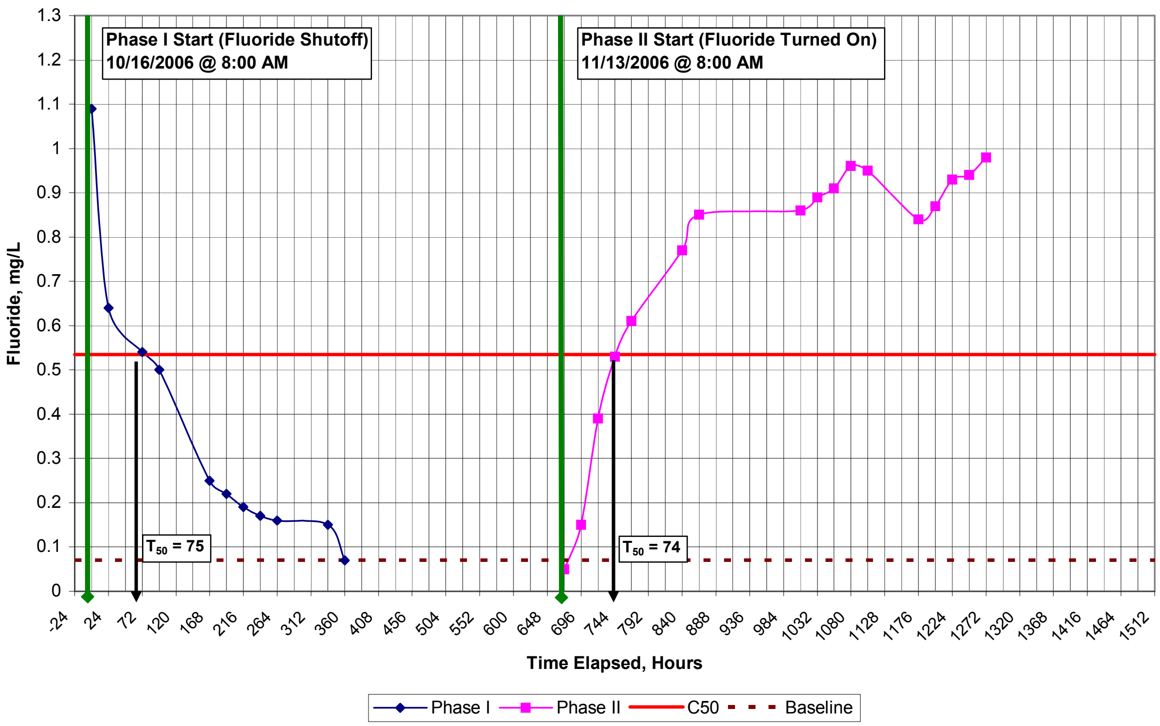

Figure 108. Site C08 - Warner Hall (CMU) tracer response curves.

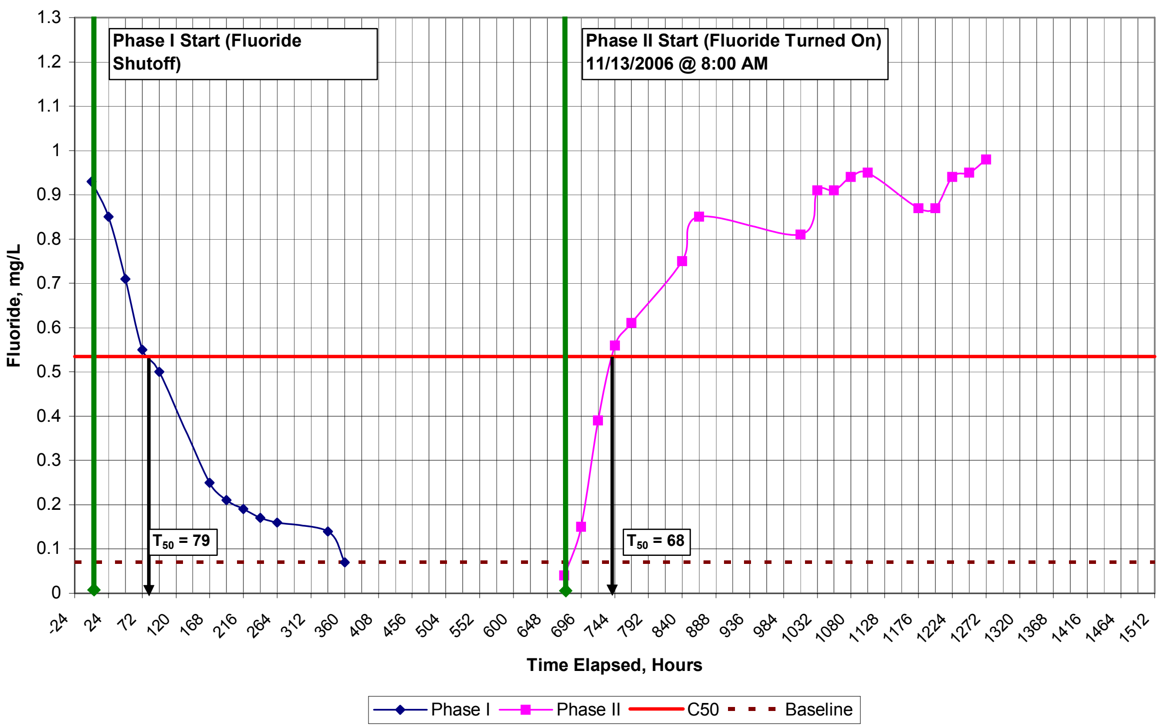

Figure 109. Site C09 - Wean Hall (CMU) tracer response curves.

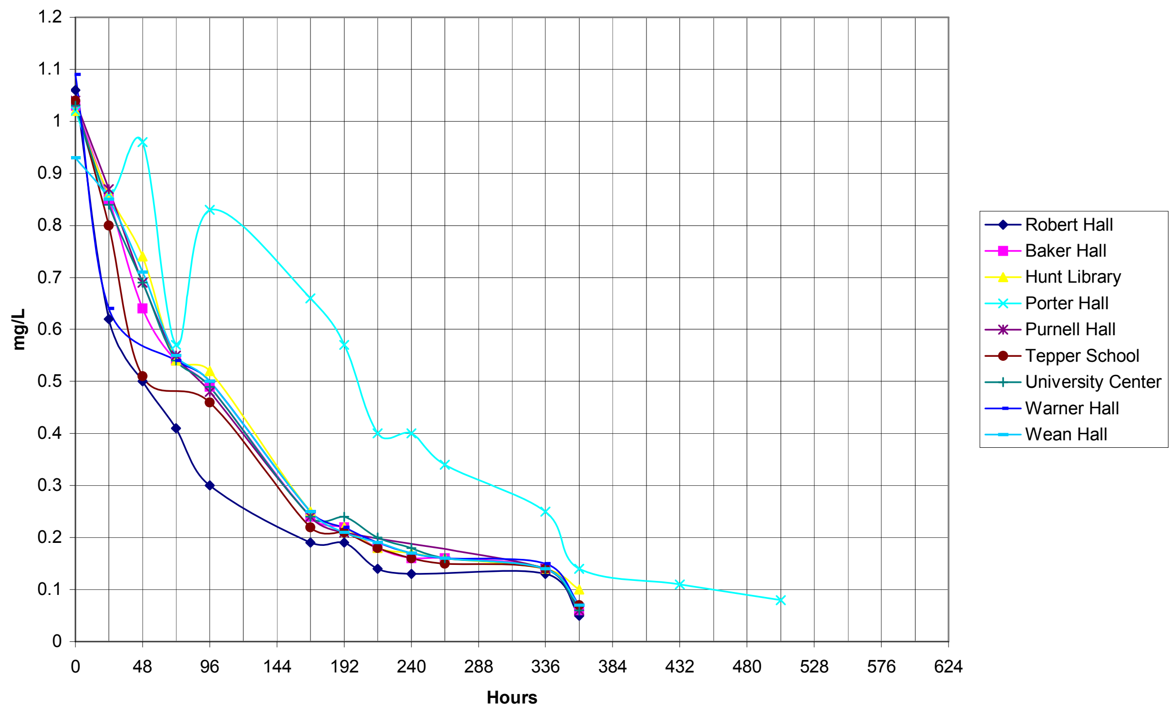

Figure 110. CMU Sites C01 through C09 - Phase I tracer response curve comparison.

