THE EFFECTS OF TANK OPERATION AND DESIGN CHARACTERISTICS ON WATER QUALITY IN DISTRIBUTION SYSTEM STORAGE TANKS

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TABLE OF CONTENTS

TABLE OF CONTENTS iii
LIST OF ABBREVIATIONS vii
LIST OF TABLES ix
LIST OF FIGURES xi
ACKNOWLEDGEMENTS xvi
EXECUTIVE SUMMARY xvii
CHAPTER 1: INTRODUCTION 1
1.1 Background 1
1.2 Purpose and Scope 1
CHAPTER 2: LITERATURE REVIEW 3
2.1 Introduction 3
2.2 Factors Affecting Mixing and Water Age in Storage Tanks 3
2.2.1 Temperature Considerations for Water Storage Tanks 3
2.2.1.1 How Stratification Impacts Mixing in Tanks 3
2.1.1.2 Methods to Predict and Overcome Stratification in Tanks 5
2.2.1.3 Modeling Heat Transfer into Tanks 8
2.2.2 Tank Design Considerations to Promote Mixing 9
2.2.2.1 The Effects of Inlet Size and Configuration on Mixing 10
2.2.2.2 The Effects of Tank Geometry on Mixing 16
2.2.2.3 Installation of Artificial Mixers 16
2.2.2.4 Tank Capacity and Location in the Distribution System 17
2.2.3 The Effects of Tank Operation on Mixing and Water Quality 18
2.3 Modeling Mixing in Tanks 20
2.3.1 Systematic Models 20
2.3.2 Computational Fluid Dynamics 21
2.3.3 Scale Modeling 22
2.3.4 Testing of Models 22
2.3.4.2 Exterior Sampling 23
2.4 The Effects of Water Age on Water Quality 24
2.4.1 Introduction to Disinfectants 24
2.4.1.1 Free Chlorine 24
2.4.1.2 Combined Chlorine (Chloramines) 24
2.4.2 Disinfectant Decay 24
2.4.2.1 Free Chlorine Decay 25
2.4.2.2 Chloramines 26
2.4.3 Nitrification 28
2.4.4 Regulations Relating to Water Age 28
2.4.4.1 Safe Drinking Water Act 29
2.4.4.2 Disinfectants and Disinfection Byproduct Rules 29
2.4.4.3 Total Coliform Rule 29
CHAPTER 3: MATERIALS AND METHODS 30

3.1 Introduction 30
3.2 South Dakota Rural Water Tank Survey 30
3.3 Selection of Tanks for Further Study....................31
3.3.1 Long Term Tank A 32
3.3.2 Long Term Tank B....................33
3.3.3 Long Term Tank C....................34
3.3.4 Long Term Tank D 35
3.3.5 Long Term Tank E....................35
3.3.6 Short Term Tank 1 36
3.3.7 Short Term Tank 2 37
3.3.8 Short Term Tank 3 37
3.3.9 Short Term Tank 4 38
3.3.10 Short Term Tank 5 39
3.3.11 Short Term Tank 6 40
3.3.12 Short Term Tank 7 41
3.3.13 Short Term Tank 8 42
3.4 Equipment to Measure Water Quality and Water Level in Tanks....................43
3.4.1 Long Term Study Apparatus....................43
3.4.2 Short Term Study Apparatus 46
3.5 Sample Collection and Preservation....................49
3.5.1 Long Term Tank Sample Collection and Preservation....................49
3.5.2 Short Term Tank Sample Collection and Preservation....................51
3.6 Water Quality Measurements 51
3.6.1 Temperature Measurements....................51
3.6.2 On-site Water Quality Measurements....................53
3.6.3 Nitrate 53
3.7 Analysis of Mixing Characteristics 54
3.7.1 Extraction of Critical Data Points from Water Level Data....................54
3.7.2 Aspect Ratio of Water Column....................55
3.7.3 Flow Rate during Fill....................55
3.7.4 Velocity of inflow....................55
3.7.5 Reynolds Number 55
3.7.6 Detention Time 56
3.7.7 Fill Time Required to Achieve a 90% Mixed Tank....................56
3.7.8 Volumetric Exchange Required to Achieve a 90% Mixed Tank....................56
3.7.9 Velocity Gradient Calculation for Ice prevention Mixer....................57
3.7.10 Special Consideration for Short Term Tank 5 57
3.8 Analysis of Temperature Affects on Tank Performance 57
3.8.1 Correlating Ambient Temperature to Internal Tank Temperature....................57
3.8.2 Strategies to Overcome Stratification in Reservoirs....................58
3.8.2.1 Densimetric Froude Number....................58
3.8.2.2 Other Hydraulic Considerations for Stratified Tanks....................58
3.8.2.3 Critical Temperature Difference to Cause Stratification 58
3.9 Systematic Modeling of Tanks....................58

CHAPTER 4: RESULTS AND DISCUSSION 61
4.1 Introduction 61
4.2 South Dakota Rural Water Tank Survey 61
4.3 Long Term Tank Studies 64
4.3.1 Long Term Tanks A and B 64
4.3.2 Long Term Tank C 69
4.3.3 Long Term Tank D 73
4.3.4 Long Term Tank E 78
4.4 Short Term Tank Studies 84
4.4.1 Short Term Tank 1 84
4.4.2 Short Term Tank 2 85
4.4.3 Short Term Tank 3 86
4.4.4 Short Term Tank 4 88
4.4.5 Short Term Tank 5 90
4.4.6 Short Term Tank 6 92
4.4.7 Short Term Tank 7 94
4.4.8 Short Term Tank 8 96
4.5 Comparison of Long and Short Term Temperature Data 98
4.6 Analysis of Mixing Parameters 101
4.6.1 Operational Aspect Ratios 101
4.6.2 Reynolds Number of Filling Jet 103
4.6.3 Fill Time and Volumetric Exchange Ratio Requirements 104
4.6.4 Critical Temperature Difference to Cause Stratification 109
4.6.5 Densimetric Froude Number 110
4.6.6 Dimensionless Mixing Parameter 116
4.6.7 Tank Detention Time 119
4.7 Relating Stratification to Ambient Temperature 120
4.8 Disinfectant Decay Models in Long Term Tanks 127
4.8.1 Long Term Tank A 127
4.8.2 Long Term Tank B 128
4.8.3 Long Term Tank C 130
4.8.4 Long Term Tank D 133
4.8.5 Long Term Tank E 136
CHAPTER 5: SUMMARY AND CONCLUSIONS 139
5.1 Summary of Work Tasks 139
5.2 Conclusions 139
CHAPTER 6: OPERATION AND DESIGN CONSISDERATIONS FOR TANKS 144
CHAPTER 7: RECOMMENDATIONS FOR FUTURE WORK 145
REFERENCES 146
APPENDIX A 150
APPENDIX B 152
APPENDIX C 164
APPENDIX D 165
APPENDIX E 171

APPENDIX F 180
APPENDIX G 194
APPENDIX H 208
APPENDIX I 222

LIST OF ABBREVIATIONS

H:D Ratio	Height to diameter ratio (or aspect ratio)
^{0}C	Degrees Celsius
ft/s	Feet per second
gpm	Gallons per minute
ft	Feet
ft/s^2	Feet per second squared
slug/ft^3	Slug per cubic foot
ft^3/s	Cubic feet per second
BTU	British thermal unit
lb/ft^3	Pounds per cubic foot
ft-s/lb	Feet-second per pound
lb-ft/s	Foot pounds per second
lb-s/ft^2	Pound-second per square foot
sec	Second
s^{-1}	Per second
CFD	Computational fluid dynamics
TTHM	Total trihalomethanes
HAA5	Haloaecetic acid
NDMA	*N*-Nitrosodimethylamine
ng/L	Nanograms per liter
EPA	Environmental Protection Agency
SCADA	Tank system control and data acquisition
mg/L	Milligrams per liter
mg/L as N	Milligrams per liter expressed as nitrogen
MCL	Maximum contaminant level
DBP	Disinfection byproduct
AOB	Ammonia oxidizing bacteria
NOB	Nitrite oxidizing bacteria
NOM	Natural organic matter
LTA	Long term tank A
LTB	Long term tank B
LTC	Long term tank C
LTD	Long term tank D
LTE	Long term tank E
ST1	Short term tank 1
ST2	Short term tank 2
ST3	Short term tank 3
ST4	Short term tank 4
ST5	Short term tank 5
ST6	Short term tank 6
ST7	Short term tank 7

ST8	Short term tank 8
Mgal	Million gallons
WEERC	Water and Environmental Engineering Research Center
SDSU	South Dakota State University

LIST OF TABLES

Table E.1. Characteristics of selected tanks for long term study. xx
Table E.2. Tanks selected for short term studies xx
Table 2.1. Slopes of densimetric Froude number as a function of water height/inlet diameter (Rossman and Grayman 1999)... 6
Table 2.2. Summary of scale model studies with single inlets and buoyancy effects (Roberts et al. 2006).. 8
Table 2.3. Dimensionless mixing times to achieve complete mixing in unstratified ground storage facilities (using data from Roberts et al. 2006). 13
Table 2.4. Dimensionless mixing times to achieve complete mixing in unstratified standpipes (using data from Roberts et al. 2006)... 14
Table 2.5. Guidelines for water turnover rate in storage tanks (Kirmeyer et al. 1999). .. 19
Table 2.6. Free chlorine decay constants from pipes on the Norfolk Navy Base (Jones 2002). 26
Table 2.7. Combined chlorine decay constants from pipes on the Norfolk Navy Base (Jones 2002). 27
Table 3.1. Characteristics of selected tanks for long term study. 31
Table 3.2. Tanks selected for short term studies... 32
Table 3.3. Response times for thermocouple cables. 45
Table 3.4. Specifications for HOBO Prov2 Water Temperature data loggers................. 47
Table 3.5. Specifications for HOBO U20 Water Level Data Loggers. 47
Table 3.6. Methods and reagents used for on-site water quality testing. 53
Table 4.1. Comparisons of most similar long term tank to short term tank based on operational aspect ratio 100
Table 4.2. Operational aspect ratios of tanks studied. 102
Table 4.3. Reynolds numbers of filling jets. 103
Table 4.4. Average fill time and volumetric exchange data and requirements each tank. 108
Table 4.5. Characteristics of critical temperature difference to cause stratification...... 110
Table 4.6. Characteristics of densimetric Froude numbers for the various tanks. 115
Table 4.7. $M^{1/2}/(B^{1/3}H^{2/3})$ required and actual values for each tank............................. 119
Table 4.8. Detention time characteristics for all tanks (hours). 120
Table 4.9. Empirical relationships between temperature inside and outside of tanks. .. 122
Table 4.10. Inputs for the long term tank A model.. 127
Table 4.11. Inputs for the long term tank B model. 129
Table 4.12. Inputs for the stratified long term tank C model. 130
Table 4.13. Inputs for the completely mixed long term tank C model. 132
Table 4.14. Inputs for the stratified long term tank D model. 133
Table 4.15. Inputs for the completely mixed long term tank D model. 135
Table 4.16. Inputs for the stratified long term tank E model. 136
Table 4.17. Inputs for the completely mixed long term tank E model. 137
Table A.1. Systematic Models for Mixing Characteristics in Storage Tanks................ 150

Table B.1. Data points used in sample calculations for mixing parameters. 152
Table B.2. Data to calculate total chlorine decay coefficients (Drews, 2009).............. 162
Table C.1. Information collected from the South Dakota rural water tank survey........ 164
Table D.1. Water quality data collected for long term tank A (concentrations in mg/L).. 165
Table D.2. Water quality data collected for long term tank B (concentrations in mg/L).. 166
Table D.3. Water quality data collected for long term tank C (concentrations in mg/L).. 166
Table D.4. Water quality data collected for long term tank D (concentrations in mg/L).. 167
Table D.5. Water quality data collected for long term tank E (concentrations in mg/L).. 168
Table D.6. Water quality data collected for short term tanks (concentrations in mg/L).. 170

LIST OF FIGURES

Figure 2.1. Temperature effects as a result of positively and negatively buoyant jets (Adapted from Grayman et al. 2004). 4
Figure 2.2. CFD model comparing a negatively buoyant jet to isothermal conditions (Mahmood et al. 2005). 5
Figure 2.3. Ideal jet mixing characteristics using vertical and horizontal jets (adapted from Grayman, et al. 2004). 10
Figure 2.4. Inlet configurations which have an increased risk of poor mixing (Adapted from Grayman et al. 2004). 15
Figure 2.5. Temperature data collection apparatus used to validate CFD models (Mahmood et al. 2005). 23
Figure 2.6. Disinfectant loss in mixed and plug flow tanks with continuous inflow/outflow (Grayman et al. 2000) 25
Figure 3.1. Long term tank A. 33
Figure 3.2. Long term tank B. 34
Figure 3.3. Long term tank C. 34
Figure 3.4. Long term tank D. 35
Figure 3.5. Long term tank E. 36
Figure 3.6. Short term tank 1. 36
Figure 3.7. Short term tank 2. 37
Figure 3.8. Short term tank 3. 38
Figure 3.9. Recirculation pump in short term tank 3. 38
Figure 3.10. Short term tank 4. 39
Figure 3.11. Short term tank 5. 40
Figure 3.12. Short term tank 6. 41
Figure 3.13. Short term tank 7. 42
Figure 3.14. Short term tank 8. 42
Figure 3.15. Visual representation of the data logging and sampling system. 43
Figure 3.16. Photograph of the OCTTEMP series data logger. 44
Figure 3.17. Computer interface connection (*www.omega.com*). 45
Figure 3.18. Short term temperature apparatus. 46
Figure 3.19. Attachment of short term tank cables to tank. 48
Figure 3.21. Apparatus to draw samples from tanks. 50
Figure 3.22. Apparatus to prime sampling tubes. 50
Figure 3.23. Unfiltered tank depth temperatures 52
Figure 3.24. HACH DR/890 colorimeter. 53
Figure 3.25. Example of extracted water level data. 55
Figure 4.1. Distribution of tanks in SD's regional water systems by number of tanks. 62
Figure 4.2. Distribution of tanks in SD's regional water systems by total storage volume. 62
Figure 4.3. Minimum, average, and maximum volumes for various tank types. 63
Figure 4.4. Distribution of at-grade tanks by aspect ratio category. 64

Figure 4.5. Long term tank A temperature profile (operational H:D = 0.13). 66
Figure 4.6. Long term tank B temperature profile (operational H:D = 0.54). 67
Figure 4.7. Water quality in long term tank A on October 21, 2010. 68
Figure 4.8. Water quality in long term tank B on October 21, 2010. 68
Figure 4.9. Long term tank C temperature profile (operational H:D = 0.88). 70
Figure 4.10. Water quality in long term tank C under stratified conditions. 71
Figure 4.11. Water quality in long term tank C under unstratified conditions. 71
Figure 4.12. Long term tank C enhanced temperature profile. 72
Figure 4.13. Long term tank D temperature profile, sampling events and operations (operational H:D = 3.55). 74
Figure 4.14. Long term tank D water quality data on August 11th. 75
Figure 4.15. Long term tank D enhanced temperature profile during and after drain. 76
Figure 4.16. Long term tank D water quality data following the first drain of the tank.. 77
Figure 4.17. Long term tank D water quality data following the second drain of the tank. 78
Figure 4.18. Long term tank E temperature profile (operational H:D = 4.80). 80
Figure 4.19. Water quality in long term tank E prior to any operational changes. 81
Figure 4.20. Water quality in long term tank E after ice prevention mixer installation. . 81
Figure 4.21. Water quality in long term tank E after overflow. 82
Figure 4.22. Water quality in long term tank E on October 20th. 83
Figure 4.23. ST1 temperature profile and water level. 84
Figure 4.24. ST1 total chlorine concentrations. 85
Figure 4.25. ST2 temperature profile and water level. 86
Figure 4.26. ST3 temperature profile and water level. 87
Figure 4.27. ST3 total chlorine concentrations. 88
Figure 4.28. ST4 temperature profile and water level. 89
Figure 4.30. ST5 temperature profile and water level. 91
Figure 4.31. ST5 chlorine concentrations. 91
Figure 4.32. ST6 temperature profile and water level. 92
Figure 4.33. Water level, ambient temperature, and measurement points in ST6. 93
Figure 4.34. ST6 chlorine concentrations. 94
Figure 4.35. ST7 temperature profile and water level. 95
Figure 4.36. ST7 total chlorine concentrations. 96
Figure 4.37. ST8 temperature profile and water level. 97
Figure 4.38. ST8 total chlorine concentrations. 97
Figure 4.39. Comparison of short term tanks 1 and 4 with long term tank E. 98
Figure 4.40. Comparison of short term tank 2 with long term tank A. 99
Figure 4.41. Temperature profiles, and actual and required volumetric exchange ratios for long term tank A. 105
Figure 4.42. Temperature profiles, and actual and required volumetric exchange ratios for long term tank E. 106
Figure 4.43. Densimetric Froude numbers for long term tank A. 111
Figure 4.44. Densimetric Froude numbers for long term tank E. 112
Figure 4.45. Densimetric Froude numbers for long term tank C. 114

Figure 4.46. $M^{1/2}/(B^{1/3}H^{2/3})$ for long term tank A. 117
Figure 4.47. $M^{1/2}/(B^{1/3}H^{2/3})$ for long term tank E... 118
Figure 4.48. Relationship of temperature inside and outside of LT4. 122
Figure 4.49. Comparison of temperatures of water leaving the plant and LT5. 123
Figure 4.50. Long term tank D ambient, upper zone, and lower zone temperatures. 125
Figure 4.51. Long term tank E ambient, upper zone, and lower zone temperatures. 126
Figure 4.52. Completely mixed model for long term tank A....................................... 128
Figure 4.53. Completely mixed model for long term tank B. 129
Figure 4.54. Stratified three compartment model results for long term tank C. 131
Figure 4.55. Completely mixed model for long term tank C. 132
Figure 4.56. Stratified model for long term tank D. 134
Figure 4.57. Completely mixed model for long term tank D....................................... 135
Figure 4.58. Stratified model for long term tank E. 137
Figure 4.59. Completely mixed model for long term tank E. 138
Figure B.1. Schematic of short term tank 5. 155
Figure B.2. Simplified shape for short term tank 5 diameter calculation. 159
Figure B.3. Total chlorine decay at various temperatures and chlorine:ammonia ratios.. 162
Figure E.1. Comparison of short term tank 1 with long term tank E............................ 172
Figure E.2. Comparison of short term tank 2 with long term tank B. 173
Figure E.3. Comparison of short term tank 3 with long term tank B. 174
Figure E.4. Comparison of short term tank 4 with long term tank E............................ 175
Figure E.5. Comparison of short term tank 5 with long term tank C. 176
Figure E.6. Comparison of short term tank 6 with long term tank C. 177
Figure E.7. Comparison of short term tank 7 with long term tank B. 178
Figure E.8. Comparison of short term tank 8 with long term tank B. 179
Figure F.1. Temperature profile with actual and required volumetric exchange ratios for long term tank A... 181
Figure F.2. Temperature profile with actual and required volumetric exchange ratios for long term tank B. 182
Figure F.3. Temperature profile with actual and required volumetric exchange ratios for long term tank C. 183
Figure F.4. Temperature profile with actual and required volumetric exchange ratios for long term tank D... 184
Figure F.5. Temperature profile with actual and required volumetric exchange ratios for long term tank E. 185
Figure F.6. Temperature profile with actual and required volumetric exchange ratios for short term tank 1.. 186
Figure F.7. Temperature profile with actual and required volumetric exchange ratios for short term tank 2.. 187
Figure F.8. Temperature profile with actual and required volumetric exchange ratios for short term tank 3.. 188
Figure F.9. Temperature profile with actual and required volumetric exchange ratios for short term tank 4.. 189

Figure F.10. Temperature profile with actual and required volumetric exchange ratios for short term tank 5.. 190
Figure F.11. Temperature profile with actual and required volumetric exchange ratios for short term tank 6.. 191
Figure F.12. Temperature profile with actual and required volumetric exchange ratios for short term tank 7.. 192
Figure F.13. Temperature profile with actual and required volumetric exchange ratios for short term tank 8.. 193
Figure G.1. Temperature profile with actual and required densimetric Froude numbers for long term tank A.. 195
Figure G.2. Temperature profile with actual and required densimetric Froude numbers for long term tank B.. 196
Figure G.3. Temperature profile with actual and required densimetric Froude numbers for long term tank C.. 197
Figure G.4. Temperature profile with actual and required densimetric Froude numbers for long term tank D.. 198
Figure G.5. Temperature profile with actual and required densimetric Froude numbers for long term tank E.. 199
Figure G.6. Temperature profile with actual and required densimetric Froude numbers for short term tank 1.. 200
Figure G.7. Temperature profile with actual and required densimetric Froude numbers for short term tank 2.. 201
Figure G.8. Temperature profile with actual and required densimetric Froude numbers for short term tank 3.. 202
Figure G.9. Temperature profile with actual and required densimetric Froude numbers for short term tank 4.. 203
Figure G.10. Temperature profile with actual and required densimetric Froude numbers for short term tank 5.. 204
Figure G.11. Temperature profile with actual and required densimetric Froude numbers for short term tank 6.. 205
Figure G.12. Temperature profile with actual and required densimetric Froude numbers for short term tank 7.. 206
Figure G.13. Temperature profile with actual and required densimetric Froude numbers for short term tank 8.. 207
Figure H.1. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank A... 209
Figure H.2. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank B... 210
Figure H.3. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank C... 211
Figure H.4. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank D... 212
Figure H.5. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank E... 213

Figure H.6. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 1 214
Figure H.7. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 2 215
Figure H.8. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 3 216
Figure H.9. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 4 217
Figure H.10. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 5 218
Figure H.11. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 6 219
Figure H.12. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 7 220
Figure H.13. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 8 221
Figure I.1. Relationship of temperature inside and outside of long term tank D 223
Figure I.2. Relationship of temperature inside and outside of long term tank E 224

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EXECUTIVE SUMMARY

BACKGROUND

Regional water systems utilize storage facilities to meet demand variations and pressure requirements of their systems. These storage facilities drain and fill in response to system water demands and water level control settings. Storage tanks are typically placed in strategic locations to maintain a consistent pressure in the distribution system.

Storage facilities should be designed and operated such that the water is mixed to prevent stagnant water (old water that remains in the tank for an extended period). Stagnant water can lead to water quality issues, such as low disinfectant residuals, potential for microbial contamination, disinfectant by-product formation, and nitrification in chloraminated waters. Many tanks have been built without consideration of mixing. These tanks might have a single inlet/outlet, high height to diameter ratio, or have other design characteristics that do not promote mixing. Whether by design or not, tanks without artificial mixing depend upon movement of water during the filling process to mix the tank.

A wide array of storage tank types and geometries are utilized in South Dakota's regional rural water systems. Greater understanding of the relationships of these tank characteristics on stored water quality would enable water systems to optimize the design and operation of their tanks.

OBJECTIVE OF STUDY

The objective of this study was to examine the impacts of tank design and operation on mixing and water quality in storage tanks in South Dakota's regional rural water systems. This objective was met through a literature review, a survey of system characteristics and evaluation of water quality data obtained from several storage tanks.

APPROACH

In order to assess the effects of tank operations and design on water quality in tanks, several work tasks were performed.

1. A literature was review was performed to summarize the work of others who have examined relationships between tank mixing and water quality and provide a basis on which to compare the results of experimental work conducted in this study.
2. A survey of rural water systems throughout the state was conducted to gather information about rural water system tanks and to identify study tanks which

would represent the tank population. Five long-term tanks and 8 short-term tanks were selected for water quality monitoring.

3. Apparatuses were constructed and installed in the long-term study tanks to record temperature and draw samples from various depths. Two apparatuses were constructed to record water level and temperature from various depths within the short-term study tanks. Water quality samples were taken during site visits to long term tanks to test for residual disinfectant concentrations and evidence of nitrification. Temperature measurement equipment for short-term tanks was removed, data downloaded, reconfigured for the next short term tank and installed in the next tank. Several water samples taken when the equipment was installed, removed, or both were analyzed for residual disinfectant concentrations, and other water quality parameters.
4. Water level data was obtained from water systems for long term study tanks and from pressure transducers installed in short term tanks. These data were used to calculate the following parameters for use in data analysis:
    a. Aspect ratio of the water column
    b. Reynolds number
    c. Tank detention time
    d. Fill time to mix the tank
    e. Volumetric exchange required to mix the tank
    f. Densimetric Froude number
    g. Dimensionless mixing parameter
    h. Critical temperature difference to cause stratification
5. The CompTank program was used to create models that predicted chlorine decay in tanks under various mixing configurations.

SUMMARY OF RESULTS AND CONCLUSIONS

Literature Review

Selected aspects of the literature review are summarized as follows:

1. Variations in temperature between stored and filling water can form stratified layers in the tank and negatively impact mixing. When the inflow is colder than the stored water, a negatively buoyant jet is formed, where younger (inflow) water will sit at the base of the water column. If the inflow is warmer than the surrounding volume, a positively buoyant jet will form and the younger water will rise to the top. Literature suggests a correlation between temperature stratification and low chlorine residuals in dead zones of tanks.
2. Hydraulic parameters are presented in this literature review provide guidance to design engineers and operators to optimize mixing in tanks, including: the Reynolds number, filling time (and its related volumetric exchange), critical temperature difference to cause stratification, densimetric Froude number, and a dimensionless mixing parameter.

3. Inlet configuration and sizing can affect mixing. Literature suggests that under negatively buoyant jets, vertical inlets promote mixing better than horizontal inlets, while under positively buoyant conditions, horizontal inlets are better. Certain inlet configurations have an increased risk of poor mixing, including: tangential inlets, inlets directed at wall, baffles or deflectors, and large diameter inlets. Smaller diameter inlets can increase the momentum of the inflow and subsequently promote mixing in tanks.
4. Taller, more slender tanks (such as standpipes) tend to be more difficult to mix than shorter, wider tanks.
5. Proprietary mixing systems are available to install in tanks which are prone to poor mixing.
6. Tank location in the distribution system and capacity can lead to long turnover time and increased chlorine decay. Guidelines for detention time from various sources range from one to seven days.
7. Systematic models are introduced, which consist of applying model equations to tracer data to predict the mixing characteristics of in place tanks.
8. Computational fluid dynamic (CFD) models are introduced which apply three-dimensional hydraulic calculations to visualize flow patterns within tanks. CFD simulations require the use of computers to perform the thousands of calculations required to produce accurate model results.
9. Methods of drawing samples and taking temperature measurements from various locations within tanks are introduced. These samples can be used to verify CFD or systematic models, or to simply provide information on water quality at those various points in a tank.
10. The effects of high water age on water quality are introduced, including disinfectant decay, disinfectant byproduct formation, and nitrification. Regulations relating to water age are also introduced, including the Safe Drinking Water Act, Stage 1 and 2 Disinfection/Disinfection By-product Rule, and the Total Coliform Rule.

Survey of Storage Tanks in South Dakota's Rural Water Systems

A survey tool was created to assess the characteristics of tanks used in South Dakota's regional rural water systems. The survey results indicated that fifty-one percent of the storage tanks were above-ground reservoirs or standpipes and the remaining tanks were elevated tanks, under-ground reservoirs or clearwells. Above-ground reservoirs and standpipes contained sixty-six percent of the total storage volume provided by rural water system storage facilities. Since the above-ground reservoirs and standpipes comprised the majority of storage volume, they became the focus of the water quality monitoring tasks.

Five above-ground reservoirs and standpipes were selected based on height to diameter ratio for long term studies (three to four months). All five long term study tanks were operated by systems using surface water sources and chloramine as a secondary disinfectant. Characteristics of the five tanks selected for long term study are shown in Table E.1. The artificial mixers in tanks D and E were installed for ice prevention.

Table E.1. Characteristics of selected tanks for long term study.

H:D Group	Tank Name	Capacity (gal)	Height (ft)	Diameter (ft)	H:D Ratio	Common Inlet/Outlet	Artificial Mixer Installed
0-0.5	A	948,000	24	81	0.30	Y	N
0.5-1	B	559,000	38	50	0.76	N	N
1-2	C	65000	28	20	1.41	Y	N
2-4	D	175,000	75	20	3.75	Y	Y
>4	E	140,000	86	14	6.14	Y	Y

Eight tanks were selected for short term study (one to four weeks). Characteristics of these tanks are shown in Table E.2.

Table E.2. Tanks selected for short term studies

ST Tank Number	Type	Capacity (Mgal)	Storage Height (ft)	Diameter (ft)	H:D Ratio	Surface Water	Chloramine	Single Inlet/Outlet	Multiple Inlet/Outlet	Artificial Mixer	Notes
1	Standpipe	241,000	107	20	5.4	N	N	Y	Y	N	Far drawdown in winter causes pressure problems
2	Elevated	300,000	45	26[1]	0.59	N	Y	Y	N	N	
3	Elevated	440,000	31	49[1]	0.63	N	N	Y	N	Y	Recirculation pump in winter
4	Standpipe	100,000	120	12	10	N	N	N	Y	N	Static mixer to be installed fall 2010 or spring 2011
5	Elevated	500,000	50	32.7[2]	1.53	N	N	Y	N	Y	Recirculation pump in winter
6	Standpipe	125,000	46	22	2.1	N	N	Y	N	N	Offline in winter due to ice
7	Elevated	1.5 Mgal	50	83[1]	0.60	Y	Y	Y	N	N	Near treatment plant but is always full
8	Elevated	250,000	27	40[1]	0.68	Y	Y	Y	N	N	Low demand, far end of system

[1]Calculated assuming cylindrical shape of tank volume
[2]Representative diameter, due to the turnip-shape of the tank

The Effects of Tank Geometry on Mixing and Water Quality

Tank geometry appeared to play a role in the mixing of long term tanks. Long term tanks A and B (operational H:D = 0.13 and 0.54, respectively) both exhibited good mixing characteristics based on temperature and water quality profiles. Long term tanks A and B were in the aboveground reservoir (H:D < 1) category which would lead one to believe that all tanks in this category are well mixed. However, some short term tanks which had aspect ratios less than 1.0 exhibited stratification as a result of a lack of volumetric exchange and inflow momentum. Even though the geometry of low aspect ratio tanks promotes mixing, they should be designed and operated with appropriate volumetric exchange and inflow momentum to enhance mixing.

Long term tanks D and E (H:D > 3.5) presented substantial mixing issues in August as a result of warmer water in their upper zones compared to the lower zone (the upper zone was 15 ^{o}C warmer in tank D and 7 ^{o}C warmer in tank E). Before any operational attempts to destratify the tank, the water in the warmer, upper zone of tank E contained 0.07 mg/L of total chlorine, while its bottom zone contained 0.92 mg/L. Similarly, prior to any operational de-stratification attempts, total chlorine concentrations in the warmer, upper zone of tank E ranged from 0.11 to 0.16 mg/L, while the chlorine concentrations at the bottom zone ranged from 1.26 to 1.31 mg/L. These tanks were stratified from both temperature and water quality standpoints. Short term tank data for similar aspect ratio tanks reinforced the long term tank data. The water in the top zone of short term tank 1 (H:D of 4.82) was 8 ^{o}C warmer than the bottom zone, and chlorine residuals were 0.94 mg/L at the bottom compared to 0.05 mg/L at the top. The presence of thermal stratification and depleted chlorine residuals in the upper zones of these tanks indicate that tanks with aspect ratios greater than 3.5 are at risk for poor mixing and water quality.

Based on temperature and chlorine residual profiles from tanks examined in this study, shorter, wider tanks were less susceptible to poor mixing and stratification than standpipes. While tanks with smaller aspect ratios lend to better mixing, their design and operation must still be optimized to enhance mixing.

Effects of Ambient Temperature on Mixing

A visual interpretation of long term temperature data indicated that the water temperature and water quality of standpipes with aspect ratios greater than 3.5 were strongly influenced by the ambient temperature (see Figures 4.50 and 4.51). When the ambient temperature (outside the tank) was greater than approximately 15^{0} C, the water in these standpipes tended to stratify, resulting in increased rates of chlorine decay in the upper, warmer zone. When the temperature of the upper zones of tanks was similar to that of the water filling the tanks, buoyant forces were minimized allowing tanks to mix more readily, enabling uniform chlorine residual throughout the tank depth. Stratified tanks examined in this study tended to destratify when the temperature outside of the tank reached 15 degrees C (average of the daily high and low temperatures) on a consistent basis.

Evaluation of Various Hydraulic Parameters

1. **Reynolds number**

   The Reynolds of the water jets filling the tanks were all above the threshold of 3,000 (value needed to ensure that a mix-promoting turbulent jet occurs). The lowest Reynolds number recorded was 3,670 (short term tank 1) and the lowest average Reynolds number was 6,010 (short term tank 2). Maintaining the Reynolds number greater than 3,000 was not sufficient to mix all tanks examined in the study.

2. **Fill time and volumetric exchange**

   All tanks which achieved the required filling time and associated volumetric exchange ratio were well mixed (indicated by uniform residual disinfectant concentrations throughout the tank depth). Long term tanks A, B, and C were all well mixed and achieved 341%, 209%, and 214% of their required volumetric exchange, respectively.

   Long term tank C achieved more than twice its required volumetric exchange during filling cycles, and although it presented evidence of stratification, tank C maintained adequate disinfectant residuals within the tank (1.9 mg/L to 2.3 mg/L). During the warm summer months, tanks which did not meet the required volumetric exchange exhibited stratification.

3. **Critical temperature difference to cause stratification**

   The critical temperature difference to cause stratification was higher for tanks which were well mixed, compared to that of poorly mixed tanks. For example, long term tank A would have required a 2.2 ^{0}C difference in temperature between the tank volume and filling water to stratify, while tank E would require a 0.0079 ^{0}C difference. Tank E, however appeared well mixed relative to its total chlorine profile (1.22 to 1.39 mg/L throughout the entire tank) when the filling water was 1 ^{0}C cooler than the tank contents. Tank E was mixed even though the measured temperature difference between the filling and stored water was considerably higher than the theoretical temperature to cause stratification, indicating that this parameter might be only suited for qualitative, rather than quantitative analyses. It should be noted that the equation which was used to calculate this parameter was proven using tanks whose aspect ratios were less than 1.0, which leads to uncertainty when using this parameter with standpipes.

4. **Densimetric Froude number**

   The densimetric Froude number required to overcome stratified conditions in a tank was calculated for each tank. Long term tanks A and B, as well as short term tank 7 were all well mixed and achieved 251%, 196%, and 152% of their required densimetric Froude numbers, respectively.

   With the exception of short term tank 8 (unstratified tank but only met 50% of its required densimetric Froude number), all tanks which did not meet the required densimetric Froude number experienced some degree of stratification, indicating tanks designed and operated to achieve the required densimetric Froude number would be well mixed. The densimetric Froude number can be increased by maximizing the velocity of the filling water, which can be accomplished by increasing flow rates or decreasing inlet diameters. Additionally, by drawing water levels to a low level, the required densimetric Froude number can be reduced.

5. **Dimensionless mixing parameter**

The dimensionless mixing parameter ($M^{1/2}/(B^{1/3}H^{2/3})$) presented in Roberts et al. (2006) was maintained above the required threshold in the tanks which did not present any evidence of stratification. Long term tank A required a dimensionless mixing parameter of 1.3 to be mixed, and achieved a value of 2.0. Long term tank B and short term tank 7 each achieved dimensionless mixing parameter values of 1.5, compared to 0.8 which was required to mix the tanks.

For all other tanks which were studied, the average value of the dimensionless mixing parameter was below the threshold required to ensure complete mixing. When the temperature of the upper zone of the tank became more consistent with that of the filling water, some values of the dimensionless mixing parameter for long term tanks C and E increased above the threshold to ensure complete mixing. When the value of the dimensionless mixing parameter was above the threshold, tanks C and E both appeared well mixed from a temperature profile standpoint. The occurrence of complete mixing in tanks which met the required value of the dimensionless mixing parameter indicates that designing and operating tanks to achieve the required value should result in well mixed tanks. The dimensionless mixing parameter can be increased by maximizing the inlet momentum or decreasing the initial water level prior to a fill cycle. Inlet momentum can be increased by either increasing flow rates or velocity (or both). Inflow velocity can be increased by decreasing inlet diameters.

CONSIDERATIONS FOR TANK DESIGN AND OPERATION

1. Tall standpipes appear to experience the most prevalent stratification, and therefore experience water quality problems. Accordingly, these tank types should be avoided when new tanks are designed, unless supplemental passive or active mixing devices designed for use in storage facilities are provided.
2. Tanks which are found to experience water quality problems as a result of stratification may be drained into the distribution system before disinfectant residuals above the stratified layer diminish to unsafe concentrations, and then refilled with water containing higher disinfectant concentrations.
3. Of the hydraulic parameters evaluated in this study, the densimetric Froude number, dimensionless mixing constant from Roberts et al. (2006), and volumetric exchange during fill cycles were found to be the most effective in predicting the potential for stratification. Tanks can be optimized to enhance

mixing by reducing inlet diameters to increase the momentum of the inflow and by maximizing volumetric exchange during fill cycles.

4. Although not examined in this study, tanks with poor mixing and potential water quality problems can be mixed using active or passive mixing systems.

5. Monitoring water quality at the bottom of a stratified storage tank will not provide water quality data for the water above the stratified layer. Systems desiring knowledge of storage tank water quality should collect samples from both the top and bottom of the tank to monitor water quality throughout the entire tank contents.

CHAPTER 1: INTRODUCTION

1.1 Background

Hundreds of water storage tanks are employed by rural water systems in South Dakota to meet the demand variations of their customers. Elevated towers, standpipes, ground storage tanks and below grade storage tanks are included in the storage tank inventory. Storage tanks fill and drain in response to pump controls and system demands. A common practice in operations is to keep the tanks nearly full, enabling the system to respond to an unusually high demand.

Many tanks have been built without consideration of mixing. These tanks might have a single inlet/outlet, high height to diameter ratio, or have other design characteristics that do not promote mixing. Whether by design or not, tanks without artificial mixing depend upon movement of water during the filling process to mix the tank. If a tank is poorly mixed, the potential for stagnant water exists, which may lead to low disinfectant residuals, high disinfection byproduct levels and nitrification in chloraminated systems.

Recent nitrification episodes and conditions of low chlorine residuals in tanks have caused water system operators and managers to question the mixing conditions in water storage tanks and seek advice on modifying tank operations to improve mixing. A few systems have installed mixing devices in their tanks to prevent ice accumulation.

1.2 Purpose and Scope

The hypothesis of this study is that tank design and operation have impacts on mixing, and therefore, water quality in water storage facilities. To examine this hypothesis, the objective of this project is to determine which types of tank designs and operational parameters promote or inhibit mixing in tanks. The scope of this project included a literature review, a survey of tanks in South Dakota's rural water systems, collection of water quality and operational data from the tanks, and evaluation of the water quality data relative to hydraulic parameters and systematic models.

A literature review was performed to summarize the work of others who have examined tank mixing and water quality in reservoirs. The results of this literature review provided a basis on which to compare the results of experimental work.

Tanks which could be considered representative of a wide range of tanks in the state were selected for experimental study. A survey of rural water systems was employed to enable the selection of representative tanks. Five tanks were selected to be studied long term, and eight additional tanks were selected for shorter term studies based on contact with regional water systems. Temperature and water quality parameters were measured at varying depths within the long-term tanks, whereas only temperature profiles were measured in the short-term tanks. The data from these measurements were correlated with operational and design characteristics of each tank.

Finally, various hydraulic mixing parameters and models were evaluated and compared with experimental data. If these hydraulic parameters and models prove effective at predicting mixing and water quality in reservoirs, they could be used by water systems to optimize their tank and by engineers in tank design.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A literature review was performed to provide background information for the project. The effects of distribution storage on water age and subsequent impacts on water quality are introduced. Methods of modeling mixing and water quality are summarized.

2.2 Factors Affecting Mixing and Water Age in Storage Tanks

Storage facilities can be a source of high water age in distribution systems as a result of both poor mixing within tanks and placement at low demand points. When tanks are poorly mixed, water can spend a substantial amount of time in dead zones, resulting in high water age. Temperature variations between the tank volume and filling water lead to stratification and dead zones which, in turn lead to high water age. High water age in reservoirs can also be the result of tank design elements, such as inlet location/orientation, height to diameter ratio, poor placement in the distribution system, or oversized tanks. High water age can also be caused by operational factors such as daily turnover and the tank volume added during fill cycles.

2.2.1 Temperature Considerations for Water Storage Tanks

Causes of stratification within the water tank are introduced in this section, as well as methods to predict how the ambient temperature affects temperatures within tank volumes. The inlet orientation, momentum of the water filling the tank, and type of buoyancy also can affect whether a tank stratifies or not. Hydraulic parameters are described in this section that predict the occurrence of stratification in tanks, as well as determine inflow conditions which would be required to overcome stratification in tanks.

2.2.1.1 How Stratification Impacts Mixing in Tanks

Stratification occurs when water entering a tank has a different density than the water which is already stored in the tank. Density is influenced by water temperature, so stratification can occur when the temperature of water filling the tank is different than the water stored in the tank.

Whenever a flow discharges from an orifice into a reservoir, a jet is formed. In cases where artificial mixing is not employed, the fluid movement caused by this jet is the only means of mixing the tank contents. According to Grayman et al. (2004), even when strong turbulent jets are achieved temperature variations (and thus density differences) between inflow and water in the tank can cause stratification, which can prevent the jet from mixing the tank. This stratification can lead to dead zones in the tank as shown by Figure 2.1.

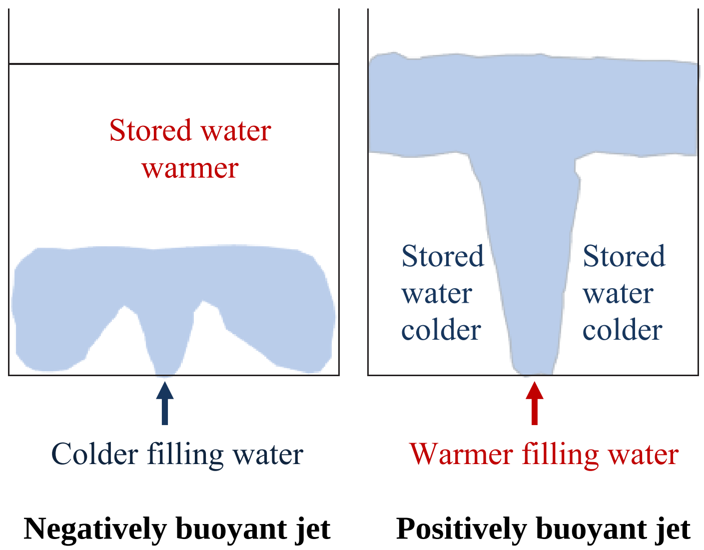


Figure 2.1. Temperature effects as a result of positively and negatively buoyant jets (Adapted from Grayman et al. 2004).

Figure 2.1 shows two cases of how stratification can occur in tanks. When the inflow is colder than the surrounding volume, a negatively buoyant jet is formed, where younger (inflow) water will sit at the base of the water column. If the inflow is warmer than the surrounding volume, a positively buoyant jet will form and the younger water will rise to the top (Grayman et al. 2004).

A comparison of negatively buoyant jets and isothermal conditions were modeled by Mahmood et al. (2005) using computational fluid dynamic software. An image created by this model is shown in Figure 2.2. The image on the left of Figure 2.2 used an inflow which was one degree Celsius colder than the stored water. The image on the right had the same temperature of inflow as the water initially in the tank. The isothermal jet was able to reach the top of the tank, while the tank with a temperature difference was only able to mix the bottom 1/3 of the tank. Mahmood et al. (2005) also collected samples from a tank whose bottom temperature was two degrees Celsius cooler than the top, and found that the average concentration of chlorine at the top was top 0.1 mg/L, while the bottom maintained 0.9 mg/L. The results of Mahmood et al. (2005) show that even small differences in temperature between the top and bottom of a tank can lead to thermal stratification and diminished water quality in the top of the tank.

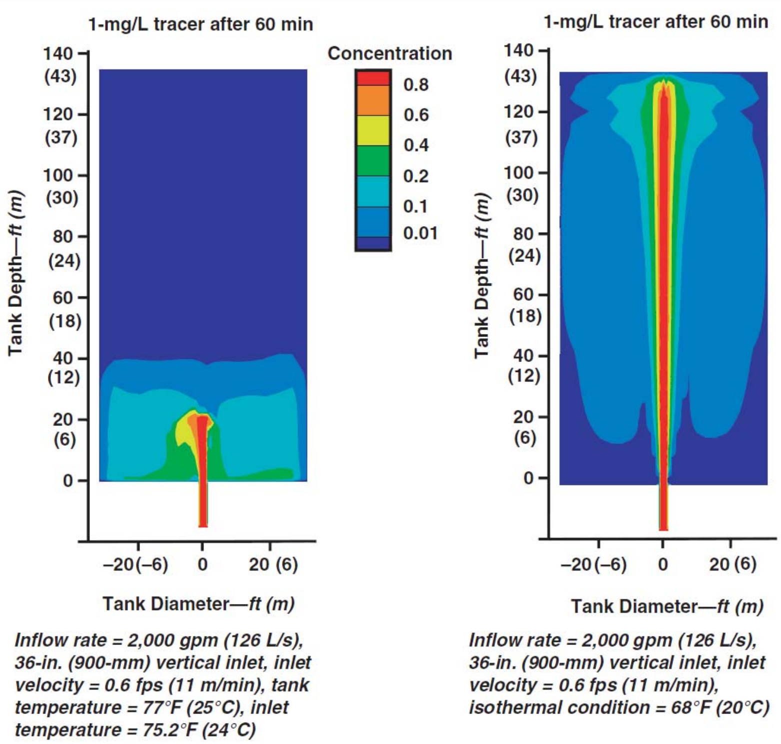


Figure 2.2. CFD model comparing a negatively buoyant jet to isothermal conditions (Mahmood et al. 2005).

2.1.1.2 Methods to Predict and Overcome Stratification in Tanks

Hydraulic parameters to predict the occurrence of stratification in tanks are introduced in this section. The relationship of the densimetric Froude number and its required value provide a relationship to predict whether tanks will stratify, and the temperature difference between filling water and stored water which would cause stratification can also be calculated. An additional parameter which relates inflow momentum, buoyant force, and water depth to stratification is presented.

Density differences between filling water and stored water cause buoyant forces. The densimetric Froude number is the ratio of the inertial force (of the inflow) to that buoyant force. If the densimetric Froude number can overcome a certain required value, a tank will not stratify. Work to predict the occurrence of stratification in unconfined bodies of water was described by Fischer et al. (1979) for negatively buoyant jets, and Lee and Jirka (1981) for positively buoyant jets. These publications illustrated that the occurrence of stratification was related to the densimetric Froude number, inlet diameter, and water depth. Rossman and Grayman (1999) used scale model tracer studies to expand on the work of Fischer et al. (1979) and Lee and Jirka (1981) to study stratification in water storage tanks. Rossman and Grayman (1999) defined Equation 1 as the densimetric Froude number:

$$F_d = \frac{u}{\sqrt{g'd}} \tag{1}$$

in which: F_d = densimetric Froude number (dimensionless); u = vertical velocity of inflow (ft/s); d = inlet diameter (ft); g'=g ($\Delta\rho/\rho_a$), (g = 32.2 ft/s^2; $\Delta\rho$ = difference in density between the tank volume and incoming water; ρ_a = density of the water in the tank volume). The density may be determined using standard tables, or approximated to +/- 0.2% using an equation suggested in White (2008), which is:

$$\rho \approx \frac{1}{515.379}\left(1000 - 0.0178|T-4|^{1.7}\right) \tag{2}$$

in which: ρ = density (slug/ft^3); and T = temperature (^{0}C).

Rossman and Grayman (1999) filled scale model tanks with deionized water and submerged conductivity meters at a variety of points in the tank. Tap water was pumped into the tank as the inflow and conductivity was monitored as a tracer. The densimetric Froude numbers for scale model tanks which achieved fully mixed conditions were plotted as a function of the water depth to inlet diameter ratio, following the methods of Fischer et al. (1979) and Lee and Jirka (1981). The slope of this relationship between densimetric Froude number (x-axis) and water height/inlet diameter (y-axis) was determined. Slopes for various tank configurations are presented in Table 2.1 (Rossman and Grayman 1999).