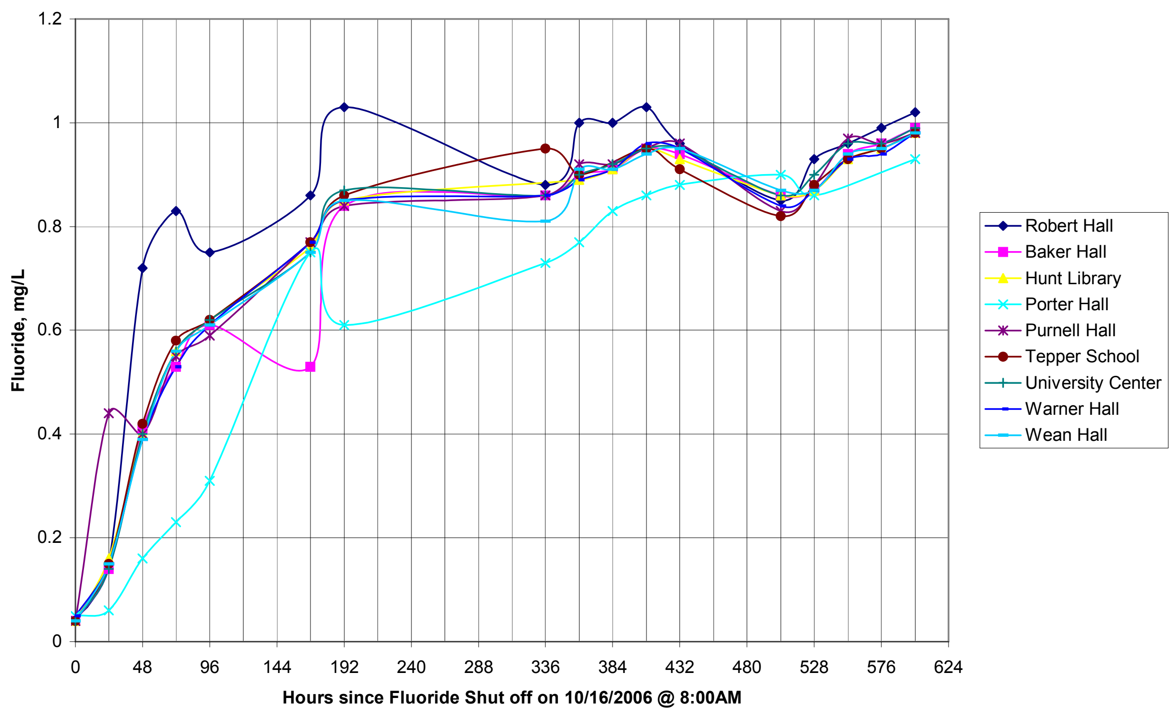

Figure 111. CMU Sites C01 through C09 - Phase II tracer response curve comparison.

APPENDIX B

SAMPLING SITE WATER AGES AND TTHM CONCENTRATIONS

Table 13. PWSA average water ages and corresponding TTHM concentrations.

Location ID	Sample Location Description	Phase I T_{50} (Hours)	Phase I TTHM (µg/L)	Phase II T_{50} (Hours)	Phase II TTHM (µg/L)
W01	Clearwell	11	- - - -	23	27
Autosamplers - 4-hour samples					
A01	Lanpher Reservoir East Effluent	250	43	148	41
A02	Lanpher Reservoir West Effluent	300	84	195	42
A03	Lanpher Reservoir Influent (Aspinwall Pump Sta.)	17	44	< 24 *	23
A04	Bruecken Pump Station (Influent Highland No. 1)	29	34	< 24*	26
A05	Bruecken Pump Station (Influent Highland No. 2)	29	34	27	28
A06	Highland Reservoir No. 1 Effluent	103	42	116	35
A07	Highland Reservoir No. 2 Effluent	98	57	121	41
A08	Howard Pump Station (Lanpher Reservoir)	147	60	146	52
A09	Mission Pump Sta. (Highland No. 2 Reservoir)	115	61	127	43
A10	Herron Hill Pump Station, Herron Hill Reservoir Influent (AWTP & Highland No. 1 Reservoir)	-----	43	55	35
A11	Herron Hill Reservoir Effluent	88	48	100	47
Pittsburgh Homes: 12-hour grab samples					
P01	27 Perryview Avenue (Brashear Tanks)	319	79	332	
P02	3133 Brunot Avenue (Allentown Tanks)	321	49	280	59
P03	1114 Colfax Street (McNaugher Reservoir)	206	64	203	57
P04	6433 Forward Avenue (Herron Hill Reservoir)	131	69	126	50
P05	5838 Darlington Road (Lincoln Tank)	75	50	> 72 *	41
Hydrants: periodic grab samples					
H01	Hydrant 1 - 401 Well Street (Allentown Tanks)	140	42	202	64
H02	Hydrant 2 - 1713 Brighton Rd (Lanpher Reservoir)	208	73	207	60

Table 13 (continued)

H03	Hydrant 3 - Termon Avenue, between McClure and California Avenue (McNaugher Reservoir)	n/a	- - - -	218	64
H04	Hydrant 4 - 4260 Evergreen Road, intersection with Ivory Avenue (Brashear Tanks)	272	24	307	71
H05	Hydrant 5 - Perrysville Avenue, intersection with Legion Street (Brashear Tanks)	170	68	180	59
H06	Hydrant 6 - Penn Avenue, between 39th and 40th Street (Highland No. 1 Reservoir)	130	47	59	45
H07	Hydrant 7 - Lincoln Avenue, intersection with Joshua Street (Lincoln Tank)	196	76	87	59
H08	Hydrant 8 - Love Street, first hydrant on left off Whipple Street (Highland No. 1 Reservoir)	90	58	75	52
H09	Hydrant 9 - Bigelow Street and Tesla Street intersection, Hazelwood Ave. (Squirrel Hill Tank)	190	70	229	- - - -
H10	Hydrant 10 - Chartiers Street and Lorenz Street intersection (Allentown Tanks)	164	71	184	58
H11	Hydrant 11 - Mon Warf Parking Lot (Highland No. 2 Reservoir)	154	71	160	57
Millvale Borough: daily grab samples					
M01	114 Grant Ave., Grant's Bar (Aspinwall Pump Sta.)	152	- - - -	159	51
M02	1201 North Ave., Hardees (Aspinwall Pump Sta.)	168	81	166	57
M03	232 North Avenue, Lincoln Drug/P&G Diner (Aspinwall Pump Station)	158	49	159	43
Reserve Township: daily grab samples					
R01	4000 Mt Troy Road, Saint Mary's Cemetery (Brashear Tanks)	320	90	321	72
R02	116 Biscayne Terrace, Fire House (Brashear Tanks)	352	85	348	77
R03	33 Lonsdale Street, Municipal Building/Mt Troy Volunteer Fire Co., Station 239 (Brashear Tanks)	332	94	364	78
R04	2000 Mt Troy Road, Mt. Troy Savings Bank (Brashear Tanks)	358	91	372	83
R05	3367 Spring Garden Road, Spring Garden Volunteer Fire Co., Station 240 (Brashear Tanks)	389	99	382	88
Fox Chapel: daily grab samples					
F01	PWSA Feed at Rockwood Valve Station (Aspinwall Pump Station)	16	45	12	30
F02	1003 Fox Chapel Road (Aspinwall Pump Station)	38	45	41	33
F03	280 Kappa Dr. (Aspinwall Pump Station)	106	51	55	59
F04	Hampton Twp. Interconnect (Aspinwall Pump Sta.)	75	56	60	39
F05	Blawnox Boro Interconnect (Aspinwall Pump Sta.)	> 96 *	61	60	57
F06	928 Field Club Road (Aspinwall Pump Station)	69	58	61	56
F07	341 Kittanning Pike (Aspinwall Pump Station)	71	57	66	44
F08	503 Guys Run Road (Aspinwall Pump Station)	81	64	90	53
F09	3563 Harts Run Road (Aspinwall Pump Station)	114	60	136	59
F10	502 Guyasuta Road (Aspinwall Pump Station)	196	59	> 216*	60
Carnegie Mellon University: daily grab samples					
C01	Baker Hall	74	- - - -	74	- - - -