Table 2.1. Slopes of densimetric Froude number as a function of water height/inlet diameter (Rossman and Grayman 1999)

Inlet Orientation	**Inflow Buoyancy**	**C**
Vertical	Negative	0.8
Vertical	Positive	1.5
Horizontal	Negative	1.5
Horizontal	Positive	0.8

Rossman and Grayman (1999) stated that if the densimetric Froude number calculated using Equation 1 is greater than the right hand side of Equation 3, stratification will not occur in a tank. Equation 3 is as follows:

$$F_d > C\frac{H}{d} \tag{3}$$

in which: F_d = densimetric Froude number (dimensionless); C = coefficient from Table 2.1; H = water height (ft); d=diameter of inlet (ft).

The higher the coefficient from Table 2.1, the higher the required densimetric Froude number to overcome stratification in a tank, and the more likely stratification is to occur. Rossman and Grayman (1999) concluded that for vertical inlets, stratification is more likely to occur under positively buoyant conditions, while horizontal inlets are more likely to develop stratification under negatively buoyant conditions.

Rossman and Grayman (1999) then developed Equation 4 to predict the critical temperature difference between filling and stored water required to produce stratified conditions in a tank whose height to diameter ratio was less than or equal to 1.0. This was accomplished by algebraically combining Equations 1 and 3 and using a linear approximation of water density as a function of temperature. The calculation of this critical temperature difference is as follows (Rossman and Grayman 1999):

$$|\Delta T| < \left(\frac{9{,}371}{gC^2}\right)\left(\frac{Q^2}{H^2 d^3}\right) \tag{4}$$

in which: T = degrees C; g = 32.2 ft/s^2; C = coefficient from Table 2.1; Q = flow rate into tank (ft^3/s); H = height of water column (ft); and d = diameter of the inlet (ft).

According to Rossman and Grayman (1999) if the temperature difference between filling water and stored water is greater than the result of Equation 4, stratification will occur. Validation of Equation 4 would also validate Equations 1 and 3, because they are interrelated. Rossman and Grayman (1999) attempted to validate these relationships in the field by using Equation 4 to calculate the critical temperature difference to cause stratification in a prototype tank. The result of this calculation for the prototype tank showed that if the inflow was 3.4 ^{O}C colder than the water in the tank, stratification would occur. However, when sampled in the field, the filling water of the prototype tank was 0.3 ^{O}C warmer than the tank volume, and the tank did not stratify. This validation attempt did not validate Equations 1, 3, and 4, because stratification was not observed in the field.

Roberts et al. (2006) derived a dimensionless parameter which related the occurrence of stratification to inflow momentum, buoyant force, and water depth. Roberts et al. (2006) then tested this relationship using three-dimensional laser induced fluorescence tracer studies on a variety of tank types, inlet configurations, and buoyancy types. For tanks with H:D ratios ranging from 0.25 to 2.5, vertical inlets, and negatively buoyant jet conditions, a simple criterion for tanks to be mixed is Equation 5:

$$\frac{\sqrt{M}}{(B)^{1/3}H^{2/3}} > 0.85 - 0.05n \tag{5}$$

in which: M = momentum of the inflow (ft^4/s^2) (M = flow rate (ft^3/s)* velocity of inflow (ft/s)); B = buoyant force (ft^4/s^3) ; H = water depth (ft); and n = number of inlets. The buoyant force (B) is obtained from Equation 6 (Roberts et al. 2006):

$$B = g\left(\frac{\Delta\rho}{\rho_a}\right)Q \tag{6}$$

in which: $g = 32.2$ ft/s^2; $\Delta\rho$ = difference in density between the tank volume and incoming water; ρ_a = density of the water in the tank volume; and Q = flow rate (cfs). The density may be determined using standard tables, or approximated to +/- 0.2% using equation 2. If Equation 5 is true by its left hand side being greater than its right hand side, the tank should be mixed.

Roberts et al. (2006) also conducted scale model studies for other ranges of tank and inlet geometries, as well as both positive and negatively buoyant jets. The results of those studies for commonly used tank and inlet geometries are presented in Table 2.2.

Table 2.2. Summary of scale model studies with single inlets and buoyancy effects (Roberts et al. 2006).

Tank Geometry	Buoyancy Type	Inlet Configuration	Result of Study
H:D Ratio ≤ 1.0	Positive	Vertical, single inlet	No scale model tanks became mixed as a result of new water rising to the surface and forming a layer on top of the initial volume
H:D Ratio ≤ 1.0	Positive	Horizontal, single inlet	Tanks whose value of $M^{1/2}/(B^{1/3}H^{2/3}) > 1.3$ became mixed
0.25<H:D<2.5	Negative	Horizontal, single inlet	No scale model tanks became mixed as a result of new water hitting the sidewall, losing momentum, and forming a layer at the bottom of the tank

The fact that some tanks configurations were unable to become mixed in Roberts et al. (2006) does not necessarily mean that it is not possible to mix those tanks, as Rossman and Grayman (1999) were able to mix tanks under similar conditions. The conditions which did not completely mix in Roberts et al. (2006) were the same conditions for which the C-values from Rossman and Grayman (1999) (Table 2.1) were at their highest (1.5). The fact that Roberts et al. (2006) was unable to mix any tanks under the conditions which Rossman and Grayman (1999) found most difficult to mix, supports that these conditions are more likely to develop stratified conditions. These conditions are that for vertical inlets, stratification is more likely to occur under positively buoyant conditions, while horizontal inlets are more likely to develop stratification under negatively buoyant conditions. Attempts to validate the parameter $M^{1/2}/(B^{1/3}H^{2/3})$ presented by Roberts et al. (2006) were not found in the literature. A case study illustrating how changing a tanks inlet configuration from horizontal to vertical, while under negatively buoyant conditions is presented in Section 2.2.2.1.

2.2.1.3 Modeling Heat Transfer into Tanks

Moran et al. (2003) describes the methods of heat transfer by conduction and convection. Conduction is caused by differences in temperature between two points, for example, warmer air outside heating water inside through the walls. Convection relates to fluid movement in a system. Convection can be either free or forced. Free convection occurs when the density of the fluid is different than that of the surrounding volume. In the case of a water tank, this would occur inside the tank by heating water at the tank wall. The warmer water floats towards the surface, while cooler water sinks to the bottom. Forced convection occurs when external disturbances cause fluid movement. An example of this type of convection is wind blowing against the outside of a tank, or artificial mixing of the fluid within the tank. A third factor which can impact heat transfer is solar radiation. This is described by Mills (1995) as electromagnetic waves emitted by the sun, and transported through space to the Earth. Factors including time of day, season of the year, latitude on the earth, and weather conditions influence the intensity of radiation on an object on the earth. The surface of the object does not absorb all of radiation which reaches it, some is reflected. The ability of an object to absorb radiation is dependent on material of construction and color. Dark colors tend to have more ability to absorb solar radiation than lighter colors. Moran et al. (2003) describes the equation for the rate of heat transfer as:

$$q_x = UA(T_1 - T_2) \tag{7}$$

in which: q_x = heat transfer rate (BTU/hr); U = overall heat transfer coefficient (BTU/(ft^2*^{0}F*hr)); A = surface area of the wall (ft^2), T_1 = warmer temperature (F); and T_2 = cooler temperature (F). Thermal resistances caused by conduction, convection, and radiation from Moran, et al. (2003) were algebraically combined to calculate the overall heat transfer coefficient:

$$U = \frac{1}{[(1/h_1) + (L/K) + (1/h_2) + (1/h_{rad})]} \tag{8}$$

in which: U = overall heat transfer coefficient (BTU/(ft^2*^{0}F*hr)); h_1 = convective heat transfer coefficient outside of the tank (BTU/(ft^2*^{0}F*hr)); h_2 = convective heat transfer coefficient inside of the tank (BTU/(ft^2*^{0}F*hr)); L = thickness of the tank wall (in); K = thermal conductivity of the tank wall (BTU*in/(ft^2*^{0}F*hr)); and h_{rad} = radiation heat transfer coefficient.

The conductive heat transfer coefficient is simply a function of the material of construction. The convective heat transfer coefficients are related to the shape of the tank and the movement of fluids near the tank wall (both air outside and water inside).

The change in temperature per hour is determined by dividing q_x (calculated using Equation 8) by the weight of water in the tank. This is valid because one BTU is the heat required to heat one pound of water one degree Fahrenheit.

2.2.2 Tank Design Considerations to Promote Mixing

In addition to temperature variations within tanks causing stratification, the design of storage tanks has substantial impacts on mixing in those facilities. The height to diameter ratio, inlet diameter/orientation, capacity, and location in the distribution system can affect water quality in storage facilities. Strategies to artificially mix tanks are also presented in this section.

2.2.2.1 The Effects of Inlet Size and Configuration on Mixing

Inlet size and configuration have substantial impacts on mixing in tanks. When tanks are filled, the flow can be considered as a jet. A jet can be classified by its Reynolds number as laminar or turbulent. The effectiveness of the jet to mix a tank is related to the momentum of the inflow. A tank mixing time is related geometry, volume, and inflow momentum. The inflow momentum is related to inlet diameter and flow rate. Variations on mixing times are presented in the literature representing different mixing times for alternative types of inlets. The literature also reveals configurations of inlets which lead to poor mixing.

Whenever a flow moves from an orifice into a reservoir, a jet is formed. An illustration of the mixing patterns produced by ideal (unstratified) vertical and horizontal jets is presented in Figure 2.3.

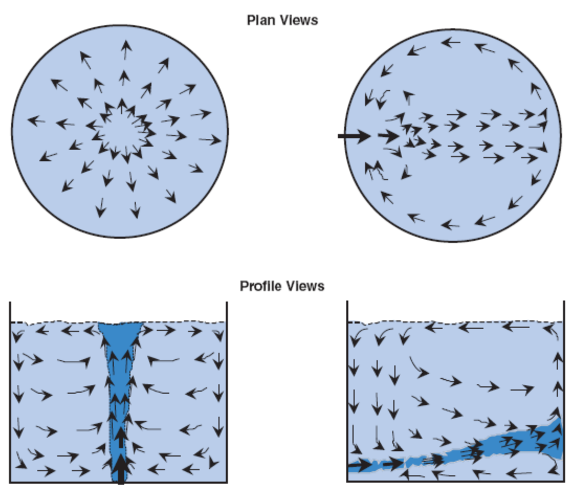


Figure 2.3. Ideal jet mixing characteristics using vertical and horizontal jets (adapted from Grayman, et al. 2004).

Rossman and Grayman (1999) describe how jets are used to circulate water in tanks. In the case of either vertical or horizontal inlets, water enters the tank, and causes circular movement of the tank volume as shown by Figure 2.3. McNaughton and Sinclair (1966) state that jets can be classified using their Reynolds number (Re), and can be laminar (Re < 1,000), turbulent (Re > 3,000), or transitional (1,000 < Re < 3,000). The Reynolds number is defined as the ratio of the inertial forces to the viscous forces (White, 2008), and is calculated using Equation 9 according to Grayman, et al. (2000):

$$Re = \frac{\rho u d_i}{\mu} \tag{9}$$

in which: Re = Reynolds number (dimensionless); ρ = density of water (62.4 lb/ft^3); u = velocity of incoming jet (ft/s); d_i = inlet diameter (ft); and μ = viscosity (ft*s/lb), all in consistent units.

According to Rossman and Grayman (1999), laminar jets do not have sufficient momentum to establish strong mixing patterns within tanks. Grayman et al. (2000) used Equation 9 to determine a ratio of inflow (gpm) to inlet diameter (ft) to ensure turbulent inflow conditions. This ratio should be maintained greater than 11.5 at 20 degrees C, and 17.3 at 5 degrees C (Grayman et al. (2000)).

According to Rossman and Grayman (1999) the performance of jet mixers can be measured by the tank's mixing time, or time to reach a certain degree of uniformity. Many different equations have been developed in the field of chemical engineering to determine the ideal mixing time for jet flows. Some of these have been modified to fit water distribution storage facilities. Rossman and Grayman (1999) used scale model studies and dimensional analysis to examine jet mixing time in tanks whose height-to-width ratios are less than 1.0. They developed an empirical formula for jet mixing time based on experimental data from the scale model studies. This mixing time assumes that the incoming flow is the same temperature as the water already in the tank, and therefore does not account for stratification in a tank. The result is Equation 10:

$$t = \tau_m \frac{V^{2/3}}{M^{1/2}} \qquad (10)$$

in which: t = time to completely mix the tank (sec); τ_m = dimensionless mixing time (10.2); V=tank volume (cubic feet); and M= momentum (ft^4/s^2) (M = flow rate (ft^3/s)* velocity of inflow (ft/s)). Rossman and Grayman (1999) performed a tracer study in a full size reservoir verifying the validity of Equation 10 in the field. Mahmood et al. (2009) performed CFD modeling and full scale temperature testing on tanks which were also evaluated using Equation 10. The results of Mahmood et al. (2009) showed that tanks which did not meet the required volumetric exchange were not well mixed in models or field studies.

Roberts et al. (2006) expanded the work of Rossman and Grayman (1999) to include standpipes by performing more scale model tracer studies. Instead of using conductivity as a tracer (as in Rossman and Grayman 1999), Roberts et al. (2006) used a mixture of water, fluorescent dye, and sodium chloride. The use of this tracer allowed for the use of three-dimensional laser induced fluorescence to evaluate mixing in the tank, rather than submerged probes. Laser induced fluorescence provided more detailed measurement of fluid movement in the tank. Equation 10 was also used in the Roberts et al. (2006) study; however, the dimensionless mixing time (τ_m) was modified to fit a wide range of conditions. Roberts et al. (2006) determined the following relationship for dimensionless mixing time related to H:D ratio:

$$\tau_m = 10.0 \; for \; \frac{H}{D} \leq 1.0 \qquad (11)$$

$$\tau_m = 10.0 + 3.5\left(\frac{H}{D} - 1\right)\ for\ \frac{H}{D} > 1.0$$

in which: τ_m= dimensionless mixing time; H = tank height (ft); and D = tank diameter (ft).

Dimensionless mixing times for use in Equation 11 (used to calculate the time to completely mix a tank) for a variety of alternative inlet configurations were also evaluated in Roberts et al. (2006). Several scale model tracer experiments were performed, and the dimensionless mixing time for each trial was presented in Appendix B of Roberts et al. (2006). Those dimensionless mixing times for each inlet configuration were averaged, the results of which are presented in Tables 2.3 (ground storage tanks) and 2.4 (standpipes). Additionally, dimensionless mixing times for rectangular tanks were performed in Roberts, et al. (2006), the results of which are similar to ground storage facilities. However, because none of the tanks studied in this research were rectangular, those mixing times are not included.

Relative to the dimensionless mixing times reported in Tables 2.3 and 2.4, lower dimensionless mixing time will result in a lower time to mix (result of Equation 10), and the faster a tank will mix by an incoming water jet. Hence, modifying a tank's inlet configuration can improve mixing, as illustrated by Tables 2.3 and 2.4.

Using Equation 10, Rossman and Grayman (1999) suggest that the movement of water in a tank is largely related to the momentum of the flow entering the tank. An increase in momentum will reduce the time required to mix a tank. Momentum can be increased by increasing either flow rate or velocity. Increasing flow typically requires changing pumping rates, while increasing velocity can be accomplished by reducing inlet diameters. These concepts were applied by Mahmood et al. (2005) who performed computational fluid dynamic modeling and full scale testing of reservoirs in which temperature profiles were measured at various depths. The effects of increasing inflow momentum were evaluated by comparing temperature profiles in two tanks, identical in design (150 ft tall, 48 ft diameter standpipes), with the exception of a modified inlet orientation and diameter. The unmodified tank had a 24 inch horizontal inlet, while the modified tank was filled using a 12 inch vertical inlet. The modified standpipe was effective in preventing stratification in the tank, while the unmodified tank was not. Mahmood et al. (2005) states that in cases of smaller diameter tanks, the inflow can impact the interior wall of the tank and lose momentum, resulting in poor mixing. Mahmood, et al. (2005) recommended the use of vertical inlets located near the center to optimize mixing in standpipe style tanks. The center location minimized the effect of the tank wall on the water jet.

Inlet location and orientation can have substantial impacts on the mixing characteristics of a tank. Inlet configurations which have the potential for mixing problems are shown in Figure 2.4.

Table 2.3. Dimensionless mixing times to achieve complete mixing in unstratified ground storage facilities (using data from Roberts et al. 2006).

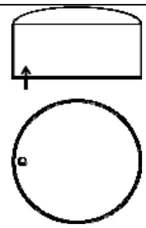
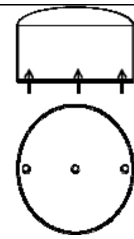
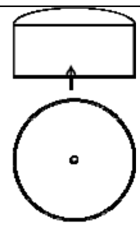
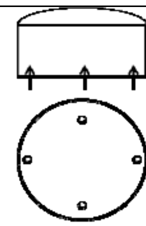
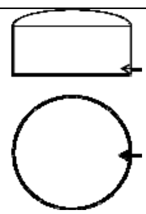
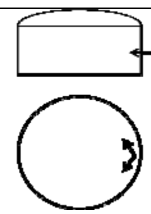
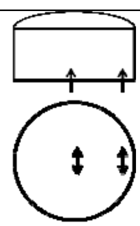
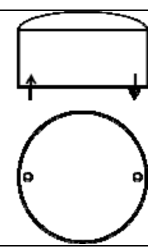
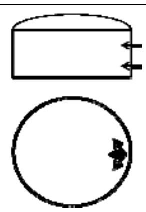
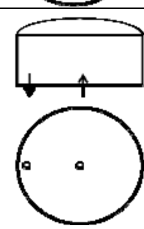
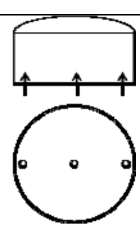
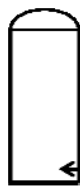
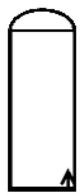
Inlet Configuration		**Dimensionless Mixing Time**	**Inlet Configuration**		**Dimensionless Mixing Time**
	One port, bottom, side, vertical	10.1		Six ports on three inlet pipes	8.4
	One port, bottom, center, vertical	15.3		Four ports, each quadrant, vertical	6.2
	One port, bottom, side, horizontal	11.4		Two ports on one inlet pipe	8.8
	Five ports, arranged on two inlet pipes	11.2		One port, bottom, side, vertical (inflow and outflow at same rate)	13.4
	Three ports on one inlet pipe	9.2		One port, bottom, center, vertical, (inflow and outflow at same rate)	13.7
	Three ports, centerline, equally spaced, vertical	8.2			

Table 2.4. Dimensionless mixing times to achieve complete mixing in unstratified standpipes (using data from Roberts et al. 2006).

Inlet Configuration		**Average Dimensionless Mixing Time**
	One port, bottom, side, horizontal	18.4
	One port, bottom, side vertical	15.4
	One port, bottom, center, horizontal	15.4
	Two ports, horizontal	10.6
	Seven ports, horizontal	13
	One port, center, vertical, with draft tube	Did not mix under isothermal condition

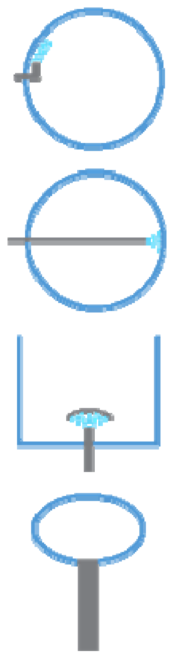


Figure 2.4. Inlet configurations which have an increased risk of poor mixing (Adapted from Grayman et al. 2004).

Figure 2.4 shows four configurations which have an increased risk of poor mixing. The reasoning for each of these inlet types being poorly mixed according to Grayman et al. (2004), are as follows:

- **Tangential inlet -** can lead to swirling which may result in a dead spot in the center of the tank
- **Inlet directed at wall** – does not allow jet to develop completely, which may result in incomplete mixing or lengthy mixing times
- **Deflectors or baffles** – do not allow jet to mix completely which may result in incomplete mixing or lengthy mixing times
- **Large-diameter inlets** – may lead to low inlet velocities and low momentum, which increases mixing time

Inlet size and orientation are also interrelated to the temperature effects introduced in Section 2.2.2. As temperature differences between the tank volume and filling water increase, the buoyant force impeding mixing also increases. This added force decreases both the densimetric Froude number (Equation 1), and the dimensionless parameter for a tank to be mixed presented by Roberts et al. (2006) (Equation 5). To compensate for these temperature differences, the strength of the inflow muse be increased in order to maintain those hydraulic conditions such that the tank will mix. This increase can be accomplished by an increase in velocity. If the inlet diameter is decreased enough and flow is conserved, the velocity, and subsequently, the densimetric

Froude number will increase such that the tank will mix. Additionally, with small diameter inlets, the required densimetric Froude number (calculated by Equation 3) is decreased. The parameter for a tank to be mixed presented by Roberts et al. (2006) (Equation 5) is related to the momentum of the inflow. An increase in momentum by either increasing flow rate or velocity increases this parameter, which promotes mixing in tanks. Both Roberts et al. (2006) and Rossman and Grayman (1999) suggested that decreasing inlet diameter increases inflow velocity which improves mixing in tanks.

2.2.2.2 The Effects of Tank Geometry on Mixing

Tank geometry is a key factor relating to tank mixing and water quality. Kennedy et al. (1993) performed tracer studies on full scale tanks, and determined that standpipes (tanks which are taller than wide) have a greater tendency for dead zones and stratification than elevated tanks and ground storage reservoirs. This is the result of older water remaining in the upper zones in the tank, while new water enters at the base and does not mix, a phenomenon known as short circuiting.

Several parameters which have already been introduced in this literature review also relate to tank geometry, including:

- the densimetric Froude number required to overcome stratification in a tank increases with increasing tank height (Equation 3) (Rossman and Grayman 1999),
- the critical temperature difference between the inflow and stored water to cause stratification decreases with taller tanks (Equation 4) (Rossman and Grayman 1999),
- the hydraulic parameter presented in Roberts et al. (2006) (Equation 5) for a tank to be mixed when density differences exist between inflow and tank volume is more difficult to achieve in taller tanks,
- and the dimensionless mixing time, and subsequent tank mixing times are increased with increasing H:D ratios (Equation 11) (Roberts et al. 2006).

Each of these parameters indicate that the taller the tank, or the higher the H:D ratio, the more difficult a tank is to mix, indicating that shorter, wider tanks are more easy to mix than tall, slender tanks.

2.2.2.3 Installation of Artificial Mixers

In cases where jet flow is inadequate for mixing tanks, artificial mixers can be installed. Mixers can use an impeller, pump and draft tube, or system of hydraulic recirculation using a pump and piping to physically circulate the tank contents.

The velocity gradient is a measure of the power applied to water in a mixing system (Reynolds and Richards 1992). Reynolds and Richards (1992) defines the velocity gradient as the following equation:

$$G = \sqrt{\frac{P}{(V\mu)}} \tag{12}$$

in which: G = velocity gradient (s^{-1}), P = power (lb*ft/s), V = ft^3, μ = absolute viscosity (lb*s/ft^2). Kirmeyer et al. (1996) stated that hydraulic recirculation systems with a velocity gradient of 10 s^{-1} in two reservoirs within the Seattle Public Utilities distribution system were capable of mixing those tanks; however, methods used to evaluate mixing in those tanks were not presented.