Table 13 (continued)

C02	Hunt Library	78	- - - -	68	- - - -
C03	Porter Hall	197	- - - -	133	- - - -
C04	Purnell Hall	77	- - - -	70	- - - -
C05	Robert's Hall	41	- - - -	40	- - - -
C06	Tepper School	46	- - - -	65	- - - -
C07	University Center	74	- - - -	68	- - - -
C08	Warner Hall	75	- - - -	74	- - - -
C09	Wean Hall	79	- - - -	68	- - - -

* Value is either greater than or less than value listed. Value is uncertain due to incomplete fluoride tracer response curve.

APPENDIX C

TTHM AND CHLORINE RESIDUAL GRAPHS

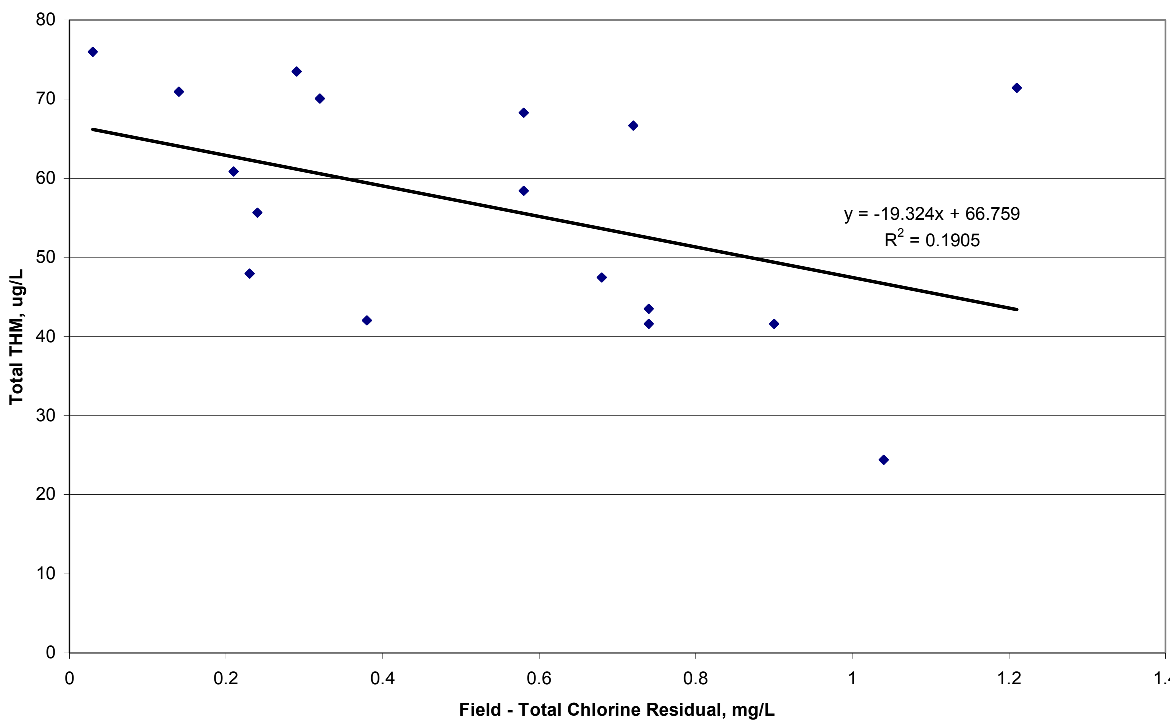

Figure 112. Phase I and Phase II TTHM versus total chlorine residual.

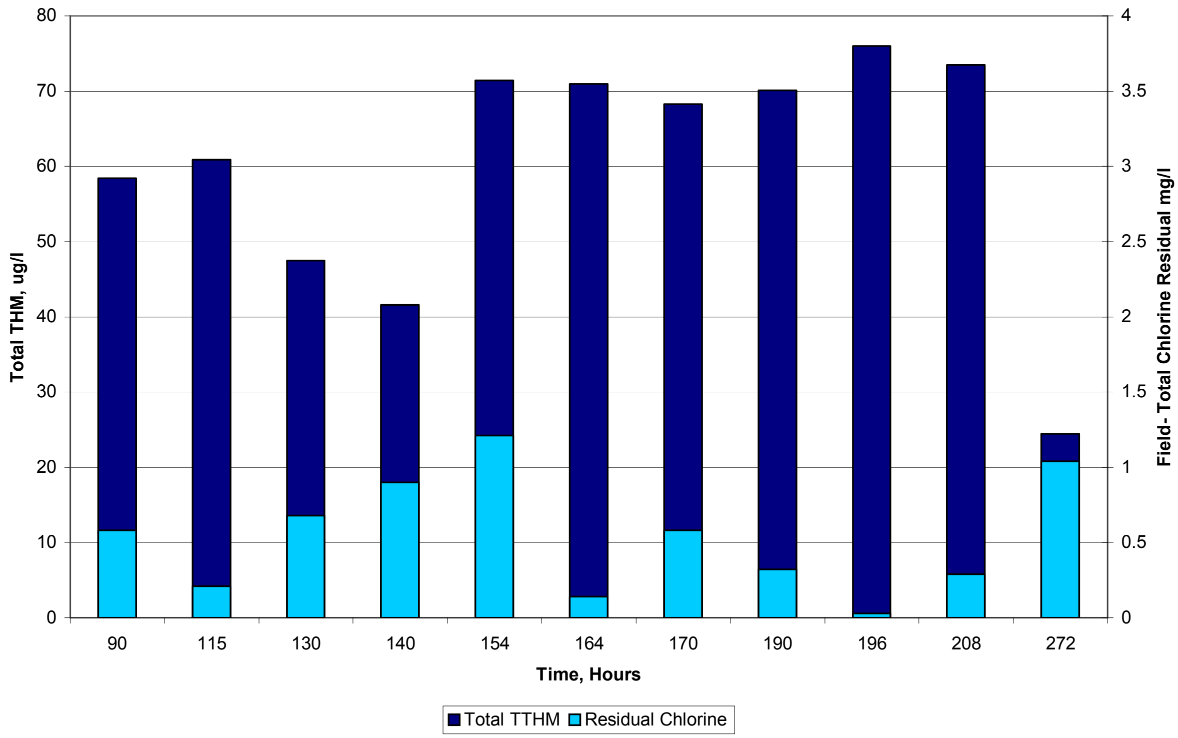

Figure 113. Phase I - TTHM & total chlorine Residual versus time.