Giguere and Fiske, (2010) presented two case studies of active mixing using lily flower shaped impellers mounted on a 1/3 hp motor. Mixing in the tanks was evaluated by placing temperature probes at various depths in each tank. Additionally, computational fluid dynamic modeling was used to predict the fluid movement in the tank and power requirements for the mixer. The first case study was in a 500,000 gallon aboveground reservoir with a diameter of 52 ft, and height of 32 ft. This tank was stratified thermally, with a five degree Celsius difference in water temperature between the bottom and top of the tank. The mixer was installed, and four hours after its implementation, the thermocline had disappeared. According to the hydraulic model for this tank, the power required to mix this tank at its full level was 223 watts. Assuming that the tank is full, at ten degrees Celsius (μ=2.73*10^{-5} lb*s/ft^2), this power corresponds to a velocity gradient of approximately 9.5 s^{-1} (using Equation 12). The second case study was in a 2.75 million gallon square reservoir, 140’ on each side. Thirty-six pillars were arranged in a grid formation inside of the tank to support the roof. This tank was thermally stratified with a ten degree Celsius difference in water temperature between the bottom and top of the tank. The mixer was installed, and after five hours of operation, the thermocline had disappeared. The power consumption was not predicted for the second tank using CFD modeling. However, because the study used a 1/3 hp motor, a velocity gradient can still be calculated. Assuming that the tank is full, water is 10 degrees C, and all of the motor’s power is imparted to the water, the mixer imparts a velocity gradient of approximately 1.56 s^{-1} to the water in the tank (using Equation 12). It is noteworthy that the lily shaped impeller for these mixers was designed specifically for mixing in a water storage tank, and as a result, if different impeller types are used, required velocity gradients may need to be adjusted. These case studies did not provide information regarding the operational water levels or the initial jet mixing characteristics of the tank.

2.2.2.4 Tank Capacity and Location in the Distribution System

Even in the cases of well mixed tanks, there is still potential for high water age caused by storage facilities that are oversized or poorly placed tanks in distribution systems.

Edwards and Maher, (2008) illustrated how tank location in a distribution system can impact water quality. They presented a case study of a standpipe whose hydraulic grade line was floating on the system, but located spatially outside of its pressure zone. An extended period simulation hydraulic/water quality model was performed to estimate water age in the tank. The simulation showed that water leaving the tank into the demand area was pushed back into the tank when during fill cycles. This flow reversal caused a sloshing effect of the same water moving in and out of the storage facility, leading to a water age of 17 days. The standpipe was replaced in the model by a smaller elevated tank in the same location, which reduced water age to 11 days. The model was modified again by placing the elevated tank within its pressure zone, further reducing water age to 6 days. This shows an example of how water quality can be improved by reducing tank volume and placement of tanks at optimal locations in the distribution system.

Oversized tanks lead to low daily turnover. Daily turnover is also related to tank operation, and is discussed in Section 2.2.3.

2.2.3 The Effects of Tank Operation on Mixing and Water Quality

Tank operation can have one of the most substantial impacts on how well existing tanks are mixed. The literature suggests that both maximizing the volumetric exchange during fill and draw cycles, and minimizing a tanks detention time by optimizing daily turnover can improve water quality in a tank.

Rossman and Grayman (1999) expanded on the mixing time parameter (Equation 10) to derive an equation relating the volumetric exchange required during a single fill cycle to fully mix a tank. This derivation used the filling time for a tank (filling time = volume added to tank / flow rate), and the results of that derivation are:

$$\frac{\Delta V}{V} = \frac{9d_i}{V^{1/3}} \tag{13}$$

in which: ΔV= volume added to the tank during a fill cycle (ft^3); V=tank volume (ft^3); d_i=inlet diameter (ft). This equation is relevant to tanks whose H:D ratios are less than 1.0. Rossman and Grayman (1999) validated this equation in the field using the same full scale tracer study used to validate Equation 10. A more general derivation to this equation applicable to standpipes and other inlet configurations is presented in Section 3.7.8. Either Equation 13 or the equation developed in Section 3.7.8 (Equation 18) can be used to calculate the fill volume needed to fully mix a tank. Mahmood et al. (2009) performed CFD modeling and full scale temperature testing on tanks which were also evaluated using Equation 13. Those results showed that tanks which were not well mixed also did not achieve their required volumetric exchange ratio.

Kennedy et al. (1993) performed full scale water quality studies on a variety of storage tanks. Water quality in two tanks (one standpipe, one ground storage reservoir) was compared relative to a single fill and draw cycle which lasted 24 hours. The standpipe experienced a 10% change in volume, whereas the ground storage tank exchanged 64% of its contents throughout its fill cycle. The standpipe experienced a 50% loss in chlorine residual, while the aboveground reservoir lost approximately 30%. These data indicate larger volumetric exchanges mix the tanks, enabling chlorine residual to be preserved. Kennedy, et al (1993) also suggests that taking tanks off line during low demand periods will improve turnover in the remaining tanks by reducing total storage volume in the system.

In cases of completely mixed tanks, a mean residence time, or daily turnover rate can be used to estimate water age in a tank. Kirmeyer et al. (1999) states that a tanks turnover rate can be described in one of two ways: 1) the average time (detention time) that the entire tank contents spend in the facility and 2) the percent of the tank volume which is exchanged per day. Grayman et al. (2004) provides a calculation of detention time (method 1 from Kirmeyer et al. (1999)) for a completely mixed tank under fill and draw conditions (no flow leaves the tank during fill cycles) as:

$$DT = \left[0.5 + \frac{V}{\Delta V}\right](t_{Draw} + t_{Fill}) \tag{14}$$

in which: DT = Detention time (hr); V = volume of water in the tank at the start of the fill cycle (ft^3); ΔV is the change in water volume during the fill period (ft^3); t_{draw} = draw time (hr); and t_{fill} = the fill time (hr). Kirmeyer et al. (1999) compiled guidelines for turnover rates from the literature and through interviews with state regulators. These guidelines are presented in Table 2.5, along with a conversion of those guidelines to detention time in days.

Hydraulic retention times for nineteen different tanks were calculated by Mahmood et al. (2009). Mahmood et al. (2009) classified detention times less than four days as desirable, four to seven days as marginally desirable, and greater than seven days as undesirable. Detention times for the tanks studied in Mahmood et al. (2009) ranged from two to 44 days.

Table 2.5. Guidelines for water turnover rate in storage tanks (Kirmeyer et al. 1999).

Source	**Guideline**	**Guideline converted to detention time**	**Comments**
Georgia Environmental Protection Division	Daily turnover goal equals 50% of storage facility volume; minimum desired turnover equals 30% of storage facility volume	Goal: 2 days Minimum: 3.3days	As part of this project, state regulators were interviewed by telephone.
Virginia Dept. of Health, Water Supply Engineering Division	Complete turnover recommended every 72 hours	3 days	As part of this project, state regulators were interviewed by telephone.
Ohio EPA	Required daily turnover of 20%; recommended daily turnover of 25%	Recommended: 4 days Required: 5 days	Code of state regulations; turnover should occur in one continuous period rather than periodic water level drops throughout the day.
Baur and Eisenbart 1988	Maximum 5 to 7 day turnover	Maximum of 5 to 7 days	German source, guideline for reservoirs with cement-based internal surface.
Braid 1994	50% reduction of water depth during a 24 hour cycle	2 days	Scottish source.
Houlmann 1992	Maximum 1 to 3 day turnover	Maximum of 1 to 3 days	Swiss source.

Kirmeyer et al. (1995) presented a case study of a 95 foot tall standpipe in the Philadelphia Water District which experienced low chloramine residuals as well as high levels of nitrite and heterotrophic place count bacteria as a result of nitrification. The water system drained the tank, and when put back online increased its daily turnover by lowering the low water level an additional ten feet three to four days a week. This reduced the mean residence time by two or three days and prevented future nitrification in the tank. Several years later, customer complaints regarding low water pressure led to the system increasing the low water level once again, which increased the tanks residence time. When the residence time was increased, nitrification occurred again, which depleted the chloramine residual. This indicates that the higher residence times can lead to poor water quality in tanks.

2.3 Modeling Mixing in Tanks

Systematic, computational fluid dynamic, or scale models can be used to model water age, mixing conditions, or disinfectant residuals in tanks. Systematic methods compare field data with model results to provide an estimate of how well a tank is mixed. Computational fluid dynamics utilize complex hydraulic calculations to provide detailed illustrations of how water moves within the tanks. Scale modeling uses dimensional analysis to scale tank sizes such that they can be studied in a laboratory setting. Regardless of the method employed, it is important to verify the model with field data.

2.3.1 Systematic Models

Systematic or "compartment" models have been developed to illustrate mixing in water storage tanks. These models are highly conceptual, rather than physical in their equations. They act more as a "black box", rather than describing the fluid movement occurring within a tank. According to Grayman, et al. (2000), systematic models break the tank into separate, completely mixed compartments, with flows between each compartment. The authors of two papers present different approaches to compartmentalization in terms of their detail. Mau et al. (1995) assumed steady-state conditions for each inflow rate and outflow rate, while Clark et al. (1996) approximated time-varying flow rates using polynomials. A basic overview of each of these models may be found in Appendix A. These models (with the exception of the two-compartment model, stratified-three-compartment model under continuous flow, three-and-one-half compartment model under fill/draw conditions, and the four-compartment model) may be modeled using a software package titled CompTank, which accompanies Grayman et al. (2000).

According to Grayman, et al. (2000), because of the highly simplified conditions used in the systematic approaches, model calibration is critical. The most effective method of calibration is to perform a tracer study and fit a model to experimental results using trial and error. In the absence of field data, the experience of the modeler is the only way to determine the appropriate model and essential input data.

2.3.2 Computational Fluid Dynamics

This section introduces basic elements of modeling using computational fluid dynamics (CFD). A brief introduction to how CFD modeling works, the methods of CFD which can be used, and types of software associated with CFD models are presented.

Grayman et al. (2000) describes a summary of how CFD may be used to model the physical processes governing the fluid flow. CFD models are useful in both the design and operation of storage tanks. They may be used to predict how changing operational or physical characteristics affect the mixing properties of the tank. For example, CFD models can show the effect on fluid flow within the tank by changing the location or orientation of the inlet or outlet, adding baffles, or including pillars in the tank. Benefits of CFD models compared to compartmental models are: the ability to visually see the mixing characteristics, more accurately representing what is happening in the field, and better identification of mixing or water quality problems. CFD models allow complex mathematical equations governing fluid flow to be solved, which would not be possible without the use of computers. Even with computers, run times can range from hours to even several days for detailed analyses.

According to Grayman, et al. (2000), in CFD software, two different strategies may be used. The first method breaks the area of interest into a series of nodes (mesh) and the program computes the characteristics of each node to approximate its surrounding volume. The second method is purely computational, using either a finite element or finite volume method and integrating throughout the volume to obtain a solution. Important input parameters for both methods include: tank geometry, boundary conditions, turbulence data, and any thermal properties of the system. Among the equations solved are the conservation of mass, momentum, and energy. The general equations governing these processes can be proven mathematically, however the applications of such equations to a working model become extremely complex due to the number of iterations required. Aside from the three fluid processes described above, phenomena such as turbulence, multiple phase mixing, and phase changes can be modeled using CFD software.

Grayman, et al. (2000) describes two types of software which may be used to model fluid flow in tanks: traditional CFD, or an adaptation of CFD designed specifically for water storage tanks. Traditional CFD software may be used to model almost any situation that the user requires. However, generic CFD software can be very expensive, and requires extensive user training to become proficient. An application was developed using traditional CFD software to model common drinking water tanks. This program is titled HydroTank, and accompanies Grayman, et al. (2000). This program has the benefits of ease of use and low cost compared to traditional CFD software packages. Limitations associated with this application are that it cannot model more than one inlet (or outlet), odd shaped tanks, and tanks with pillars.

In order to ensure that systematic or CFD models represent the physical process of mixing in a tank, some form of calibration must be performed. Calibration can either be small scale using dimensional analysis and scaling, or full scale testing of an existing structure. Three types of full scale studies are presented in Grayman et al. (2000), which include water quality, tracer, and temperature studies.

2.3.3 Scale Modeling

Scale model studies utilize dimensionless analysis and scaling to simulate actual conditions within a prototype tank. They are useful for both qualitative and quantitative experiments. Rossman and Grayman (1999) used scale models to develop the equation for mixing time and predict the occurrence of stratification in tanks. Additionally, Roberts et al. (2006) used laser-induced fluorescence to provide detailed measurements of fluid flow in tanks. These measurements were used to develop dimensionless mixing times for several tank geometries, inlet configurations, and stratified conditions.

2.3.4 Testing of Models

Full scale testing of storage facilities is a common way to validate systematic, CFD, and scale models. Sampling may be performed at the inlet, outlet, or inside of tanks. The most common and complete practice is to utilize all three testing locations. The same tests used in scale models may be performed in full scale tanks: water quality, tracer, and temperature studies. For such studies, the flow to and from the tank as well as concentrations entering, within, and leaving the tank are monitored. Using this information, potential mixing or water quality problems within the tank may be identified.

2.3.4.1 Interior Sampling

The benefit of interior sampling is that the mixing characteristics of the tank may be evaluated where the mixing is actually occurring. According to Grayman et al. (2000), for an interior sampling study, sampling taps are installed at 5-10 foot increments, or a sampling apparatus is lowered into the tank. Samples are then collected from different depths and horizontal locations in the tank at various times during tank operation. These samples can be field or lab tested for a variety of water quality, tracer, or temperature data. These data can be used to identify problematic areas in the tank, or provide recommendations to the owners on optimizing their tank operations. Important data include inflow and outflow rates, water and air temperature, water level, and daily hours of sunlight. Some examples of methods which have been used to perform interior sampling studies are presented below.

Mahmood, et al (2005) conducted computational fluid dynamic modeling of several storage facilities, and used temperature profile data to validate those models. A representation of the apparatus used to collect temperature data is shown by Figure 2.5.

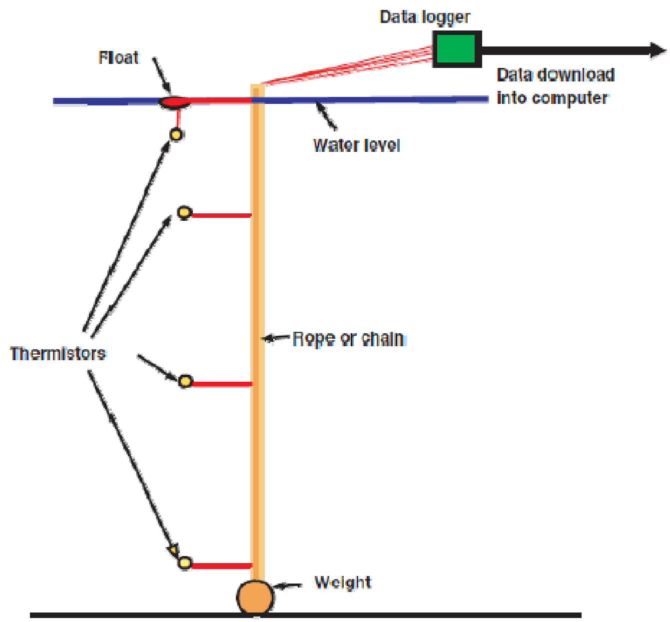


Figure 2.5. Temperature data collection apparatus used to validate CFD models (Mahmood et al. 2005).

Temperature sensors in Figure 2.5 were lowered into the tank on a rope or chain, along with one attached to a float on the surface. The chain was attached to a weight to ensure that the apparatus hangs in a straight line down the tank. A data logger was used to collect temperature data which was downloaded to a computer.

Kennedy, et al. (1993) performed studies of tanks in which samples were collected from various depths in the tank using a lake sampling device. These samples were tested for residual disinfectant concentrations.

Boulos et al. (1996) performed full scale testing of a reservoir by installation of equipment directly to the tank. The equipment consisted of rigid pipes entering the tank at two locations on the roof, the vent and hatch. Seven pipes were installed in each location, each pipe terminating at a different depth in the tank such that samples could be drawn from every four foot interval from the base of the tank. A pump was connected to each pipe, and the discharge side of each pump was connected to a hose which extended to the ground. The pumps were only needed to start the flow in the hoses, which was maintained by siphon after being primed.

2.3.4.2 Exterior Sampling

In the case of exterior sampling, the inflow and outflow concentrations and flow rate are monitored. Grayman et al. (2000) states that the sole use of an outlet tracer is not an effective diagnostic tool to evaluate tank mixing. This is because short-circuiting and stratification are common problems being investigated, and the use of an outlet tracer would not necessarily identify water quality problems in the upper zone of the tank. However, outflow concentrations should still be measured, as validation of models requires concentrations at many points in the tank to be known, including the effluent.

2.4 The Effects of Water Age on Water Quality

After leaving the treatment plant, the time that water spends in the system has a substantial impact on water quality. The major parameters that relate water age and quality can be traced back to disinfection. Chemicals used in disinfection react with substances (by oxidation/reduction reactions), resulting in a loss of disinfection residual. This loss of residual disinfectant can create the potential for harmful bacterial growth, indicated by failed coliform tests, as well as increased levels of disinfection byproducts and nitrate. A brief introduction to disinfection and disinfectant decay, nitrification, and regulations related to water age are introduced in this section.

2.4.1 Introduction to Disinfectants

Disinfection is applied to water systems in order to kill harmful organisms which would otherwise pass through the treatment process (primary disinfection), and further protect water within the distribution system from contamination (secondary disinfection).

2.4.1.1 Free Chlorine

Sawyer et al. (2003) describes the use of chlorine gas, hypochlorous acid, and hypochlorite ion as free chlorine. Although free chlorine has a strong capability to disinfect, the residual tends to dissipate rather quickly compared to combined chlorine.

2.4.1.2 Combined Chlorine (Chloramines)

Combined chlorine is produced when free chlorine reacts with ammonia to produce chloramine. Sawyer et al. (2003) states that a greater concentration of chloramine compared to free chlorine is required to produce the same disinfection result. A common practice is to disinfect with free chlorine, and inject ammonia after contact time for primary disinfection has been achieved to form a longer lasting chloramine residual. According to Hack (1984), the main reasons for the use of chloramine in a distribution system are to reduce trihalomethanes and control bacterial growth.

Three forms of combined chlorine can exist in a system: monochloramine (NH_2Cl), dichloramine ($NHCl_2$), and trichloramine (NCl_3). The following reactions described in Harrington et al. (2003) describe the formation of the various chloramine species:

$$NH_3 + HOCl \leftrightarrow NH_2Cl + H_2O$$
$$NH_2Cl + HOCl \leftrightarrow NHCl_2 + H_2O$$
$$NHCl_2 + HOCl \leftrightarrow NCl_3 + H_2O$$

Monochloramine formed at a weight ratio of 4:1 to 5:1 Cl_2:NH_3-N provides the best combined chlorine residual that minimizes free ammonia concentrations and avoids taste and odor complaints due to di- and tri-chloramine.

2.4.2 Disinfectant Decay

When disinfectants react with substances ranging from organisms, organic matter, or pipe walls, the concentration of the disinfectant is reduced. This loss of disinfectant can pose a risk of microbiological contamination in the distribution system. Additional concerns are byproducts of the disinfectant decay including trihalomethanes, haloaecetic acids, nitrate, nitrite, and nitrate, and *N*-Nitrosodimethylamine.

Grayman et al. (2004) states that tanks operating under plug flow will lose their disinfectant residual at a faster rate than mixed flow tanks, a phenomenon illustrated in Figure 2.6. According to Grayman, et al. (2000), the rationale for the faster decay under plug flow conditions is that the reaction rate is highest at the inlet, and continuously tapers down until the outlet. In contrast, in a completely mixed system, the reaction rate is always at its lowest throughout the tank. Hence, distribution storage tanks should be completely mixed to preserve chlorine residual.

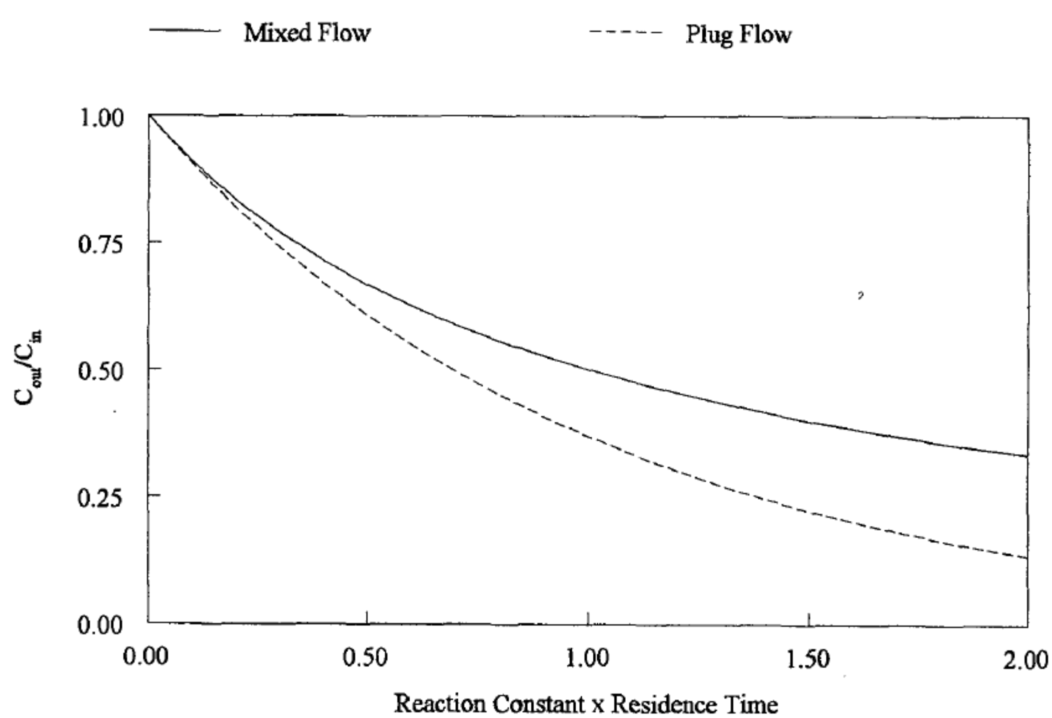


Figure 2.6. Disinfectant loss in mixed and plug flow tanks with continuous inflow/outflow (Grayman et al. 2000)

2.4.2.1 Free Chlorine Decay

Free chlorine residuals decay as chlorine reacts with pipe walls materials and coatings and with natural organic matter in the bulk water flowing through the pipeline. Reactions with natural organic matter form trihalomethanes (TTHMs) and haloaecetic acids (HAA5s).

Boorman et al. (1999) provides a summary of the health risks associated with these DBPs, namely cancer. Additionally, Boorman et al. (1999) suggest a correlation has been proposed between high TTHM levels and adverse reproductive affects.

Haestad Methods, (2003) states that chlorine decay is most commonly modeled using a first order reaction equation, where both wall and pipe reactions are grouped into a common reaction rate:

$$C_t = C_0 e^{-kt} \tag{15}$$

in which: C_t is the concentration at time "t", C_0 is the concentration at time "0", and k is the reaction rate. The reaction rate is a function of concentrations of organic matter in the bulk water and the pipe material. Jones (2002) conducted field studies to determine the reaction rate of free chlorine in various pipe materials from the Norfolk Navy Base. Those results are summarized in Table 2.6.

Table 2.6. Free chlorine decay constants from pipes on the Norfolk Navy Base (Jones 2002).

Pipe Material	**K_{total} (1/d)**	**K_{bulk} (1/d)**
12" PVC	0.3-0.5	0.3-0.4
6" Ductile Iron	0.6-1.4	0.6-1.4
8" Ductile Iron	1.0	0.5
6" Asbestos-Cement	2.1-4.0	0.5-1.6
10" Cast Iron	1.3-5.1	1.5-1.5
8" Cast Iron	3.1-12	1.0-4.6
8" Cast Iron	3.5-5.1	0.9-1.3
6" Cast Iron	4.9-7.4	0.6-2.4
6" Cast Iron	0.8-4.4	0.4-2.1

2.4.2.2 Chloramines

When chloramine decays or oxidizes other materials in the system, ammonia is released. According to Regan et al. (2007), four reactions commonly release ammonia into the distribution system:

Chloramine auto-decomposition:

$$3NH_2Cl \rightarrow N_2 + NH_4^+ + 3Cl^- + 2H^+$$

Oxiditation of organic matter by chloramine:

$$0.1C_5H_7O_2N + NH_2Cl + 0.9H_2O \rightarrow 0.4CO_2 + 0.1HCO_3^- + 1.1NH_4^+ + Cl^-$$

Reaction of chloramine with corrosion products at pipe walls (cast iron pipe):

$$0.5NH_2Cl + H^+ + Fe^{2+} \rightarrow Fe^{+3} + 0.5NH_4^+ + 0.5Cl^-$$

Oxidation of nitrite by chloramine:

$$NH_2Cl + NO_2^- + H_2O \rightarrow NH_3 + NO_3^- + HCl$$

Several kinetic models have been developed to estimate chloramine decay. Gyürék and Finch, (1998) used the same first order reaction model used for free chlorine (Equation 15) to model the decay of combined chlorine. The reaction rate (k) used in Equation 15 for combined chlorine is a function of concentrations of organic matter in the bulk water and the pipe material. Jones (2002) conducted field studies to determine the reaction rate of combined chlorine in various pipe materials from the Norfolk Navy Base. Those results are summarized in Table 2.7.