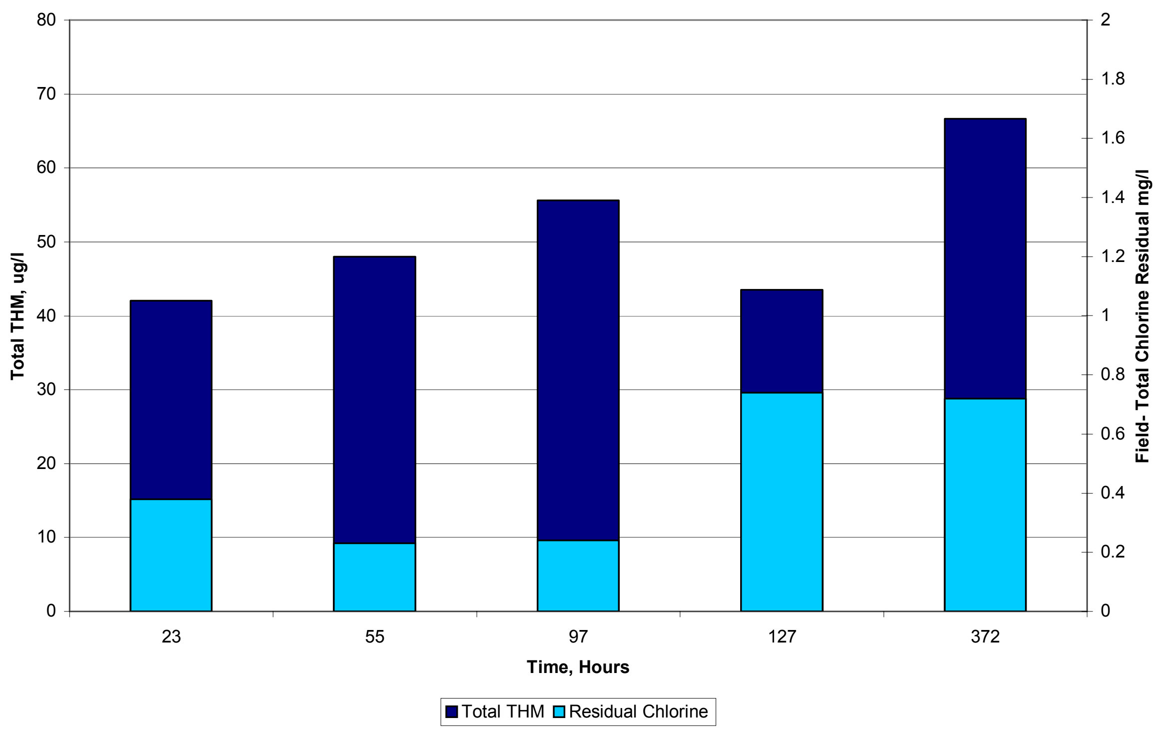

Figure 114. Phase II - TTHM & total chlorine residual versus time.

APPENDIX D

FLUORIDE GRAB SAMPLE RESULTS OVER HIGHLAND NO. 1 RESERVOIR

Figure 115. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 10/19/2006.

Figure 116. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 10/27/2006.

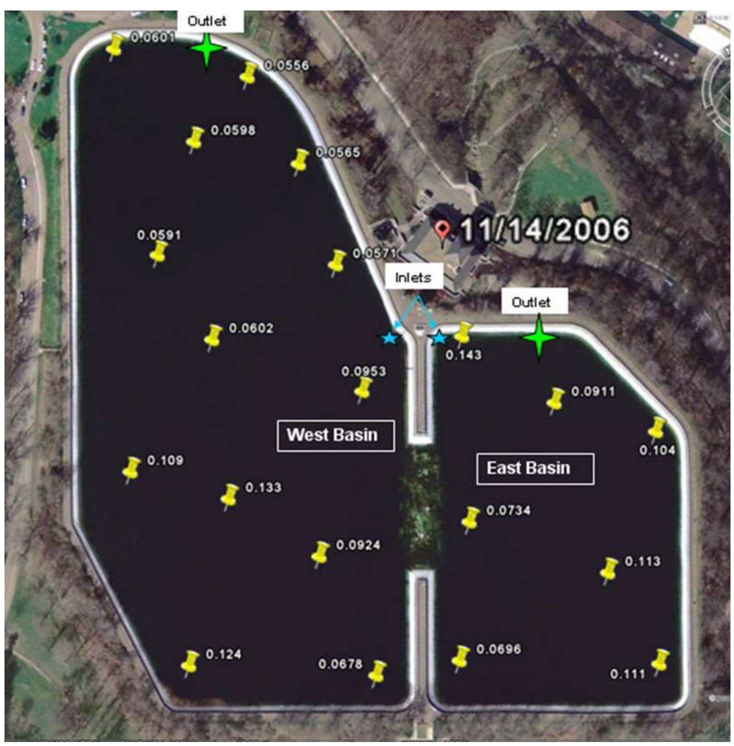

Figure 117. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/14/2006.

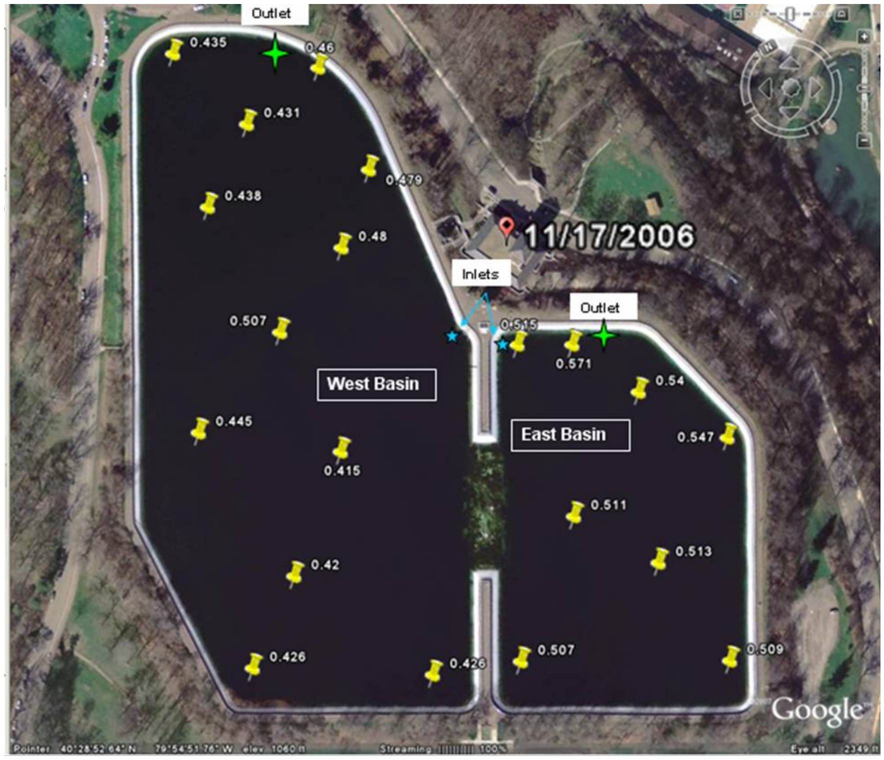

Figure 118. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/17/2006.