Table 2.7. Combined chlorine decay constants from pipes on the Norfolk Navy Base (Jones 2002).

Pipe Material	**K_{total} (1/d)**	**K_{bulk} (1/d)**
12” PVC	0.2-0.4	0.1-0.2
6” Ductile Iron	0.24	0.08
10” Cast Iron	0.4-1.0	0.13
8” Cast Iron	0.5-2.2	0.12
8” Cast Iron	0.9-3.8	0.05-0.5
6” Cast Iron	1.1-8.1	0.05-0.4
6” Cast Iron	0.1-0.7	0.1-0.2

Valentine et al. (1998) developed a simple second order reaction rate model for the decay of combined chlorine.

$$\frac{1}{[NH_2Cl]} = \frac{1}{[NH_2Cl]_0} + k_{VSC}t \qquad (16)$$

in which: $[NH_2Cl]$ = monochloramine concentration at time “t” (moles/L); $[NH_2Cl]_0$ = monochloramine concentration at t = 0 (moles/L); t = reaction time (hr) and k_{VSC} = Valentine chloramine stability coefficient. The value of k_{VSC} increases with a decreasing pH and initial chloramine concentration. It also increases as temperature and inorganic carbon increase. The calculation of k_{VSC} is as follows (Valentine et al. 1998):

$$K_{VSC} = 3\{K_{H^+}[H^+] + \alpha_0 k_{H_2CO_3} C_{T,CO_3} + \alpha_1 k_{HCO_3} C_{T,CO_3}\} + \frac{2k_3K_e}{\alpha_{0,N}[NH_3]_T} \qquad (17)$$

in which: C_{T,CO_3}= total carbonate concentration (moles); α_0 and α_0 = ionization constants for the carbonate system; $[NH_3]_T$ = total ammonia concentration (moles), K_{H^+}, $k_{H_2CO_3}$, and k_{HCO_3}= general acid catalysis rate constants; k_3 = rate constant for the reaction between monochloramine and hypochlorous acid; and K_e=equilibrium constant describing dichloramine and hypochlorous acid equilibrium.

The second order rate equation (Equation 16) did not incorporate the presence of natural organic matter (NOM) in its reaction rate constant calculation. Valentine et al. (1998) compared model results with data from actual treatment facilities and found that they fit well. However, those samples were transported to the laboratory prior to analysis, and Valentine et al. (1998) postulated that the majority of organic matter had likely been oxidized before initial readings were taken. Valentine et al. (1998) found that this model was less successful when samples contained natural organic matter.

Although the addition of chloramines can substantially reduce TTHM and HAA5 formation, Wilczac et al. (2003) describes concerns regarding the formation of *N*-Nitrosodimethylamine (NDMA). NDMA is classified by the Environmental Protection Agency (EPA) as a B2 carcinogen (reasonable anticipated to be a carcinogen). According to Crittenden et al. (2005), no federal MCL had been been set by 2003; however, California has established an action limit of 10 ng/L.

NDMA can be formed when chloraminated systems also utilize specific cationic polymers or certain anion exchange resins containing dimethylamine during treatment. Wilczac et al. (2003) states that either the over dosage of polymer, or the recycling filter backwash water can promote the formation of NDMA by providing a source of residual cationic polymer. Wilczac et al. (2003) state that NDMA formation can be reduced in chloraminated systems by allowing free chlorine contact time for a period of one to four hours prior to ammonia injection.

2.4.3 Nitrification

Wilczac et al. (1996) describe nitrification as a microbiological process in which ammonia is sequentially oxidized to nitrite and nitrate by ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), respectively. When nitrification occurs within chloraminated distribution systems, disinfectant residual is lost, along with a decrease in dissolved oxygen, alkalinity, and pH, while nitrates, nitrites, and heterotrophic bacteria can increase.

Several studies are presented in Wilczac et al. (1996) that illustrate the ability of AOB to survive in concentrations of chloramine ranging from 1.2 to 8 mg/L. Wolfe et al. (1985) presented the theory that the resistance of nitrifying bacteria to chloramine may be the caused by the organisms attaching to sediment. This theory was supported by Isaac and Morris (1983), who studied reservoirs which were affected by nitrification and found high levels of AOB in the sediments of those reservoirs.

2.4.4 Regulations Relating to Water Age

Several drinking water regulations are very closely tied to water age. Disinfectants added to water at the treatment facility can react to form undesired substances as water age increases. Of particular concern is the loss of disinfectant residual, which can lead to unwanted bacterial growth. Presented below are highlights of drinking water standards associated with high water age including the Safe Drinking

Water Act, Stage 1 and 2 Disinfection/Disinfection By-product Rule, and the Total Coliform Rule.

2.4.4.1 Safe Drinking Water Act

The Safe Drinking Water Act allowed the federal government to oversee the implementation of drinking water standards. Several primary standards from this act are directly related to water age. Systems utilizing chloramines for residual disinfectants, whether by injected or naturally occurring ammonia have potential for nitrification, which leads to the formation of nitrite and subsequently nitrate. Both nitrite and nitrate are regulated by primary drinking water standards (1 mg/L as N and 10 mg/L as N respectively).

2.4.4.2 Disinfectants and Disinfection Byproduct Rules

Disinfection byproducts (DBPs) are unwanted compounds produced when naturally occurring organic matter reacts with the disinfectant. Two chlorinated byproducts of interest are trihalomethanes (TTHMs) and haloaecetic acids (HAA5s). HAA5s have been found to increase, and then decrease as water ages in a system increases as a result of biological and chemical degradation (Chen and Weisel 1998, Speight and Singer 2005). TTHM formation tends to be more stable than HAA5 formation, by not decreasing after peaking in concentration as HAA5s do (Baribeau et al. 2005). In response to health risks associated with DBPs, the EPA adopted the Stage 1 Disinfectants and Disinfection Byproducts Rule (D/DBP Rule) (USEPA 1998). The Stage 1 D/DBP Rule set goals and maximum concentrations for DBPs and disinfectants. The disinfection byproduct rules set maximum contaminant levels as in the Stage 1 D/DBP Rule for TTHMs and HAA5s to 0.08 and 0.06 mg/L respectively. The maximum residual disinfectant levels (MRDLs) were 4 mg/L (measured as free chlorine) for systems using free chlorine and 4 mg/L (measured as total chlorine) for systems using chloramine residual in their distribution systems. The EPA later adopted the Stage 2 DBP Rule, which changed the compliance calculation from a system-wide running annual average to a locational running annual average, but left the maximum contaminant levels the same (USEPA 2009).

2.4.4.3 Total Coliform Rule

When disinfectants degrade, they lose their ability to protect against microbial growth, resulting in an increased risk of microbial contamination. Under the requirements of the Total Coliform Rule, systems collect water samples from their distribution system and have them analyzed for total coliform to indicate microbial contamination. Systems are required to control levels of total coliforms such that not more than 5% of samples tested are positive (USEPA 1989). Additionally for any positive routine or repeat sample, that sample must also be tested for fecal coliforms and *Escherichia Coli (E Coli)*. If the test for *E. Coli* is positive, a violation has occurred and the system must take steps to notify the EPA and the public.

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

This section describes methods and materials utilized in the study. A survey of rural water systems was conducted and utilized to select tanks for long term studies. Tanks were also selected for short term studies based on interest from rural water systems. Selected tanks are described based on their size, type, and other characteristics which make each tank unique. Equipment installed for water quality and temperature profile measurements is described in this section. Sample collection, preservation, and water quality analyses are introduced. Data analyses relative to tank mixing and the occurrence of thermal stratification are presented. The systematic modeling process used to predict chlorine decay in long term tanks is introduced.

3.2 South Dakota Rural Water Tank Survey

In order to characterize water storage facilities used by regional water systems, a survey was sent to the 32 regional water systems listed in the South Dakota Rural Water System Directory, as well as the Mni Wiconi core line system. Responses from these surveys provided details on the storage facilities employed by each system, including:

- Tank type (elevated tanks, at-grade ground tanks, standpipes, underground reservoirs, or clearwell),
- Tank capacity,
- Tank height,
- Tank diameter,
- Inlet orientation (horizontal or vertical),
- Number of inlets/outlets,
- Tank system control and data acquisition (SCADA) systems,
- Artificial mixer is installation (passive or active),
- Type of secondary disinfectant used, and
- Fluoridation systems.

These storage tanks were classified into several categories according to their type and geometry. At-grade tanks were classified as either standpipes or aboveground reservoirs. Standpipes are defined as those tanks which are taller than they are wide, while aboveground reservoirs are shorter than wide. Additionally, tanks were classified as elevated towers, underground reservoirs (below grade), and clearwells (used for disinfection, wet wells and backwash storage at water treatment plants).

3.3 Selection of Tanks for Further Study

The project scope required the installation of instrumentation for continuous, long-term temperature and periodic water quality measurements in five tanks. Eight additional tanks were selected for short-term continuous temperature measurement. The selection of these tanks is described below

A key factor affecting the mixing of a water storage tank is tank geometry. Tank geometry was characterized by the type of storage facility and by height to diameter ratio (H:D ratio, or aspect ratio). The H:D ratio for each standpipe and aboveground reservoir was calculated to sort the at-grade tanks relative to their geometry. Five ranges of H:D ratios (0-0.5, 0.5-1, 1-2, 2-4, and >4) were selected to provide a broad range of tanks across the state and the standpipes and above-ground reservoirs were categorized these ranges.

Elevated tanks were not included in the selection pool, particularly because geometry plays a substantial role in mixing of elevated tanks, and there is a wide range of elevated tank geometries. The H:D ratio was not provided in the survey results for the storage segment of the elevated tanks. Additionally, literature suggests that spherical tanks are of less concern than cylindrical shaped tanks (most at-grade tanks are cylindrical). Underground reservoirs also were not included in the selection pool due to their unique design characteristics.

The tank inventory was narrowed to at-grade reservoirs utilizing surface water sources with chloramine as a secondary disinfectant. Selecting tanks with surface water sources provides the greatest potential to observe temperature stratification as the source water cools in the transition from summer to winter. The use of chloraminated systems tanks will enable observation of potential nitrification episodes, providing a secondary water quality examination in addition to chlorine residual.

After extensive review of the survey data, two or three at-grade tanks in each of the five H:D ratio categories were selected as candidates for water quality instrumentation. The tank owners were then called to obtain further information regarding each tank. Responses from the phone calls narrowed the field to five tanks whose characteristics are shown in Table 3.1. The tanks are located in five regional water systems.

Table 3.1. Characteristics of selected tanks for long term study.

H:D Group	Tank Name	Capacity (gal)	Height (ft)	Diameter (ft)	H:D Ratio	Common Inlet/ Outlet	SCADA for Water Level	Artificial Mixer Installed
0-0.5	A	948,000	24	81	0.30	Y	Y	N
0.5-1	B	559,000	38	50	0.76	N	Y	N
1-2	C	65000	28	20	1.41	Y	Y	N
2-4	D	175,000	75	20	3.75	Y	Y	Y
>4	E	140,000	86	14	6.14	Y	Y	Y

An added benefit to the study was the selection of some tanks (tanks D and E) which have mechanical mixers installed, allowing the effects of having a tank artificially mixed to be studied. This is accomplished by operating the tank with the mixer turned off and then on. The primary use of mixers installed in tanks D and E are to prevent ice formation, rather than mixing to improve water quality. Coincidently, all five selected tanks were "Aquastore" brand, made of glass fused to steel material.

Systems reasonably close to the WEERC office who contributed to the funding of this project were contacted to find tanks eligible for the short-term studies. The systems contacted primarily utilized ground water; however, one used surface water as a source. Responses to these phone calls yielded a list of eight tanks of interest, as shown in Table 3.2.

Table 3.2. Tanks selected for short term studies

ST Tank Number	Type	Capacity (Mgal)	Storage Height (ft)	Diameter (ft)	H:D Ratio	Surface Water	Chloramine	Single Inlet/Outlet	Multiple Inlet/Outlet	Artificial Mixer	Notes
1	Standpipe	241,000	107	20	5.4	N	N	Y	Y	N	Far drawdown in winter causes pressure problems
2	Elevated	300,000	45	26[1]	0.59	N	Y	Y	N	N	
3	Elevated	440,000	31	49[1]	0.63	N	N	Y	N	Y	Recirculation pump in winter
4	Standpipe	100,000	120	12	10	N	N	N	Y	N	Static mixer to be installed fall 2010 or spring 2011
5	Elevated	500,000	50	32.7[2]	1.53	N	N	Y	N	Y	Recirculation pump in winter
6	Standpipe	125,000	46	22	2.1	N	N	Y	N	N	Offline in winter due to ice
7	Elevated	1.5 Mgal	50	83[1]	0.60	Y	Y	Y	N	N	Near treatment plant but is always full
8	Elevated	250,000	27	40[1]	0.68	Y	Y	Y	N	N	Low demand, far end of system

[1]Calculated assuming cylindrical shape of tank volume
[2]Representative diameter, due to the turnip-shape of the tank, see Appendix B for details

3.3.1 Long Term Tank A

Tank A was a 948,000 gallon aboveground reservoir, 24 feet tall by 81 feet in diameter (H:D = 0.30). An adjacent pump station next to it serves the downstream portion of the distribution system. This tank is approximately 70 miles (direct path) from its source. Typical operational water levels range from 9 to 16 feet of depth making it a very shallow, wide tank. This tank is controlled using a solenoid valve, which has set points to control when the tank fills. The equipment for this tank consisted of a string of thermocouples and sampling tubes at 3 foot spacing covering 27 feet of depth (Details of the equipment are described in Section 3.4.1). A photograph of tank A is shown in Figure 3.1.

Figure 3.1. Long term tank A.

3.3.2 Long Term Tank B

Tank B was a 559,000 gallon aboveground reservoir, 38 feet tall by 50 feet wide (H:D = 0.76). This tank has is identical in design to another tank in the same system, that experienced a nitrification episode. In order to prevent such an occurrence from happening in this tank, the operation was changed to a wide range of water depths, most frequently varying the depth between 25 and 35 feet. This water level in this reservoir controls the operation of a booster station, which fills the tank directly. Tank B is located approximately 50 miles (direct path) from the treatment plant that supplies its water. Tank B's inlet is separate from its outlet. The vertically-oriented tank inlet pipe is located near a wall and is reduced from 12 inches to eight inches in diameter using a mechanical joint reducer. The outlet is vertically oriented and is located at the center of the tank. The equipment for this tank consisted of a string of thermocouples and sampling tubes at 7 foot spacing covering 40 feet of depth. A photograph of tank B is shown in Figure 3.2.

Figure 3.2. Long term tank B.

3.3.3 Long Term Tank C

Tank C was a 65,000 gallon standpipe, 28 feet tall by 20 feet wide (H:D = 1.41). This tank has the smallest capacity of the tanks selected, and is also the shortest standpipe selected. A vertical six-inch inlet/outlet controlled by a solenoid valve fills the tank. Tank C is located approximately 30 miles (direct path) from the treatment plant that serves it. This tank has a common inlet and outlet at the base of the tank. The equipment for this tank consisted of a string of thermocouples and sampling tubes at 5 foot spacing covering 32 feet of depth. A photograph of tank C is shown in Figure 3.3.

Figure 3.3. Long term tank C.

3.3.4 Long Term Tank D

Tank D was a 175,000 gallon standpipe, 75 feet tall by 20 feet wide (H:D = 3.75). The water level in this standpipe controls the operation of a pump station which turns on when the tank reaches a low water level set-point. Tank D is located approximately 15 miles (direct route) from the treatment plant. This tank has a single six-inch vertical inlet/outlet at the base of the standpipe. This tank utilizes an artificial mixer in the winter to prevent the formation of ice. The system agreed that the mixer could be turned on if it would benefit the study. The equipment for this tank consisted of a string of thermocouples at 7 foot spacing covering 75 feet of depth. Because the data logger can only record up to 8 channels, three thermocouples along the cable were not connected (22.5, 36.5, and 50.5 ft from the cable base), leading to temperature measurement and water sampling points at 1.5, 8.5, 15.5, 29.5, 43.5, 57.5, 64.5, and 71.5 ft from the base of the cable. A photograph of tank D is shown in Figure 3.4.

Figure 3.4. Long term tank D.

3.3.5 Long Term Tank E

Tank E was a tall 140,000 gallon standpipe, 86 feet tall by 14 feet wide (H:D = 6.14). It is located approximately 20 miles east (direct route) of the treatment plant serving the system. The tank has a single six-inch vertical inlet at its base. This tank, similar to tank D, utilizes an artificial mixer in the winter to prevent ice formation. The system also agreed to operate the mixer to fit the needs of the study. The equipment for this tank consisted of a string of thermocouples at 7 foot spacing covering 85 feet of depth. Because the data logger can only record up to 8 channels, three thermocouples along the cable were not connected (15.5, 36.5, and 57.5 ft from the base), leading to temperature measurement and water sampling points at 1.5, 8.5, 22.5, 29.5, 43.5, 50.5, 64.5, and 71.5 ft from the base of the cable. A photograph of tank E is shown in Figure 3.5.

Figure 3.5. Long term tank E.

3.3.6 Short Term Tank 1

Short term tank one was a 241,000 gallon standpipe, 107 ft tall and 20 ft wide (H:D=5.35). The tank is of the Aquastore style, similar to the long term tanks. Based on water level information from the system, temperature measurement probes were placed at 1 ft, 31 ft, and 61 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 61 ft probe also contained a pressure sensor that recorded the water elevation in the tank. During the study, water levels in the tank consistently varied from approximately 93 feet to about 100 ft. However, during a weekend, the pump station serving the tank lost power and the tank level dropped to 82.6 ft. In winter, the tank is drawn down further than in the summer to prevent ice damage, causing low pressure issues in the system. The inlet to this tank is vertical with six-inch pipe diameter. A photograph of this tank is shown in Figure 3.6.

Figure 3.6. Short term tank 1.

3.3.7 Short Term Tank 2

Short term tank 2 was a 300,000 gallon elevated tank, 130 ft tall. The storage volume is approximately 26 ft tall, and 45 ft wide (H:D = 0.59) Based on water level information from the system, temperature measurement probes were placed at 1 ft, 7 ft, and 13 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 1 ft probe also contained a pressure sensor that recorded the water elevation in the tank. The water level in the tank ranged from approximately 16.5 to 24.5 ft. A ten-inch diameter pipe line connects to the tank to the distribution system. The ten-inch pipe connects to a 60-inch riser at the base of the tank. A photo of this tank may be seen in Figure 3.7.

Figure 3.7. Short term tank 2.

3.3.8 Short Term Tank 3

Short term tank 3 was similar to 2 in its design it was a 5-legged elevated tank. The capacity is 440,000 gallons, with a storage height of 31 ft and diameter of approximately 49 ft (H:D=0.63). Based on water level information from the system, temperature measurement probes were placed at 1 ft, 8 ft, and 15 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 1 ft probe also contained a pressure sensor that recorded the water elevation in the tank. A photo of this tank is shown in Figure 3.8.

This tank has a recirculation pump to prevent ice formation where the tank volume meets the riser pipe. A photo of the mixer is shown in Figure 3.9. The pump was turned on approximately two days after the installation of the equipment. This allowed the effects of mixing by a small recirculation pump to be studied. A photo of the pump is shown in Figure 3.9.

Figure 3.8. Short term tank 3.

Figure 3.9. Recirculation pump in short term tank 3.

3.3.9 Short Term Tank 4

Short term tank 4 was a tall standpipe, 120 ft tall, 12 ft wide, making it the second tallest standpipe, and second highest aspect ratio (10.0) in the South Dakota rural water system tank inventory. The tank's capacity is 100,000 gallons, with a common inlet/outlet of six-inch with an additional three-inch outlet line to serve a small community nearby. Based on water level information from the system, temperature measurement probes were placed at 10 ft, 44 ft, and 89 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 10 ft probe also contained a pressure sensor that recorded the water elevation in the tank. The water system tried to install an ice-prevention mixing system in the tank in the past; however the equipment failed when subjected to icing conditions. The tank is scheduled to have a passive mixing system installed in the future. A photo of this tank is shown in Figure 3.10.

Figure 3.10. Short term tank 4.

3.3.10 Short Term Tank 5

Short term tank 5 was a 500,000 gallon elevated tower with a turnip-shaped storage volume. The diameter of the storage volume ranges from 13 ft to 54 ft. The system contracts with a nearby ethanol plant to provide the water supply to their fire suppression system, requiring at least 300,000 gallons to be stored in the tank at all times. A recirculation pump is installed in the tank, which was turned on during the study, although the exact date and time of activation was unknown. Based on water level information provided by the system, temperature measurement probes were placed at 1 ft, 13 ft, and 25 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 13 ft probe also contained a pressure sensor that recorded the water elevation in the tank. The tank normally was operated between 45 and 47 ft, however, at one point during the study period, the pump station supplying the tank lost power causing the water level to drop to 37 ft. A photograph of this tank is shown in Figure 3.11.

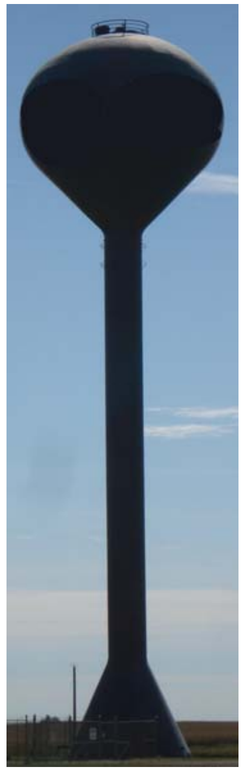


Figure 3.11. Short term tank 5.

3.3.11 Short Term Tank 6

Short term tank 6 was a 125,000 gallon standpipe, of Aquastore style, 46 ft tall and 22 ft in diameter (H:D = 2.09). The inlet to the tank is a six-inch vertical pipe at the base of the tank. Based on water level information from the system, temperature measurement probes were placed at 1 ft, 18 ft, and 35 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 18 ft probe also contained a pressure sensor that recorded the water elevation in the tank. The tank is located near a lakefront community, causing substantial seasonal demand variations. During the off-season, the tank experiences low daily turnover, leading to high detention times and when the weather cools, ice buildup. The system elected to take the tank offline when demands in that portion of the system are low (particularly late fall and winter). A photo of this tank is shown in Figure 3.12.

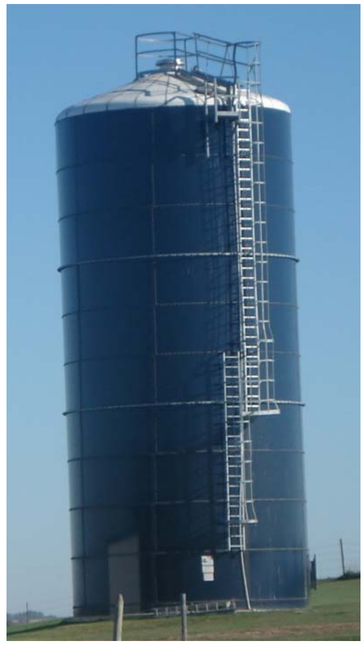


Figure 3.12. Short term tank 6.

3.3.12 Short Term Tank 7

Short term tank 7 was a 1.5 million gallon composite elevated tower. The tank volume was 83 ft in diameter, and the system estimates a height of 50 ft (H:D = 0.6). Based on water level information from the system, temperature measurement probes were placed at 1 ft, 17 ft, and 33 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 17 ft probe also contained a pressure sensor that recorded the water elevation in the tank. Water levels observed in this tank during the study were quite variable (ranging from approximately 23 to 39 ft), which was explained by the water system operators to be the result of a treatment plant upgrade in progress. A photograph of this tank is shown in Figure 3.13.

Figure 3.13. Short term tank 7.