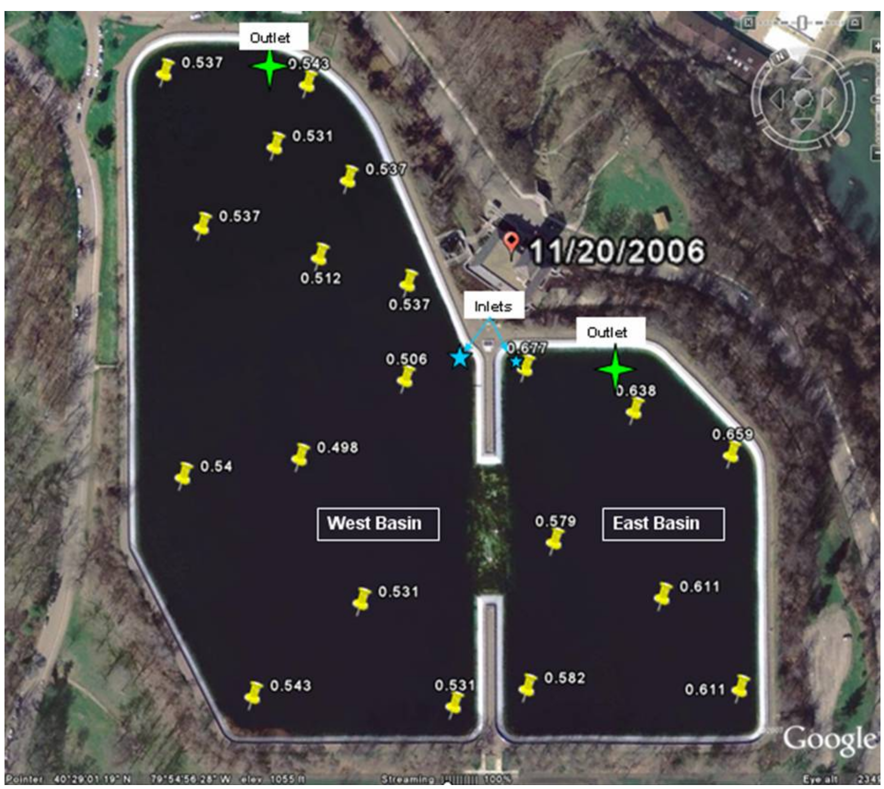

Figure 119. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/20/2006.

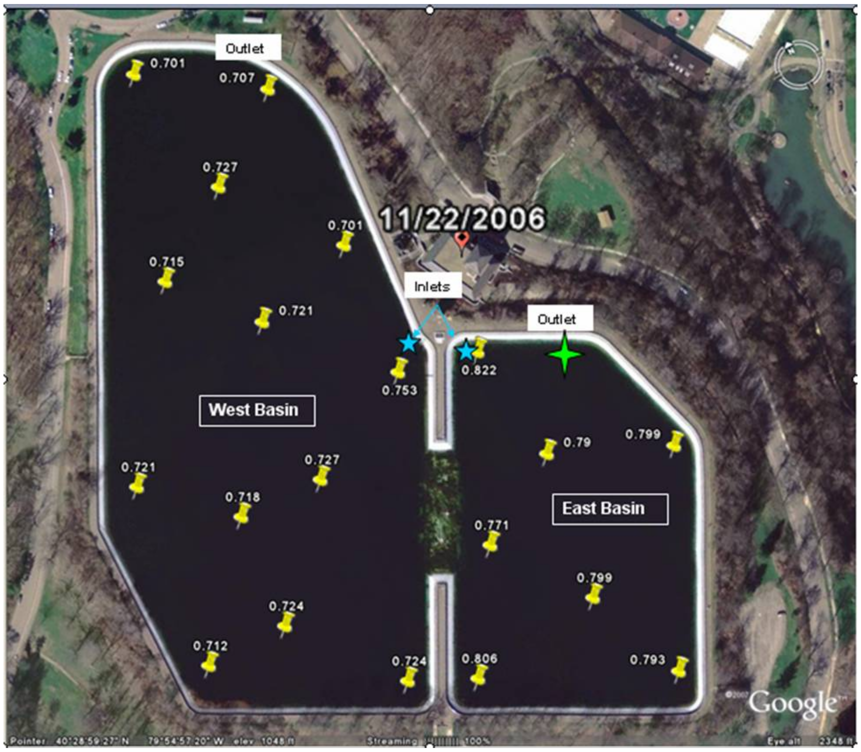

Figure 120. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/22/2006.

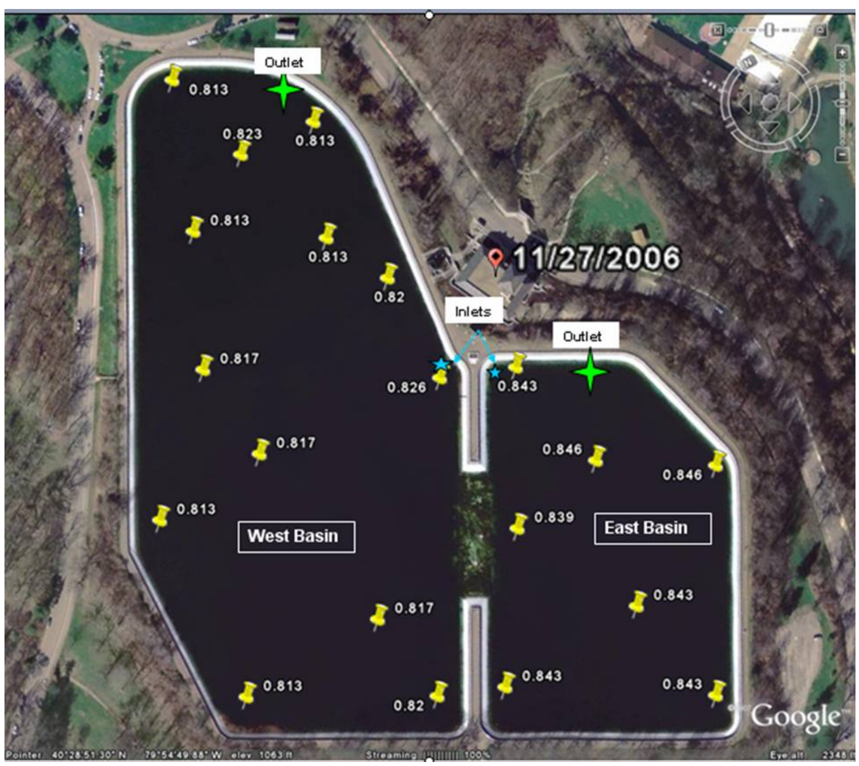

Figure 121. Highland No. 1 Reservoir surface fluoride grab samples (mg/L) 11/27/2006.

APPENDIX E

FLUORIDE GRAB SAMPLE RESULTS OVER HIGHLAND NO. 2 RESERVOIR

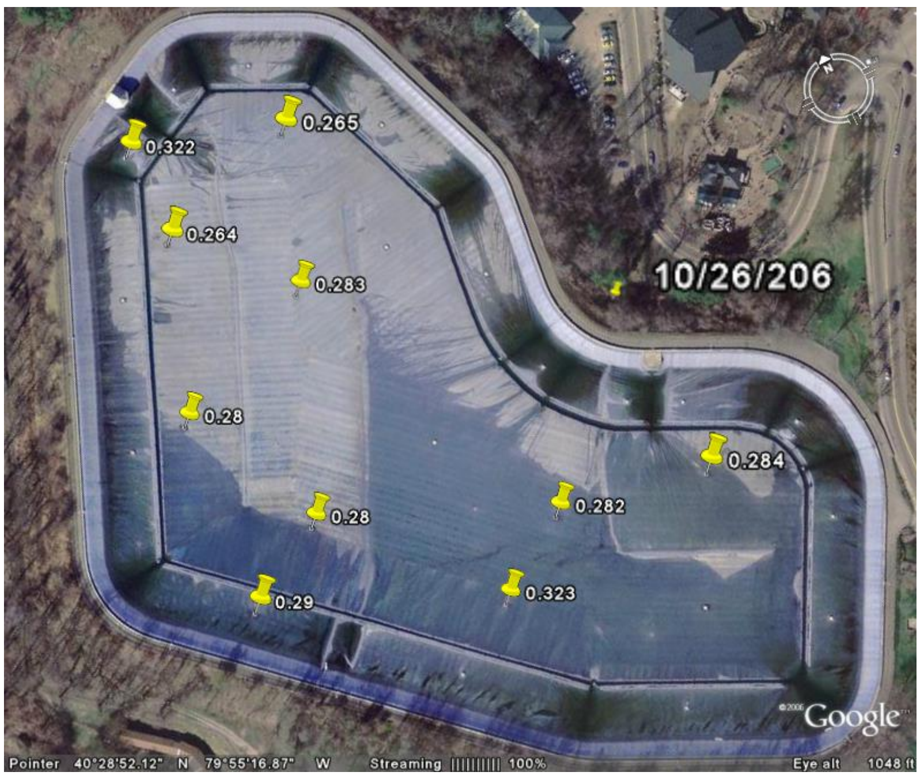

Figure 122. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 10/26/06.