3.3.13 Short Term Tank 8

Short term tank 8 was a 250,000 gallon 5 legged pedestal elevated tower. The diameter of the tank is 40 ft, and a calculated height of the storage volume is approximately 26.5 ft (H:D = 0.66). Based on water level information from the system, temperature measurement probes were placed at 1 ft, 10 ft, and 19 ft from the tank bottom, and a probe was also connected to a surface float that moved with the water level in the tank. The 1 ft probe also contained a pressure sensor that recorded the water elevation in the tank. The 10 ft probe was the pressure sensor. According to the system, the tank is located at the far end of the distribution system, and experiences low demand, with fill and draw cycles lasting approximately 24 hours. A photo of this tank is shown in Figure 3.14.

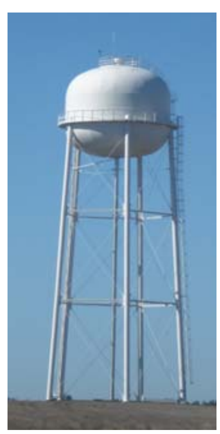


Figure 3.14. Short term tank 8.

3.4 Equipment to Measure Water Quality and Water Level in Tanks

Because measuring temperature differences within various locations in a tank is an inexpensive means of evaluating mixing, water temperatures were monitored at a range of depths in each tank. The selection of surface water tanks allows the data to show whether there is potential for stratification in tanks as a result of source water temperature changes with the seasons of the year. The instruments did not remain in tanks during the winter to prevent damage to the equipment and tank roofs. Additionally, two apparatuses to monitor temperature profiles in tanks with a ground water source were used in the study. Because ground water has fairly consistent temperatures, even as seasons change, equipment for these tanks was installed for shorter times, ranging from one week to a month per tank.

3.4.1 Long Term Study Apparatus

Equipment for measuring both temperature and drawing samples (both from several depths in each tank) was used in the study. A visual rendering of this apparatus may be seen in Figure 3.15.

Figure 3.15. Visual representation of the data logging and sampling system.

Temperature measurements were accomplished with a series of type T thermocouples spaced evenly down the length of a steel cable, and sealed with a vinyl cover. This thermocouple cable was provided by Tri-States Grain Conditioning, Inc. (Spirit Lake, IA). Quarter inch polyethylene tubing was attached to the temperature cable using zip ties, and the open end of the tubing was positioned at the same location as the thermocouples along the cable.

A steel cable with a thimble at the top extended out the top of the thermocouple apparatus. A 1/8 inch cable was looped through the thimble and secured to the cable using two cable rope clips. The apparatus was secured to the tank by looping the cable to a part of the tank. In the cases of tanks A, B, and C, the cable extended out the tank vent, and was secured to a railing, while the cable for tanks D and E were attached to an eye bolt which was installed on the interior of the tank roof. A one-foot long, one-inch diameter stainless steel rod was used as a weight to keep tension in the cable. Vinyl caps were attached to the ends of the rod using a food-safe silicone adhesive to prevent scratching of the interior coatings of the tanks. The bar was attached to the thermocouple cable by looping a short length of cable through a hole drilled in the cable, and around the eye of a bus drop grip, which was sleeved onto the bottom of the cable.

The sampling tubes and the thermocouple lead wire exited the tanks at various locations on the roof (depending on the wishes of each system), and extended down the tanks' exterior via the ladder. The thermocouple lead wires were attached to a data logger which recorded temperature data to be downloaded during site visits. During site visits, samples were drawn from the tubing and analyzed for water quality parameters presented in Sections 3.6.2 and 3.6.3.

The thermocouple string consisted of a type T (copper – constantan) thermocouples, with one constantan common wire for every six copper wires (every six thermocouples). A photograph of the wiring of the data logger is shown in Figure 3.16.

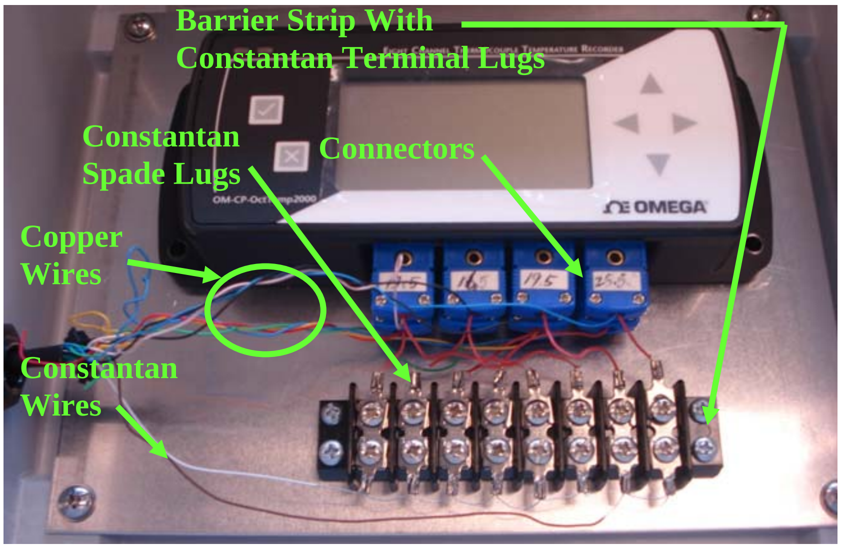


Figure 3.16. Photograph of the OCTTEMP series data logger.

The constantan common was split by attaching spade lugs to the wire. The spade lugs were attached to a barrier strip with constantan terminal lugs. Across the barrier strip, spade lugs were crimped to constantan wire, which extended to connectors plugged into the data logger. Additionally, copper wires from the thermocouples are also attached to the connectors.

The intended application of the thermocouple cable was grain bin temperature monitoring. Because the temperature cable was not specifically designed for water quality research, it was important to determine the time lag for a temperature change to penetrate the vinyl cover and become stable. In order to test this time lag, the string was lowered into three different buckets of water and the temperature was recorded every 30 seconds to determine the amount of time required for temperature to stabilize. The response time was defined as the time after which the following three minutes of data are +/- 0.1^{O} C. The temperatures of each trial and associated response times are shown in Table 3.3.

Table 3.3. Response times for thermocouple cables.

Trial Number	Initial Temperature (^{o}C)	Final Temperature (^{o}C)	Response Time (minutes)
1	Room Temperature (Approximately 19)	12.5	2
2	12.5	26.3	3
3	26.3	32.7	2.5

The longest response time recorded (3 minutes) was during trial 2, during which the temperature was changed from 12.5^{O} to 26.3^{O} C. Subsequently, the sampling time chosen for the study was 10 minutes, well above the longest response time recorded. Temperature data were downloaded to a laptop each time SDSU personnel arrived at a site to collect samples from a tank. A diagram of how the laptop was connected to the data logger is shown in Figure 3.17.

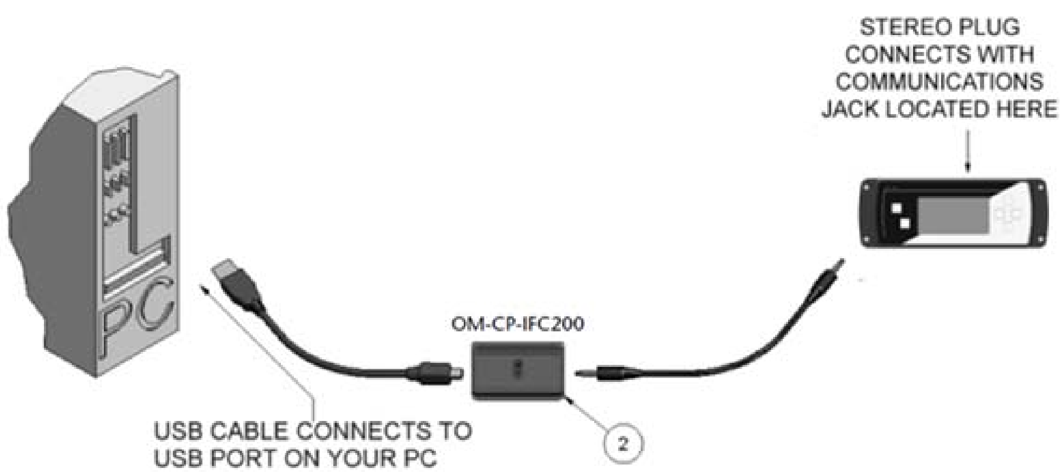


Figure 3.17. Computer interface connection (www.omega.com).

Two different models of data loggers were used in this study, both manufactured by Omega. One OM-CP-OCTTEMP-A, and four OM-CP-OCTTEMP2000 model data loggers were used. The only difference between the two was the addition of a LCD display in the OCTTEMP2000 model. These units were standalone, meaning that once started, the logger could be disconnected from the computer and still collect data. During site visits, the logger was reconnected to the computer and data downloaded. Omega characterized the accuracy of these loggers as +/- 0.5 ^{o}C, along with a resolution of 0.1 ^{o}C. The unit had the capability to log data from up to eight measurement channels. Each channel can store up 500,000 data points, which translates to 3,472 days of logging at a ten minute recording interval. However; the battery life was only 18 months while logging data at a ten minute interval.

3.4.2 Short Term Study Apparatus

Similar to the long term equipment, temperature probes were lowered into tanks at different depths. A photograph of the apparatus used for short term tanks is shown in Figure 3.18.

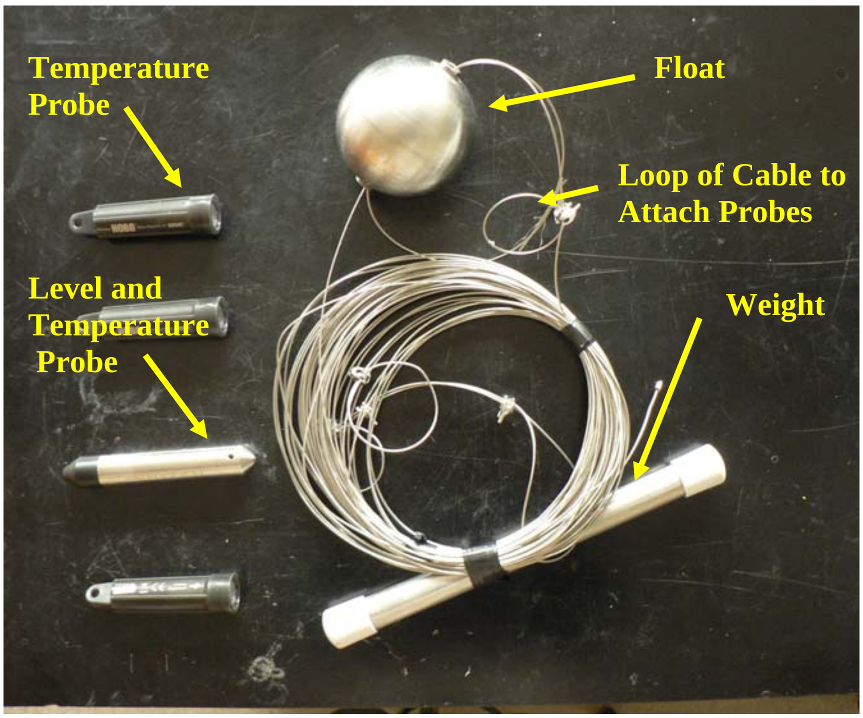


Figure 3.18. Short term temperature apparatus.

Two sets of apparatuses were used for the short term tanks enabling two tanks to be studied simultaneously. These units collect and store data within the probe itself, bypassing the need for an external data logger. All data loggers for short term studies were manufactured by Onset Computer Corporation, with four temperature probes were used in each tank. One of the four probes also had the capability to measure pressure, and by association water level. The temperature only units were HOBO Prov2 Water

Temperature data loggers (Model U22-001). Some specifications of this unit are presented in Table 3.4.

Table 3.4. Specifications for HOBO Prov2 Water Temperature data loggers.

Temperature operating range	50 ^{o}C maximum
Accuracy	+/- 0.2 ^{o}C
Resolution	0.02 ^{o}C
Response time	5 minutes
Memory	42,000 temperature data points
Battery life	6 years (with greater than 1 minute sampling intervals)

The loggers supplied to measure both temperature and pressure were HOBO U20 Water Level Data Loggers (Model U20-001-02). Specifications of this unit are presented in Table 3.5.

Table 3.5. Specifications for HOBO U20 Water Level Data Loggers.

Temperature operating range	-20 to 50 ^{o}C
Temperature accuracy	0.37 ^{o}C
Temperature resolution	0.1 ^{o}C
Temperature response time	3.5 minutes
Water level operating range	0 to 100 ft of water
Water level accuracy	0.05 ft of water
Water level resolution	0.013 ft of water
Water level response time	<1 second
Memory	21,700 pressure and temperature measurements
Battery life	5 years (with greater than 1 minute sampling intervals)

Similar to long term tanks, sampling intervals for short term studies were selected as ten minutes. This is twice the longest response time of the data loggers, ensuring that representative temperatures are measured.

Probes were zip-tied to loops on a 1/16" stainless steel cable at desired depths within the tanks, including one on a float near the surface. A one-foot long, one inch diameter stainless steel rod was used as a weight to keep tension in the cable. Vinyl caps were attached to the ends of the rod using a food-safe silicone adhesive to prevent scratching of the interior coatings of the tanks.

The cables exited tanks through hatches or vents on the roofs of the tanks and were looped around part of the tank (empty bolt holes, railings, or other, depending on what was available). An example of how a cable was affixed to a tank is shown in Figure 3.19.

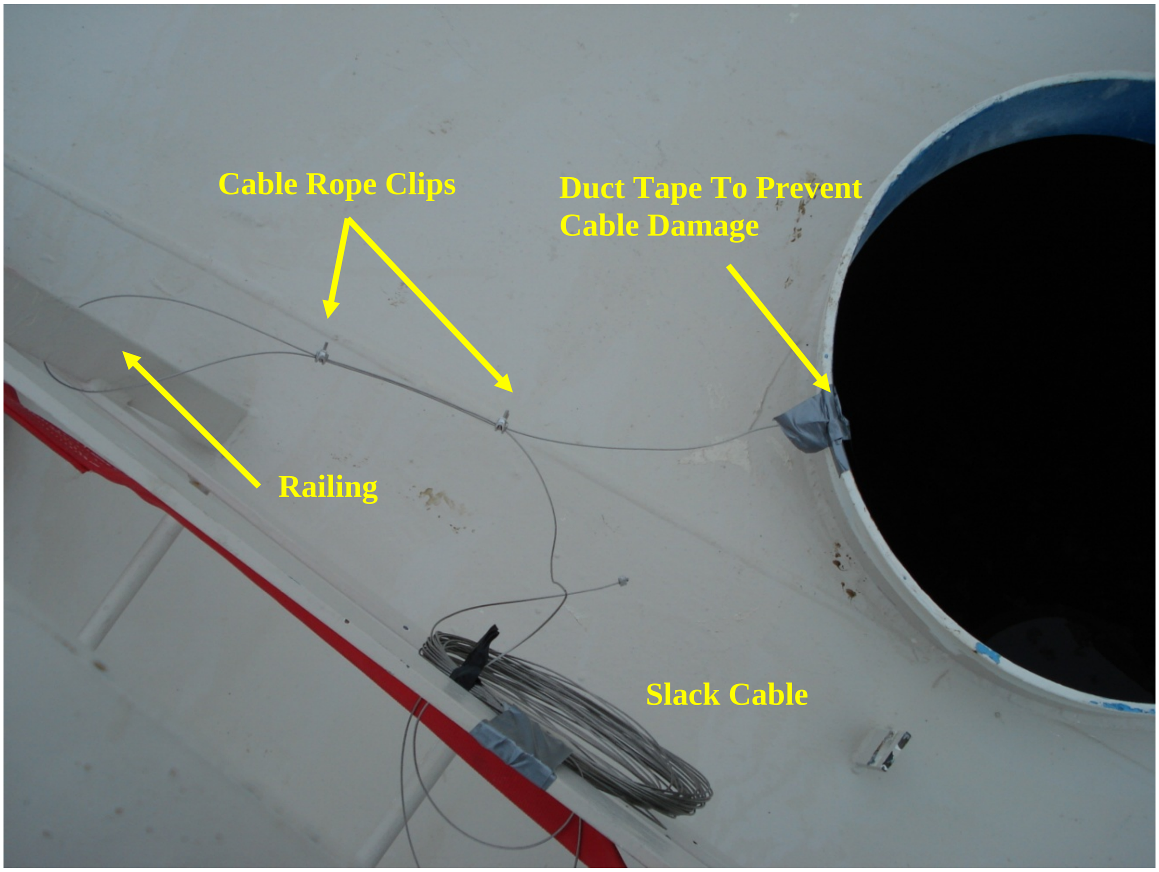


Figure 3.19. Attachment of short term tank cables to tank.

At the end of the testing period, cables were pulled from the tanks and data downloaded. Data transfer was accomplished using an Optic USB Station, manufactured by Onset Computer Corporation. Figure 3.20 shows how data was downloaded to a computer through a coupler device. The use of these probes and a separate cable allow for the equipment to be modified to fit different tank designs. In most short-term tanks water quality samples were collected from the top and bottom when the equipment was installed and removed. These samples were analyzed for the water quality parameters presented in Sections 3.6.2 and 3.6.3.

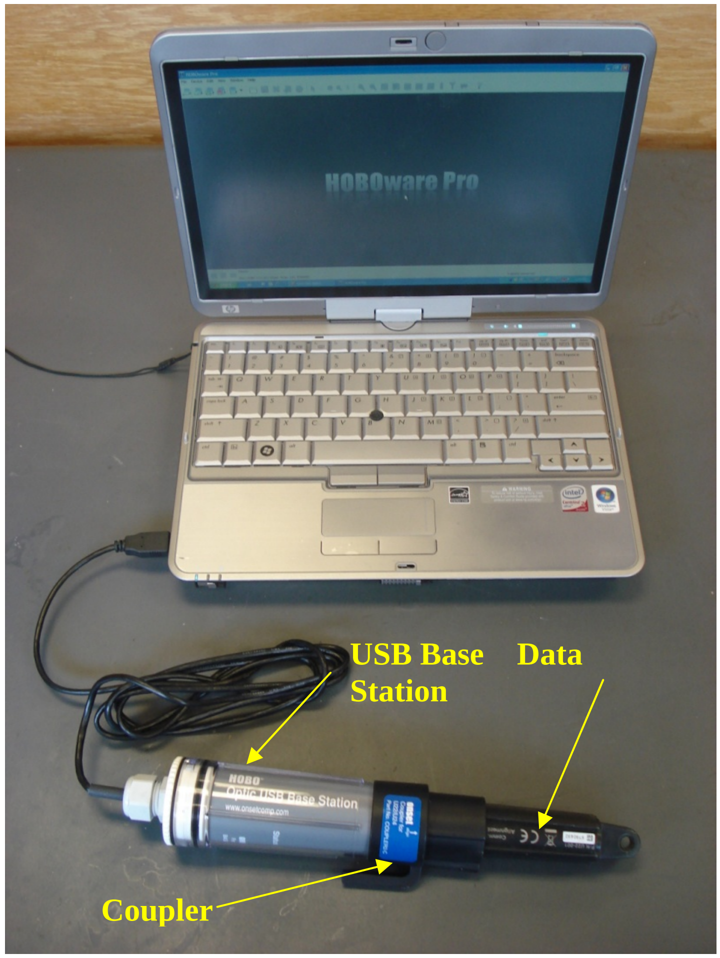


Figure 3.20. Computer connection for HOBO data loggers.

3.5 Sample Collection and Preservation

Samples were collected from both long and short term tanks for on-site or laboratory analyses.

3.5.1 Long Term Tank Sample Collection and Preservation

Tanks were sampled by siphoning water through the water sample collection tubes described in Section 3.4.1. The siphon was started using a peristaltic pump. Because of the remote locations of tanks, the pump was powered by car battery and power inverter. A photograph of the pumping system is shown in Figure 3.21.

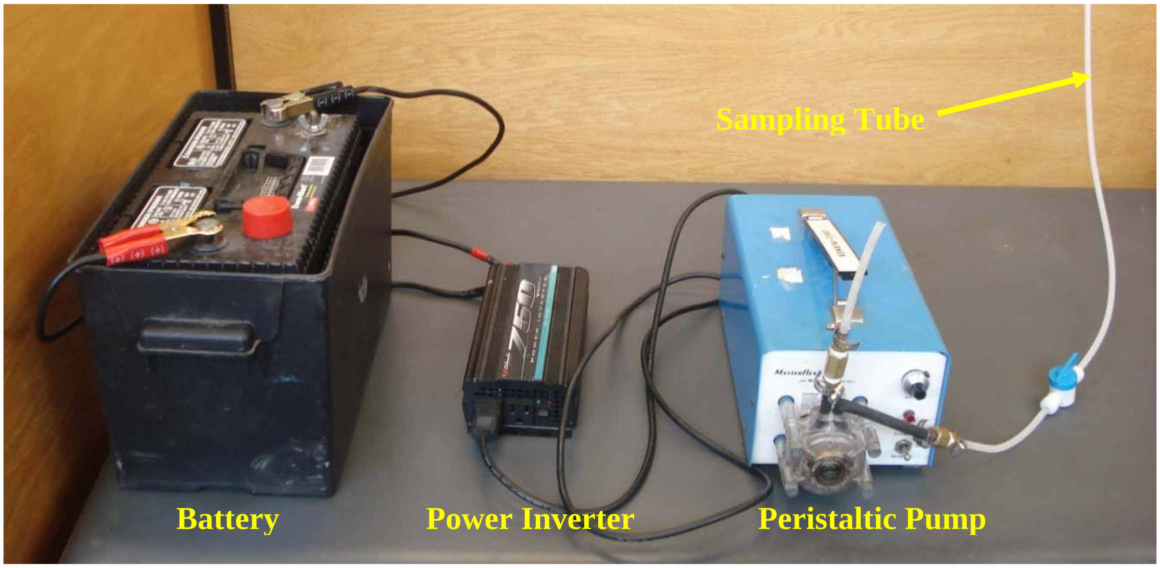


Figure 3.21. Apparatus to draw samples from tanks.

For the cases of tanks A and B, the suction required to begin the siphon was greater than the pump's head capacity, so samples were not collected at all trips. To overcome this problem water was pumped from a disinfected 5 gallon carboy filled with tap water to prime the sampling tubes (with approximately 0.5 L of water). At least 5 gallons of water were discharged from the tubes before collecting a sample to ensure that the water was representative of the tank volume, and not of the priming water. A photograph of the apparatus to prime the sampling tubes is shown in Figure 3.21.

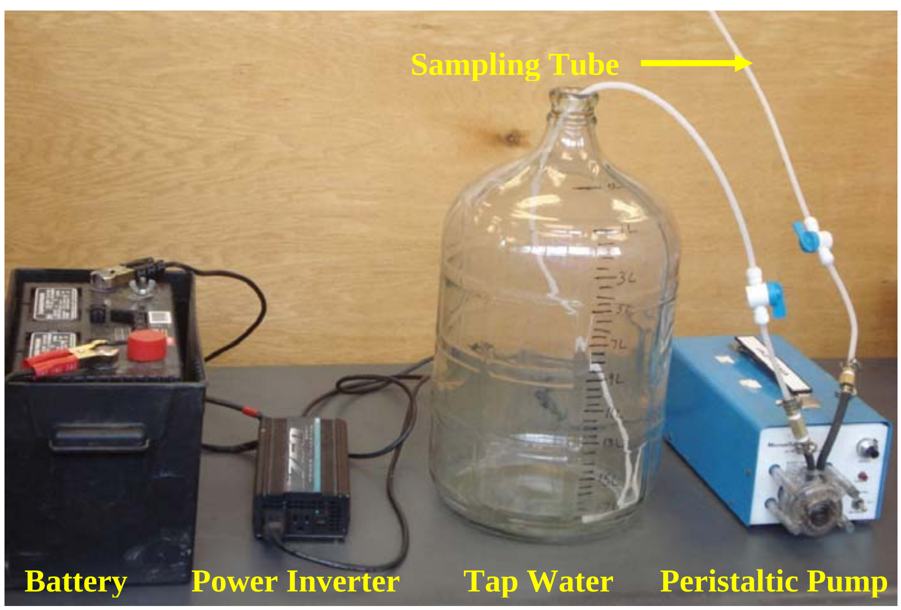


Figure 3.22. Apparatus to prime sampling tubes.