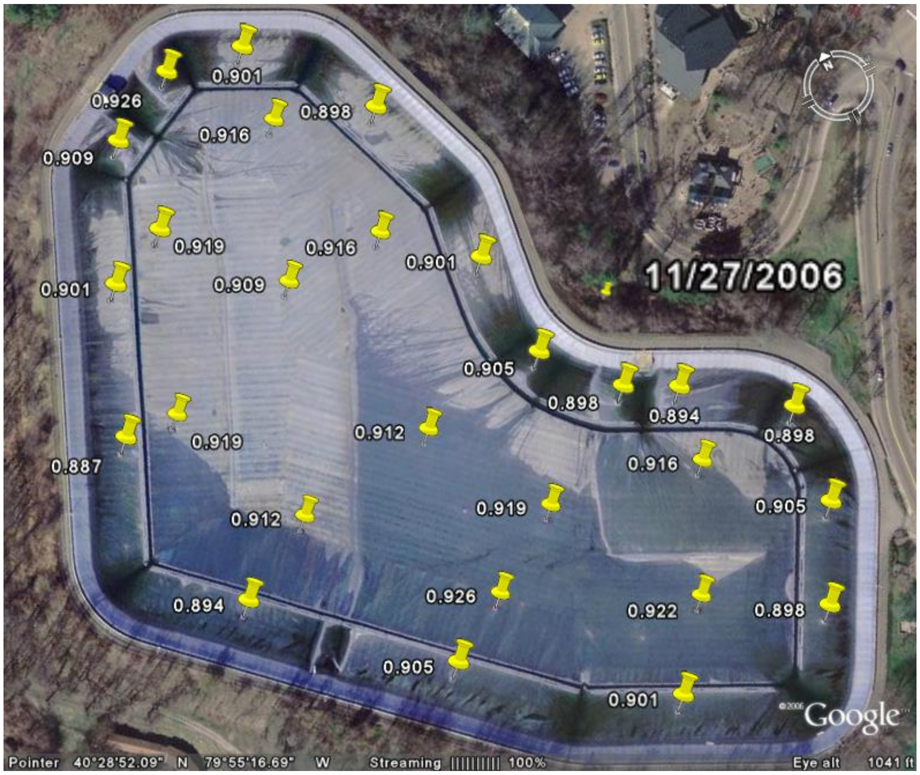

Figure 123. Highland No. 2 Reservoir fluoride floating cover grab samples (mg/L) 11/27/06.

APPENDIX F

FLUORIDE GRAB SAMPLE RESULTS OVER LANPHER RESERVOIR

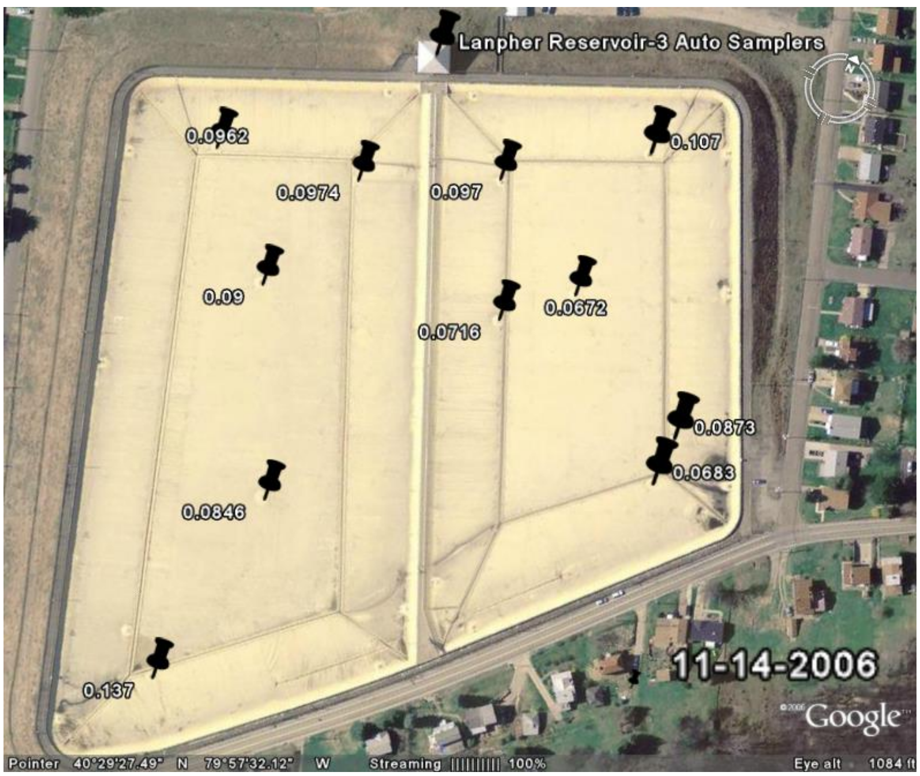

Figure 124. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/14/2006.

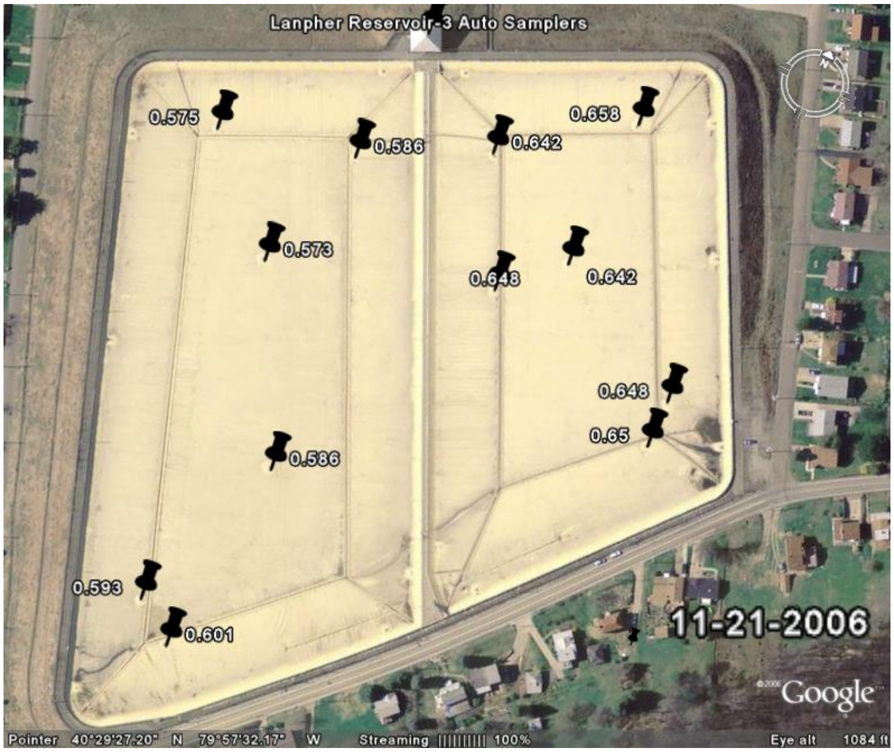

Figure 125. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/21/2006.

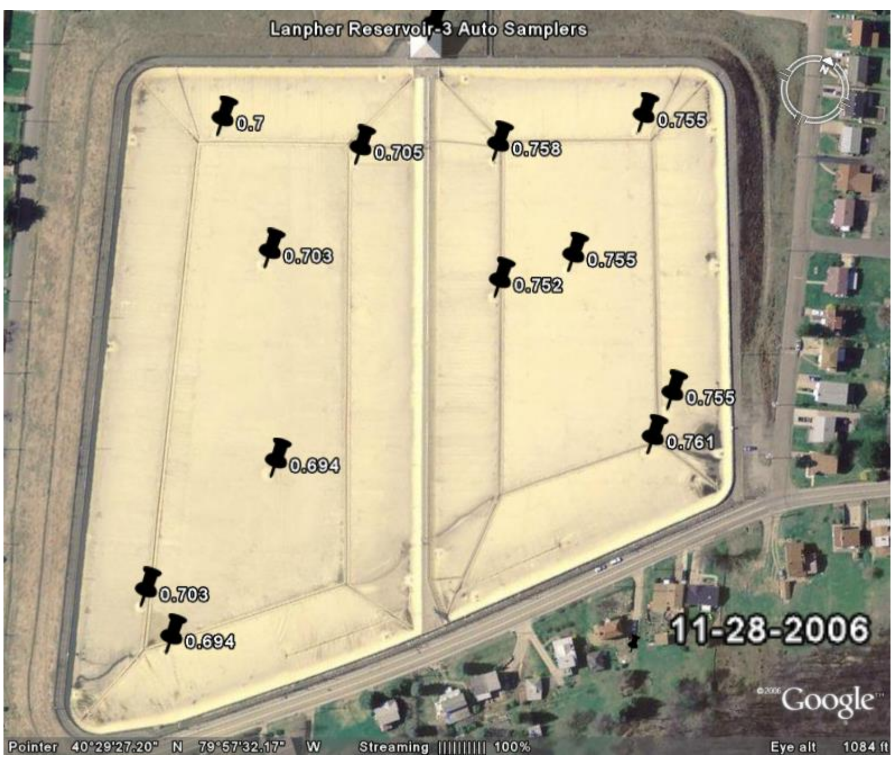

Figure 126. Lanpher Reservoir fluoride floating cover grab samples (mg/L) 11/28/2006.

BIBLIOGRAPHY

ADA. (2005). "Fluoridation Facts." Retrieved May 29, 2007, from http://www.ada.org/public/topics/fluoride/facts/fluoridation_facts.pdf.

APHA (1998). "Fluoride (4500F-)." *Standard Methods for the Examination of Water and Wastewater*. Washington, D.C.: APHA.

AWWA and EES (2002). "Effects of Water Age on Distribution System Water Quality." USEPA Office of Ground Water and Drinking Water Standards and Risk Management Division.

AWWA and EES (2002). "Finished Water Storage Facilities." USEPA Office of Ground Water and Drinking Water Standards and Risk Management Division.

Bolin, B. and H. Rhode (1973). "A note on the concepts of age distribution and residence time in natural reservoir." *Tellus* **25**: 58-62.

Brandt, M., J. Clement, J. Powell, R. Casey, D. Holt, N. Harris and C. T. Ta (2004). *Managing Distribution Retention Time to Improve Water Quality-Phase I*. Denver, Colo.: AwwaRF.

Brandt, M., J. Powell, R. Casey, D. Holt and N. Harris (2006). *Managing Distribution Retention Time to Improve Water Quality-Phase II: Guidance Manual*. Denver, Colo.: AwwaRF, AWWA and IWA.

Clark, R. M., F. Abdesaken, P. F. Boulos and R. E. Mau (1996). "Mixing in Distribution System Storage Tanks: Its Effect on Water Quality." *Journal of Environmental Engineering, ASCE* **122**(9): 814-821.

Clark, R. M., R. C. Thurnau, M. Sivaganesan and P. Ringhand (2001). "Predicting the Formation of Chlorinated and Brominated By-products." *Journal of Environmental Engineering, ASCE* **127**(6): 493-501.

Danckwerts, P. V. (1953). "Continuous flow systems, Distribution of Residence Times." *Chemical Engineering Science* **2**(1): 1-13.

Deleersnijder, E. and E. J. M. Delhez (2005). *The Constituent-oriented Age and Residence time Theory (CART).*

DiGiano, F. A., W. Zhang and A. Travaglia (2005). "Calculation of the mean residence time in distribution systems from tracer studies and models." *Journal of Water Supply: Research and Technology – AQUA* **54**(1).

Edwards, M. and A. Dudi (2004). "Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials." *Journal of American Water Works Association* **96**(10): 69-81.

EPA. (2006). "EPA 816-F-06-001 Stage 2 Disinfectants and Disinfection Byproducts Rule: A Quick Reference Guide for Schedule 1 Systems." Retrieved May 17, 2007, from www.epa.gov/safewater/disinfection/stage2.

Flaherty, T. (2002). "Annual Financial Report of the City of Pittsburgh." from http://www.city.pittsburgh.pa.us/co/assets/City_of_Pgh_CAFR_Final_2002.pdf.

GoogleEarth (200). Retrieved April 25, 2007, from www.earth.google.com.

Grayman, W. M., R. M. Clark and R. M. Males (1988). "Modeling Distribution-System Water Quality: Dynamic Approach." *Journal of Water Resources Planning and Management, ASCE* **114**(3): 295-312.

Grayman, W. M. and R. M. Clark. (1998). "Modeling Water Quality in Drinking Water Distribution Systems." *AWWA*. Denver, Colo.

Grayman, W. M. and G. J. Kirmeyer (2000). "Quality of Water in Storage." *Water Distribution Systems Handbook*. L. S. Mays. New York. NY: McGraw-Hill.

Kennedy, M. S., S. Sarikelle and K. Suravallop (1991). "Calibrating Hydraulic Analysis of Distribution Systems Using Fluoride Tracer Studies." *Journal of the American Water Works Association*(July 1991): 54-59.

Kirmeyer, G. J., M. Friedman, K. D. Martel, P. F. Noran and D. Smith (2005). "Practical Guidelines for Maintaining Distribution System Water Quality." *Water Quality in the Distribution System*. W. C. Lauer. Denver, Colo.: AWWA.

Kirmeyer, G. J., L. Kirby, B. M. Murphy, P. F. Noran, K. D. Martel, T. W. Lund, J. L. Anderson and R. Medhurst (1999). *Maintaining and Operating Finished Water Storage Facilities*. Denver, Colo.: AWWA and AwwaRF.

Lauer, W. C. (2005). "Preventing Water Quality Deterioration in Finished Water Storage Facilities." *Water Quality in the Distribution System*. Denver, Colo.: AWWA.

Lawler, D. and M. M. Benjamin (In Press). "Continuous Flow Reactors: Hydraulic Characteristics." *Physical Chemical Processes*.

Mahmood, F., J. Pimblett, N. Grace and W. Grayman (2005). "Use of CFD Modeling and Temperature Measurement to Improve Water Mixing Characteristics in Water Storage Tanks." *Water Quality in the Distribution System*. W. C. Lauer. Denver, Colo.: AWWA.