Certain water quality parameters were analyzed on site, which are presented in Section 3.6.2. Additionally, 250 mL polyethylene bottles were filled with samples from each depth, labeled, stored in a cooler, and transported to the WEERC laboratory at the SDSU campus for nitrate analysis.

Following sample collection, tubes were purged by either reversing the pump or pressing the nozzle of an air tank to the tube end and blowing compressed air into the tubes. SDSU personnel were informed midway throughout the study that the siphons had undesirably restarted at one of the tanks. To prevent the situation from repeating, the ends of sampling tubes were crimped after the samples were collected.

3.5.2 Short Term Tank Sample Collection and Preservation

Grab samples were collected from the top and bottom of most short term tanks when equipment was installed and removed. Samples from the base of tanks were taken either from taps in the filling line, or at customer hookups which are fed directly from the tank. Samples from the interior of the tank were taken using bottles previously disinfected with a bleach solution and rinsed with distilled water until no chlorine residual was detected. These bottles were tied to a string, dropped into the tank volume, and retrieved. Samples from tanks whose secondary disinfectant was free chlorine were tested for free and total chlorine on-site. Chloraminated systems were tested on-site for total chlorine, monochloramine, free ammonia, and nitrite. Samples from chloraminated tanks were also labeled, stored in a cooler, and transported to the WEERC laboratory on the SDSU campus for nitrate analysis.

3.6 Water Quality Measurements

Temperature data were collected from all tanks at various depths in each tank. Additionally, a variety of other water quality parameters were measured depending on the type of disinfectant utilized in each system.

3.6.1 Temperature Measurements

Temperatures in long-term tanks were recorded using the apparatuses described in Section 3.4. Readings were taken from various depths in the tank every ten minutes, recorded on a datalogger, and subsequently downloaded to a laptop. An example of raw data collected from one of the tanks is presented in Figure 3.23.

Because water levels fluctuate in storage tanks, some thermocouples at higher points in the tanks were periodically unsubmerged. When this occurred, spikes or drops in temperature which do not actually represent temperatures in the tank were observed as shown in Figure 3.23. Some data analyses required water temperature data from the upper zones. Those analyses would not reflect true water temperatures if these spikes were not eliminated. Additionally, temperature plots lost clarity with so many temperature spikes and drops. Therefore, temperature data recorded when the thermocouples were unsubmerged were eliminated by correlating water levels to the heights of the thermocouples in the tanks. Correlation of temperature data with water level also enables the precise height of each thermocouple to be determined. Filtered data for the same dates shown in Figure 3.23 are presented in Figure 3.24.

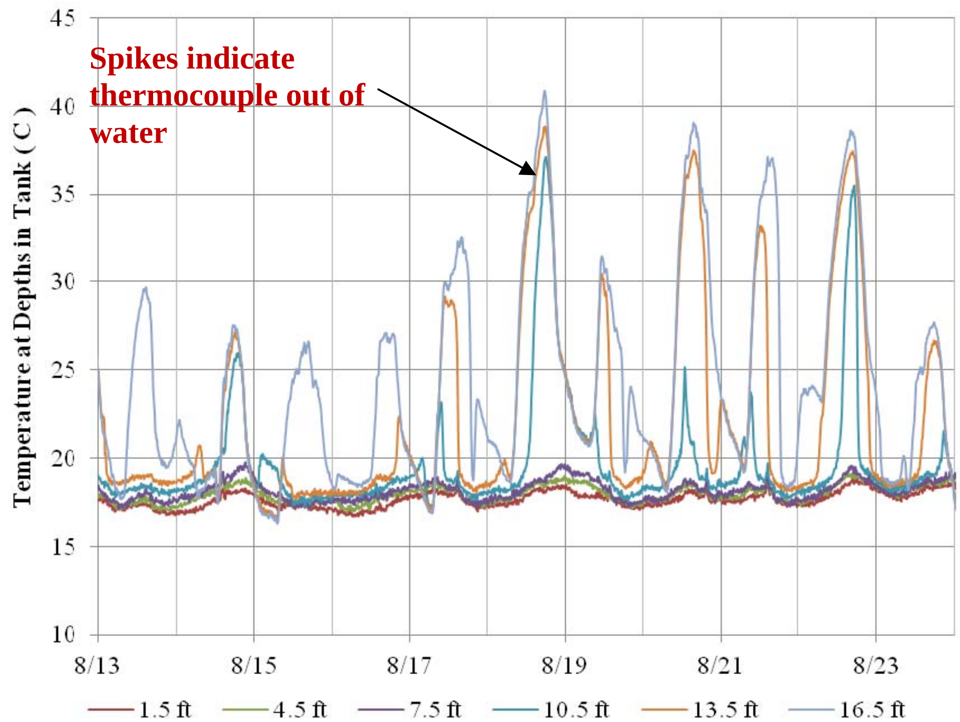


Figure 3.23. Unfiltered tank depth temperatures

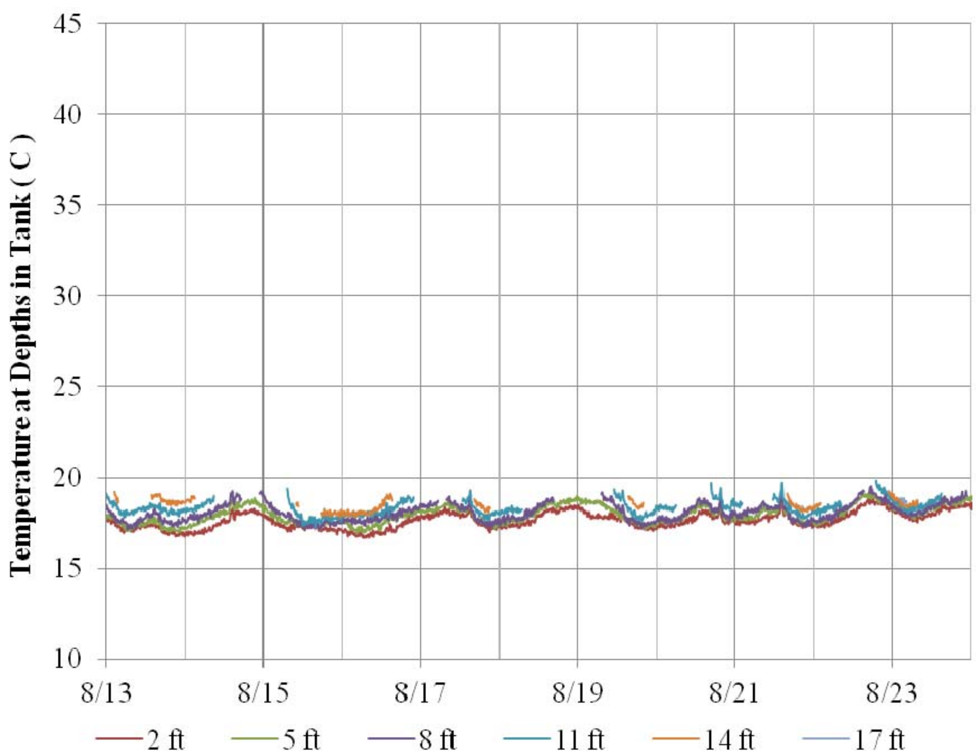


Figure 3.24. Filtered tank depth temperatures.

3.6.2 On-site Water Quality Measurements

Free and total chlorine samples were analyzed at the tank sites for systems that did not use chloramines. Water samples from systems utilizing chloramines as secondary disinfectants were not tested for free chlorine, but were also tested for monochloramine, free ammonia, and nitrite on-site. All long term tanks, along with short term tanks 7 and 8, utilize chloramines while the remainder free chlorinate. All on-site water quality tests utilized a HACH model DR/890 colorimeter. Figure 3.23 shows this colorimeter and Table 3.6 lists the HACH methods followed and reagents which were used.

Figure 3.24. HACH DR/890 colorimeter.

Table 3.6. Methods and reagents used for on-site water quality testing.

Constituent	HACH Method Number	Reagents Used	Range (mg/L)
Total Chlorine	8167	DPD – Total Chlorine Reagent (10 mL sample)	0.0-2.0
Free Chlorine	8021	DPD – Free Chlorine Reagent (10 mL sample)	0.0-2.0
Monochloramine	10020	Monochlor F Reagent	0.0-4.5
Free Ammonia	10020	Monochlor F reagent + hypochlorite solution	0.0-0.5
Nitrite	8507	Nitriver 3 Reagent	0-0.35

3.6.3 Nitrate

Nitrate samples were collected from tanks whose systems chloraminate, transported in a cooler to the WEERC laboratory on the SDSU campus. Samples were analyzed by WEERC laboratory personnel using EPA method 300.0 (Determination of Inorganic Anions by Ion Chromatography). The apparatus used for these analyses was manufactured by Dionex, and consists of the following equipment:

- Model AS40 Automated Sampler
- GP40 Gradient Pump
- Model LC20 Chromatography Enclosure
- CD20 Conductivity Detector

3.7 Analysis of Mixing Characteristics

Several parameters shown to affect mixing according to the literature review were calculated using data collected during the study. The mixing characteristics presented in this section assume that the tank volume and inflow have the same temperature. Analyses incorporating temperature affects are presented in Section 3.8. This section describes how certain data points needed for these calculations were extracted from water level data. Analyses of the following parameters are introduced in this section as well:

- Aspect ratio of the water column
- Flow rate during fill cycles
- Inflow velocity
- Reynolds number
- Tank detention time
- Fill time
- Volumetric exchange to mix a tank
- Velocity gradient for ice prevention mixer
- Certain special considerations required for short-term tank 5

3.7.1 Extraction of Critical Data Points from Water Level Data

Water level data for each tank provides information which may be used to evaluate mixing parameters. Short term tanks utilized a pressure transducer attached to the temperature measurement apparatus, while long term tank water level data was provided by the water systems. Water level data were broken into individual fill and draw cycles by extracting the critical data points from the datasets, including:

- Water level at the start of each cycle
- Water level at the end of each fill cycle
- Time of the start of each fill cycle
- Time at the end of each fill cycle

An example of the data points extracted from water level datasets is shown in Figure 3.24. Additionally, temperature data were extracted for the top and bottom of the tank for each fill cycle for analyses presented in Section 3.8. Bottom temperatures were taken as the lowest measurement point at the end of the fill cycle. Top temperatures were taken at the end of the draw cycle using the uppermost sensor which was submerged (neglecting float level on the short term tanks).

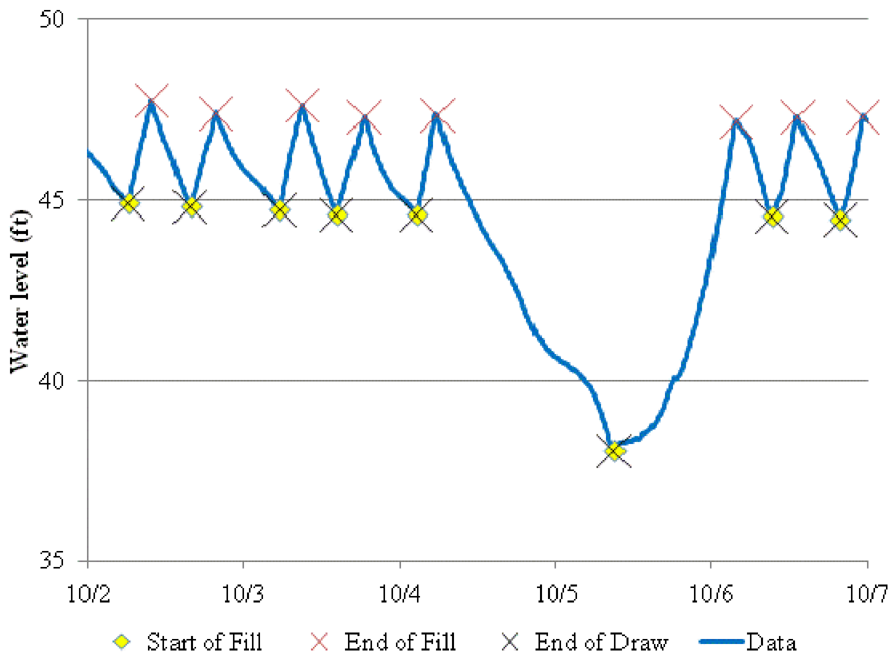


Figure 3.25. Example of extracted water level data.

3.7.2 Aspect Ratio of Water Column

Because storage tanks are not always completely filled, the aspect ratio (H:D) of the water in the tank is not necessarily the same as the aspect ratio of the tank itself. In order to classify the aspect ratio and for use in subsequent calculations, the actual aspect ratios for water in each tank were calculated for every fill and draw cycle (using the midpoint water level during the fill cycle). An example of this calculation is shown in Appendix B.

3.7.3 Flow Rate during Fill

Knowing the tank diameter, water level, and time at the start and completion of the fill cycle allows the filling flow rate to be calculated. This flow rate was calculated for each fill cycle for every tank used in several subsequent calculations of mixing parameters. An example of this calculation is shown in Appendix B.

3.7.4 Velocity of inflow

The velocity of the inflow was calculated for each fill cycle of every tank. These velocities were then used to calculate Reynolds numbers and inlet momentums. Sample calculations of inflow velocity for the inflow are presented in Appendix B.

3.7.5 Reynolds Number

The Reynolds number is a dimensionless parameter used to determine whether flows are turbulent or not. According to the literature review, turbulent jets have Reynolds numbers above 3,000, while laminar jets are below 1,000. Reynolds numbers were calculated for each fill cycle of every tank to determine whether jets achieve turbulent status. An example calculation of the Reynolds number is presented in Appendix B.

3.7.6 Detention Time

Even if tanks are completely mixed, water can still spend a substantial amount of time in a tank. The actual detention times of tanks were calculated using Equation 14 (presented in Section 2.2.2.4) for every fill and draw cycle of each tank throughout the study. Equation 14 assumes that a tank is completely mixed under fill and draw conditions (no flow leaves the tank during fill cycles). Average detention times were then calculated from the results of those calculations. An example calculation of a tank's detention time is shown in Appendix B.

3.7.7 Fill Time Required to Achieve a 90% Mixed Tank

According to the literature review, the fill time required to achieve a 90% mix is calculated using Equation 10 (coupled with Equation 11). These equations assume that there are no thermal variations within the tank (inflow water is the same temperature as the tank volume). The operational H:D ratio (see section 3.7.2) for every fill cycle of each tank was applied to Equation 10 to determine the dimensionless mixing time. Equation 11 was then applied to each fill cycle for every tank to determine the fill time required to mix the tank. Example calculations of the fill time required to achieve a 90% mix in a tank are presented in Appendix B.

Actual filling times determined from the water level data were divided by the required values calculated using Equation 11 to show the percentage of fill time achieved.

3.7.8 Volumetric Exchange Required to Achieve a 90% Mixed Tank

Equation 10 was simplified to show the fractional exchange required during a single fill cycle to mix a tank. This was accomplished using the definition of filling time $t = \Delta V / Q_{fill}$, where ΔV is the volume of new water added during the fill cycle. A special case of this is illustrated in Rossman and Grayman (1999), while a more generalized derivation may be seen in Appendix B, and the result is Equation 18:

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2} \tau_m d_i}{2V^{1/3}} \tag{18}$$

in which: ΔV = volume of water added during fill (ft^3); V=tank volume (cubic feet); τ_m = constant (see Equation 11, Tables 2.3, or Table 2.4); and d_i = inlet diameter. Equation 18 was applied to each fill cycle for every tank and compared to the actual volumetric exchanges. Because Equation 18 has a direct relationship with Equation 10, the percentage of fill time achieved is the same as the percentage of volumetric exchange achieved.

3.7.9 Velocity Gradient Calculation for Ice prevention Mixer

The velocity gradient is a parameter used to evaluate the performance of a mixer in a tank. The velocity gradient for the mixer installed in long term tank E was calculated using Equation 12. This calculation may be found in Appendix B.

3.7.10 Special Consideration for Short Term Tank 5

The varying diameter at different heights in short term tank 5 complicates the calculation of tank volumes, and thus flow rates. As a result, an equation relating height of water in the tank to its respective volume was derived using plans obtained from the water system. This derivation utilized the method of discs technique of calculus and is presented in Appendix B.

Because the aspect ratio is used to correlate tank performance, and in the case of this tank the diameter is variable at different depths, an approximate average diameter was calculated. This calculation separated the tank into two sections, and assumed those sections both had trapezoidal cross sections. The diameter at the vertical centroid of each trapezoid was calculated. The weighted average of those diameters was calculated to determine an average tank diameter. This average diameter was used to of select a dimensionless mixing time in Equation 11 (for use in Equations 10 and 18). Additionally, this diameter was used for an approximate aspect ratio to compare to a long term tank.

3.8 Analysis of Temperature Affects on Tank Performance

Because temperature can have substantial impacts on how tanks mix; it is important to characterize how tanks respond to changes in ambient temperature. The development of empirical relationships between ambient temperature and internal tank temperature is introduced in this section. Additionally, analysis of parameters relating tank performance to temperature variations between the inflow and tank volume are introduced in this section, including:

- Densimetric Froude number
- Dimensionless parameter calculated using Equation 4
- Critical temperature difference between inflow and tank volume to cause stratification

3.8.1 Correlating Ambient Temperature to Internal Tank Temperature

The atmosphere surrounding a tank affects tank contents by heating (or cooling) water in the tanks through conduction and convection. The heat transfer equations required to physically model these phenomena are quite complicated and require data that were not collected during the study. Because of these limitations, heat transfer was modeled by empirical, rather than physical methods. Empirical linear regressions were performed on datasets from the two long term tanks showing the most substantial stratification. These regressions compared ambient temperature (outside the tank) with water temperature in the uppermost submerged measurement point.

3.8.2 Strategies to Overcome Stratification in Reservoirs

Dimensional analyses summarized in the literature review show the inlet jet momentum required to overcome thermoclines in tanks. Two methods are presented to predict the strength of jets required to break through the thermal layer and mix a tank. The first is the densimetric Froude number, and the second is shown by Equation 5 in the literature review.

3.8.2.1 Densimetric Froude Number

According to the literature review, if the densimetric Froude number (calculated from Equation 1) is greater than a certain value (calculated from Equation 3) stratification will not occur. The densimetric Froude number was calculated for each fill using temperature and flow rate data taken from the datasets. These calculated densimetric Froude numbers were compared with the results of Equation 3 to determine whether the influent jet was substantial enough to overcome a thermocline in a tank. Sample calculations for these data are shown in Appendix B.

3.8.2.2 Other Hydraulic Considerations for Stratified Tanks

A dimensionless parameter (Equation 5) is presented in the literature review that illustrates the momentum required to overcome stratified conditions in a tank. This parameter was compared with required values, both graphically and in tabular form, to show which tanks meet the requirements for overcoming stratified conditions. Sample calculations for these data are presented in Appendix B.

3.8.2.3 Critical Temperature Difference to Cause Stratification

The literature review presented (in Equation 4) the critical temperature difference between tank contents and filling water to cause a stratified tank. A large temperature difference leads to strong buoyant forces, causing the tank to be more difficult to mix. This equation was applied to each tank, and the results were used in comparing tank types by showing which tanks are easier to mix. Sample calculations for these data are presented in Appendix B.

3.9 Systematic Modeling of Tanks

The program CompTank (which is discussed in Section 2.3) was utilized to model disinfectant concentrations in tanks. The loss of residual disinfectant in the upper portions of stratified tanks is influenced by both the decay rate of the disinfectant as well as the degree of mixing between stratified and active compartments in the tank. Data from bottle studies conducted using Missouri River water by Drews Nelson (2010) were used to estimate total chlorine decay coefficients for the water in the tank. The bottle studies were performed at two temperatures (20^0 C and 4^0 C). The derivations of the coefficients are presented in Appendix B. For the beginning of the study, when temperatures were warmer, the 20 ^{0}C coefficient was used. When temperatures in the tank consistently dropped below 12 ^{0}C, to enable the decay coefficient to be nearest to the conditions in the tank, the 4 ^{0}C coefficient was used (12 ^{0}C is the midpoint between 4 ^{0}C and 20 ^{0}C). For stratified long term tanks, the size of each compartment was estimated using temperature and water quality data.

Long term tank A was modeled as a completely mixed system under fill and draw conditions for the entire duration of the study. Total chlorine concentrations entering the tank varied as the study progressed, so to enable it being modeled, the filling concentration was extrapolated between sampling visits.

Long term tank B was modeled similar to tank A, under completely mixed fill and draw conditions. This tank actually operates under continuous inflow/outflow conditions (with a separate inlet and outlet). However, it is not possible to differentiate inflow from outflow rates using only water level data. This tank was sampled twice for chlorine residual, each with similar filling concentrations of total chlorine, (1.00 and 1.02 mg/L). The average of these (1.01 mg/L) was used as the filling concentration for the model. This tank was modeled until the chlorine concentrations became steady.

Long term tank C appeared to be stratified at the beginning of the study, but with substantial mixing between the upper and lower zones of the tank. However, without actual tracer data to authenticate the model, the degree of mixing between compartments was difficult to validate. Grayman et al. (2000) suggests that the flow between compartments is typically lower than the inflow/outflow rate of the tank. Flow rates between the inlet and main zone, as well as between the main and dead zones were estimated at 10 gpm each, which is approximately 25% of the inflow and 50% of the outflow rate (average values for the inflow and outflow are 40.9 and 20.9 gpm, respectively). This tank was modeled twice, once as a stratified three compartment model under fill/draw conditions, and once as a fill/draw completely mixed system. The completely mixed system represented when temperatures in the tank became consistent near the end of the study.

Temperature and residual disinfectant decay concentrations at the beginning of the study in long term tank D indicated that very little water was able to mix between the inlet zone and the rest of the tank. Because of this lack of mixing, the tank was modeled as a stratified three compartment model with no mixing between the inlet, main, and dead zones of the tank. The model start time was immediately after a deep cycle of the tank, allowing the assumption of consistent chlorine concentrations throughout the tank depth to be made (1.14 mg/L according to calculations in Appendix B). Near the end of the study, temperatures at each depth of the tank in each tank came together, indicating that the tank became better mixed. As a result, the tank modeled again using the completely mixed fill/draw condition.

Similar to long term tank D, temperature and residual disinfectant concentrations in long term tank E at the beginning of the study indicated that very little water was able to mix between the inlet zone and the rest of the tank. The tank was overflowed, allowing for the initial assumption of a well mixed tank with substantial chlorine residual (1.25 mg/L). Because the tank restratified soon after the overflow, the tank was modeled as a stratified three compartment model with no mixing between the inlet zone, main zone, and dead zone of the tank. Near the end of the study, temperatures at each depth of the tank came together. This convergence of temperatures indicates that the tank became better mixed, so the tank was modeled again using the completely mixed fill/draw condition.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The effects of distribution storage tank design and operations on water quality in South Dakota's regional water systems were examined in this study. A survey sent to various regional water systems was employed to determine the characteristics of tanks commonly used in the state. Using data from this survey, tanks that represent a wide range of storage facilities were instrumented for long-term water quality studies. A variety of other tanks of interest to water supplies were also studied on a shorter term basis.

Temperature data were collected from various depths in the tanks and correlated with residual disinfectant concentrations at those same depths. Because several systems which operate these facilities are chloraminated, water quality data to detect nitrification was also gathered.

Temperature data from short term tanks were correlated with that of similarly operated long term tanks. Evaluations of various hydraulic mixing parameters described in the literature review were made to determine whether those parameters coincided with field-scale evidence of mixing. Modeling was performed to estimate residual disinfectant concentrations in various tank geometries.

4.2 South Dakota Rural Water Tank Survey

The results of the South Dakota rural water tank survey revealed a wide range of tanks were employed by regional water systems in the state. Types of tanks were classified as aboveground reservoirs, standpipes, elevated towers, underground reservoirs, or clearwells. Data from this survey are tabulated in Appendix C. A distribution of the tanks in the state by number of tanks, and storage volume are shown in Figures 4.1 and 4.2, respectively.