Males, R. M., R. M. Clark, P. J. Wehrman and W. E. Gates. (1985). "Algorithm for Mixing Problems in Water Systems." *J. HY, ASCE* **111**(2): 206-219.

Maslanik, J. M. (2006). "Water System Model Updating Project for Pittsburgh Water and Sewer Authority." Pittsburgh, ATS Chester Engineers.

Maslanik, J. M. (2007). "Analysis of Tracer Study Results." Pittsburgh, Chester Engineers.

Maslia, M. L., J. B. Sautner, C. Valenzuela, F. J. Bove and M. M. Aral (2004). *Draft Work Plan-Preliminary Test-Hadnot Point Water Distribution System*. Water Distribution Systems Analysis Symposium (2006), Cincinnati, Ohio: Agency for Toxic Substances and Disease Registry.

Maslia, M. L., J. B. Sautner, C. Valenzuela, W. M. Grayman, M. M. Aral and J. W. Green Jr. (2005). *Use of Continuous Recording Water-Quality Monitoring Equipment for Conducting Water-Distribution System Tracer Tests: The Good, the Bad, and the Ugly*. ASCE/EWRI Congress 2005, Anchorage, Alaska.

Metcalf & Eddy, I. (2003). *Wastewater Engineering: Treatment and Reuse. 4th Edition.* New York, NY: McGraw-Hill Companies, Inc.

Monsen, N. E., J. E. Cloern, L. V. Lucas and S. G. Monismith (2002). "A Comment on the Use of Flushing Time, Residence Time, and Age as Transport Time Scales." *Limnology and Oceanography* **47**(5): 1545-1553.

MWH (2005). *Water Treatment Principles and Design. 2nd Edition*. Hoboken, NJ: John Wiley & Sons, Inc.

PADEP. (2004). "Safe Drinking Water." *Title 25 Environmental Protection* Retrieved May 29, 2007, from http://www.pacode.com/secure/data/025/chapter109/chap109toc.html.

Passantino, L., Z. Chowdhury, L. Devkota, D. Dust and W. Swanson (2005). "Creating a Planning Tool for the City of Phoenix: Using Field Test Results to Calibrate Hydraulic and Water Quality Models." *Water Quality in the Distribution System*. W. C. Lauer. Denver, Colo.: AWWA**:** 1015-1035.

PWSA (1995). "Pittsburgh Water System Schematic."

PWSA (2006). "Finished Water Total Metals Analysis 2005."

PWSA (2006). "Weekly Composite Chemical Analysis of Pittsburgh Drinking Water 2005."

Renner, R. (2005). "Chloramines again linked to lead in drinking water." *Environmental Science & Technology, Science News* Retrieved June 1, 2007, from http://pubs.acs.org/subscribe/journals/esthag-w/2005/jun/science/rr_chloramines.html.

Renner, R. (2006). "Experiment confirms chloramine's effect on lead in drinking water." *Environmental Science & Technology, Science News* Retrieved June 1, 2007, from http://pubs.acs.org/subscribe/journals/esthag-w/2006/apr/science/rr_chloramines.html.

Rossman, L. A., R.M. Clark, and W.M. Grayman (1994). "Modeling Chlorine Residuals in Drinking-Water Distribution Systems." *Journal of Environmental Engineering, ASCE* **120**(4): 803-820.

SAIC (2005). *PipelineNet User's Guide*.

Simon, D., J. Billica, K. Gertig and S. Stone (2006). "Fluoride Tracer Test Planning and Implementation to Support Water Distribution Model Calibration and IDSE Compliance." *8th Annual Water Distribution Systems Analysis Symposium*. Cincinnati, Ohio.

Singer, P. C., H. S. Weinberg, K. Brophy, L. Liang, M. Roberts, I. Grisstede, S. Krasner, H. Baribeau, H. Arora and I. Najm (2002). *Relative Dominance of Haloacetic Acids and Trihalomethanes in Treated Drinking Water*. Denver, Colo.: AwwaRF and AWWA.

States, S. (2006). "PWSA Water Quality Laboratory Manger." C. Daley. Pittsburgh.

Stewart, J. (1999). *Calculus Early Vectors. Preliminary Edition*. Pacific Grove, CA: Brooks/Cole.

Strasser, A., B. Hale and E. J. Koval (2005). "Denver Water’s System Specific Study for the Stage 2 Disinfectants and Disinfection Byproducts Rule." *EWRI 2005 World Water & Environmental Resources Congress* ASCE.

Tarara, J. S., Letter to G. Tutsock (2006). "PADEP Pittsburgh Water and Sewer Authority Fluoride Study Operational Permit." PADEP.

Teefy, S. (1996). *Tracer Studies in Water Treatment Facilities: A protocol and Case Studies*. Denver, Colo.: AWWARF and AWWA.

USEPA. (2006). "Drinking Water Contaminants." Retrieved May 5, 2007, from http://www.epa.gov/safewater/contaminants/index.html.

USEPA. (2006). "Ground Water & Drinking Water." *Drinking Water Contaminants* Retrieved April 25, 2006 from http://www.epa.gov/OGWDW/hfacts.html.

ABBREVIATIONS

ACHD Allegheny County Health Department
APHA American Public Health Association
APM all pipes model
ASCE American Society of Civil Engineers
ATSDR Agency for Toxic Substances and Disease Registry
Ave. avenue
AWTP Aspinwall Water Treatment Plant
AWWA American Water Works Association
AwwaRF American Water Works Association Research Foundation

Bldg Building
Boro Borough

C concentration
C_0 influent concentration,
C_{50} concentration that is 50 percent of the difference between the initial and final concentration
C_{After} concentration of tracer after the tracer step input
C_B baseline concentration
C_{Before} concentration of tracer before the tracer step input
C_F final concentration
CFD computation fluid dynamics
C_{in} influent concentration
CSTR continuous-flow stirred tank reactor
$C(t_i)$ concentration of tracer at the sampling time, t_i

DBP disinfection byproduct
DBPR Disinfectants and Disinfection Byproduct Rule)
DDBP disinfectants/disinfection byproduct
DPD N, N-diethyl-p-phenylenediamine
DW Denver Water

EES Economic and Engineering Services, Inc.
EPS extended period simulations

°F degrees Fahrenheit
FCU Fort Collins Utilities
F-curve cumulative age distribution function or residence time distributions
$F(t_i)$ normalized concentration at time, t_i

GIS geographical information system
gpm gallons per minute
GPS Global Positioning System

HAA5 haloacetic acids

i the i-th sample
ID identification name
IDSE initial distribution system Evaluation

IWA International Water Association

LRAA locational running annual average

MCL maximum contaminant level
mg/L micrograms per liter
MG million gallons
MGD million gallons per day
mg/L milligrams per liter
MRT mean residence time
Mt. Mount

N number of samples
N_{CSTR} number of CSTRs in series
No. number

PADEP Pennsylvania Department of Environmental Protection
PFR plug flow reactor
pH negative logarithm of the effective hydrogen-ion concentration
PWSA Pittsburgh Water and Sewer Authority

Q flow

RAA running annual average
Rd. road

RTD residence time distribution

St. street
Sta. Station
SMP Standard Monitoring Program
SSS System Specific Study

t time
T_{50} $F(t_i) = 0.5$, it is said that 50 percent of the influent molecules have passed through the sampling location and the time is referred to as T_{50}
t_d hydraulic residence time, or theoretical residence time,
t_i the time between the sample and start of the step input
THM trihalomethanes
TTHMs total trihalomethanes
Twp. Township

USEPA United States Environmental Protection Agency
V volume
vs. Versus

WTP water treatment plant