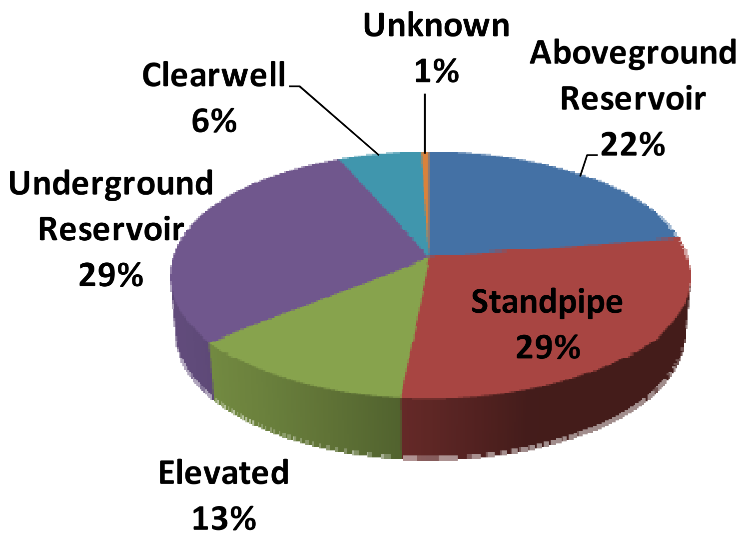


Figure 4.1. Distribution of tanks in SD's regional water systems by number of tanks.

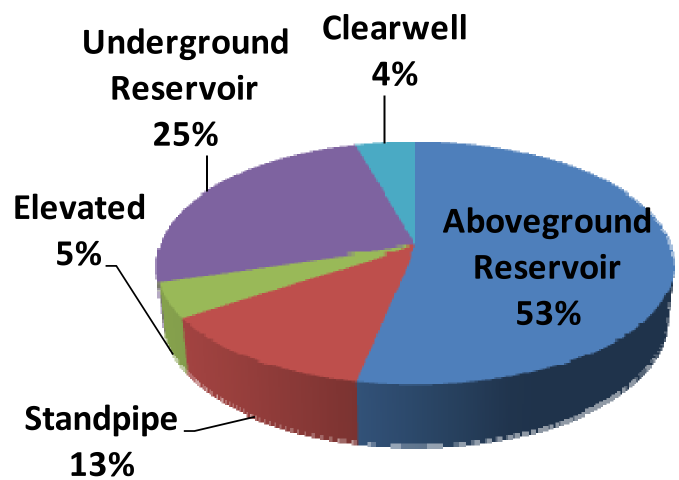


Figure 4.2. Distribution of tanks in SD's regional water systems by total storage volume.

As shown in Figures 4.1 and 4.2, it is noteworthy that the distribution of tanks is quite different when comparing the number of tanks to total volume. Although aboveground reservoirs accounted for only 22% of the number of tanks in the state, they provided 53% of the total storage volume. The percentage of the number of both elevated and standpipe tanks was substantially greater than the percentage of total storage volume of these tanks indicating that although standpipes and elevated tanks account for a large number of tanks in the state, their contribution to the storage volume is much less. Figure 4.3 illustrates the distribution of storage volumes by tank type.

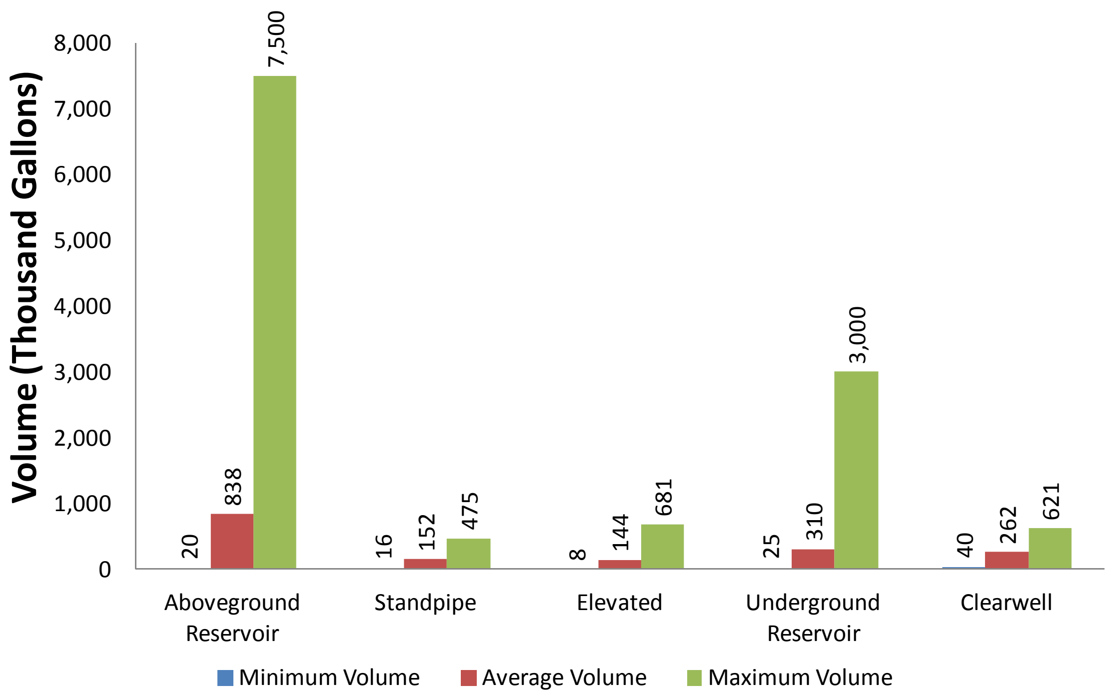


Figure 4.3. Minimum, average, and maximum volumes for various tank types.

Figure 4.3 shows that there is a wide range of volumes for each type of tank, especially in the above and underground reservoir categories.

Aboveground reservoirs and standpipes were selected as the primary study tanks because of their substantial contribution to the distribution of tanks in the state and because they were more readily instrumented. These tanks were sub-divided into five categories based on aspect (height to diameter) ratio. Characteristics of each category may be seen in Figure 4.4, including the percentage of tanks, number of tanks, average height to diameter ratio, average height, and average diameter.

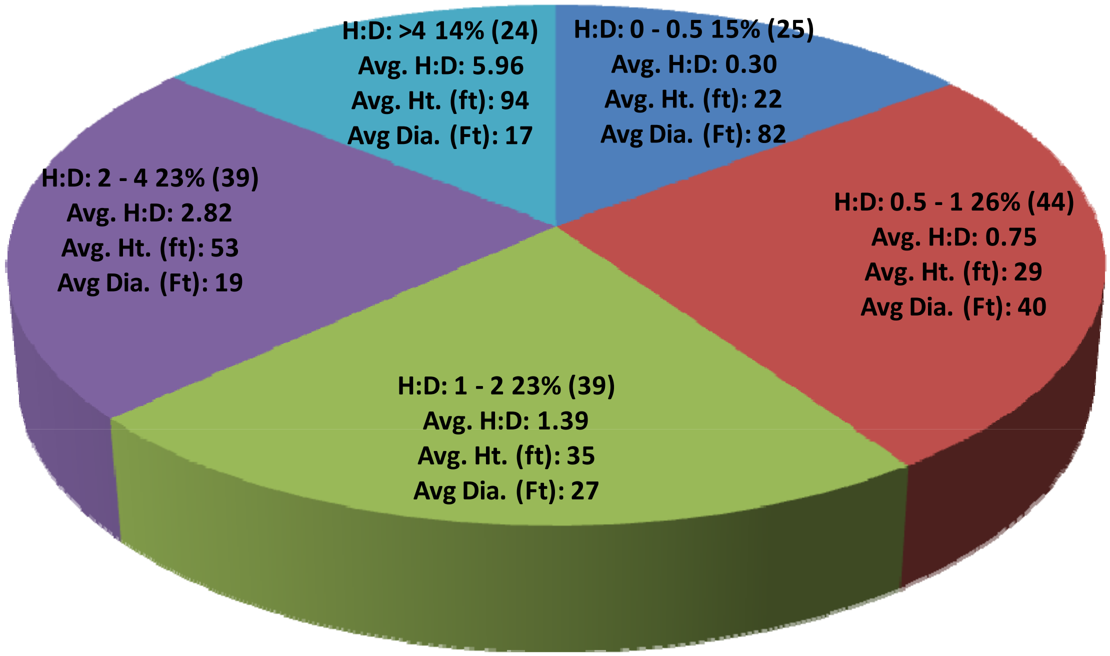


Figure 4.4. Distribution of at-grade tanks by aspect ratio category.

Each category accounted for between 14% and 26% of the at-grade tanks. As the aspect ratio category increases, the average height for that category increases while diameter decreases, indicating that taller tanks tend to be more narrow, while shorter tanks are much wider. Information from Figure 4.4 was used to select the five long term tanks to be used in this study, one from each of the five categories. The characteristics of each of the five tanks were summarized in Chapter 3.

4.3 Long Term Tank Studies

Temperature and residual disinfectant data were collected from various depths within each of the long term tanks. Temperature data was logged at 10 minute intervals, while residual disinfectant measurements were taken during on-site visits.

4.3.1 Long Term Tanks A and B

Temperatures profiles for long term tanks A and B are presented in Figures 4.5 and 4.6, respectively. Tanks A and B had average operational H:D ratios of 0.13 and 0.54, respectively. Data presented in each of these figures include internal tank temperatures on the primary y-axis, and the ambient temperature on the secondary y-axis. The ambient temperature is plotted at noon with a value halfway between the daily high and low. Sampling events are shown as vertical lines on the charts.

Temperature profiles for long term tanks A and B present minimal variation in temperature between upper and lower reaches of the water column. The minimal temperature variations indicate that these tanks were well mixed from a temperature standpoint, likely as a result of the low height to diameter ratio. Because of the minimal variations in temperature in both tanks, it is appropriate to conclude that both of these tanks behave in a similar manner. Internal temperatures do not tend to track with the ambient temperature trends, but rather follow the fill and draw cycles of the tank, indicating that the inflow is able to reach the entire height of the water column. The short-term fluctuations observed in the data match closely with the fill and draw cycles of these tanks operations. Examples of water quality data for these tanks are presented in Figures 4.7 and 4.8, respectively.

Figures 4.7 and 4.8 both indicate consistent total chlorine concentrations throughout the depths of both long term tanks A and B. Tank A total chlorine concentrations are slightly below 0.5 mg/L, while concentrations in tank B hover near 1 mg/L. The lack of concentration variations with respect to tank depth indicates that tanks are well mixed. Total chlorine data collected during other site visits are presented Appendix D. These data also indicate that these tanks were well mixed during other site visits, similar to Figures 4.7 and 4.8. Although consistent with depth during each trip to the tank, the tank's chlorine concentrations during each visit to tank A were slightly different, with residuals ranging from 0.14 to 0.6 mg/L. Both times that tank B was sampled, chlorine concentrations were near 1 mg/L. The species of chloramines in both tanks were primarily monochloramine, with some free ammonia present, ranging from 0.17 to above 0.5 mg/L as N in Tank A, and 0.18 to 0.8 mg/L as N in Tank B. Free ammonia measured on various site visits to these tanks range from 0.18 to 0.8 mg/L. The highest nitrite concentration measured for these tanks was 0.011 mg/L, indicating that the first stage of nitrification was not occurring. Nitrate concentrations ranged from 0.29 to 0.34 mg/L inside of tank A, and 0.21 to 0.27 mg/L in Tank B. Without a baseline to compare these data to, it was unclear whether nitrification had progressed to nitrate.

Data illustrated above indicates tanks A and B were well mixed in the vertical direction (with tank depth). However, very wide, short tanks, may be poorly mixed in the horizontal direction (tank width). In tank A, the inlet and outlet are located near the edge of the tank, while the sampling equipment was positioned in the center. When the equipment was installed, a sample was collected from the pump station drawing water from the tank. This sample was likely representative of water near the outlet (at the side of the tank), and may be compared to the water quality at the center. Total chlorine at the pump station measured 0.17 mg/L, while the center samples were 0.14 and 0.15 mg/L. These data show that similar water quality existed at the center of the tank compared to the inlet of the tank. A sample could not be collected at the edge of the tank opposite to the inlet/outlet.

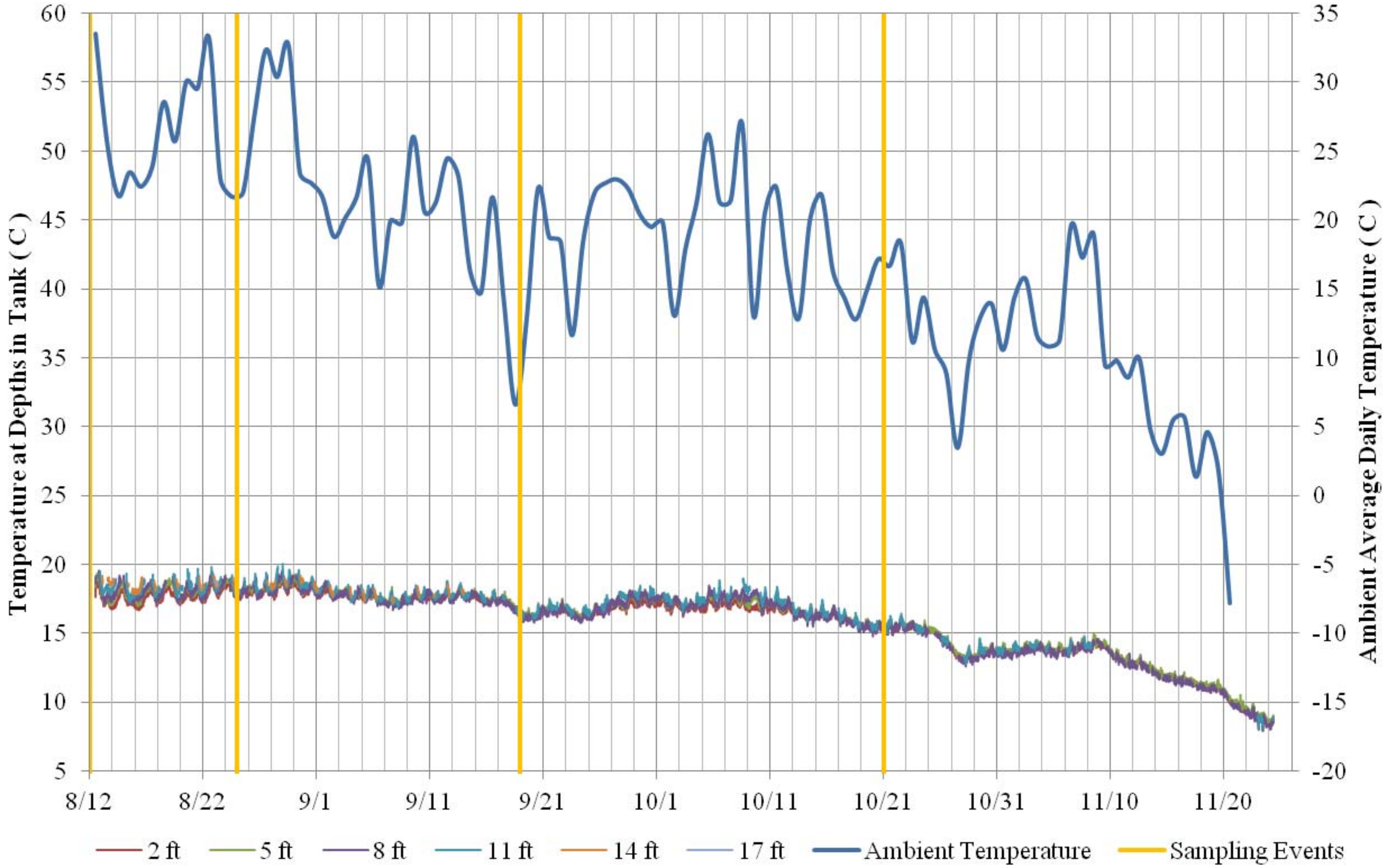


Figure 4.5. Long term tank A temperature profile (operational H:D = 0.13).

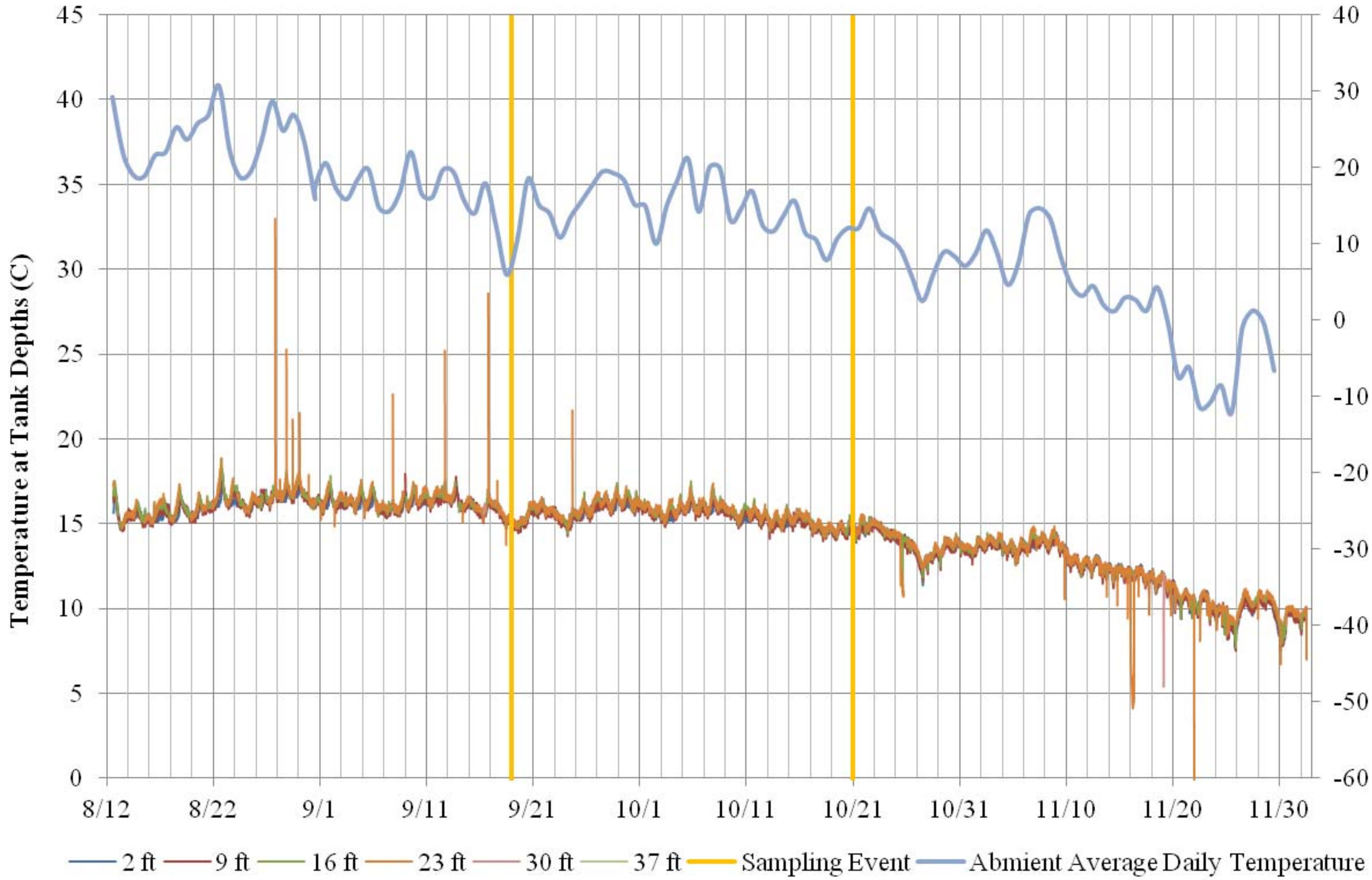


Figure 4.6. Long term tank B temperature profile (operational H:D = 0.54).

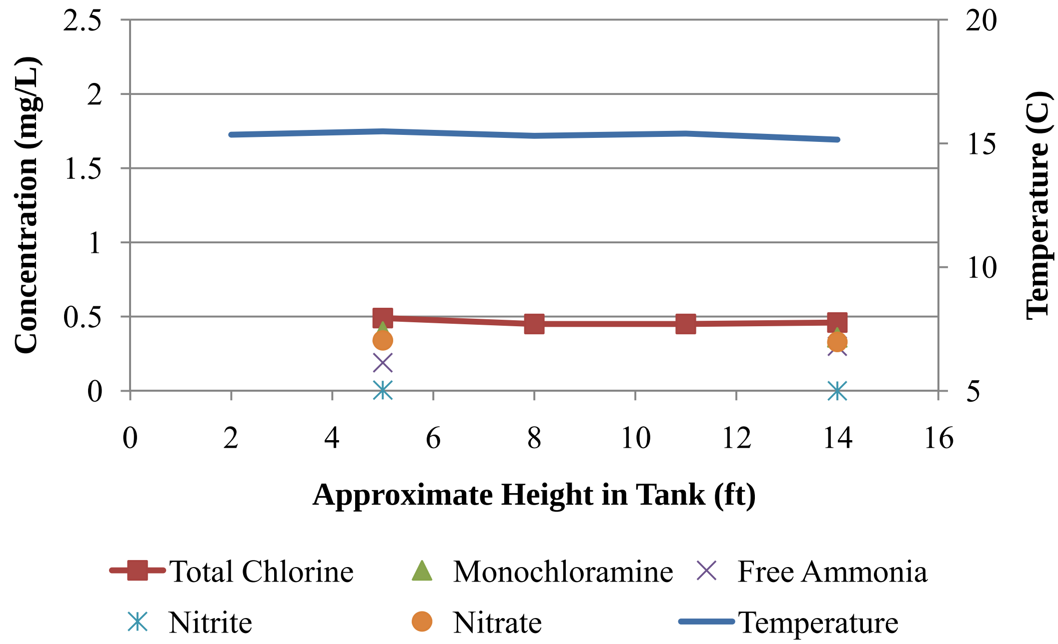


Figure 4.7. Water quality in long term tank A on October 21, 2010.

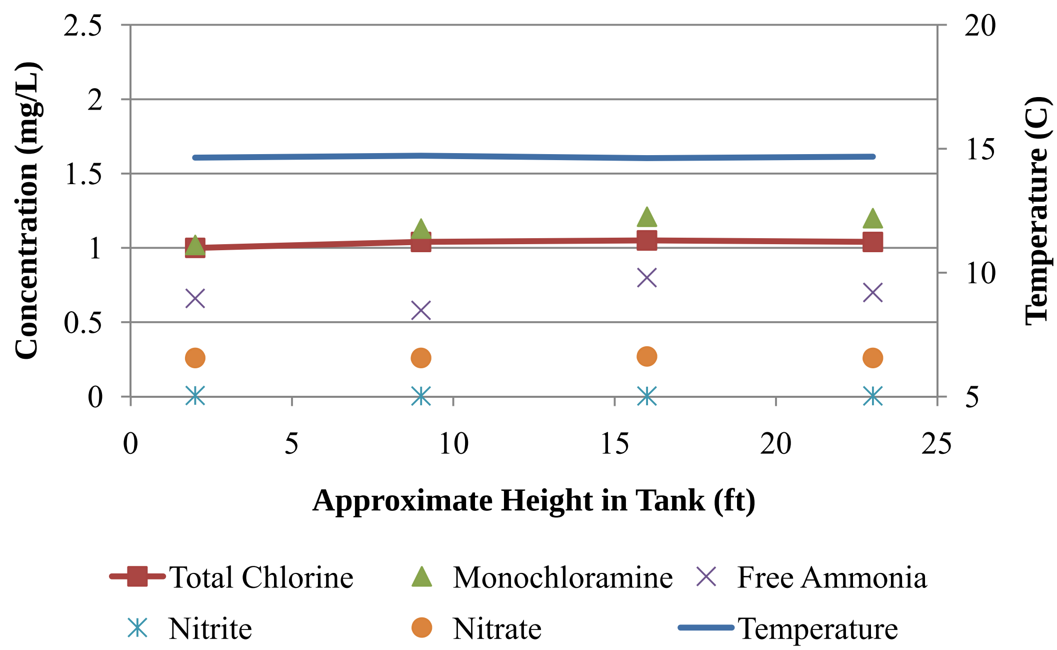


Figure 4.8. Water quality in long term tank B on October 21, 2010.

4.3.2 Long Term Tank C

Figure 4.9 presents temperature data for long term tank C, with ambient temperature and sampling events also shown. The average operational aspect ratio for tank C was 0.88.

Figure 4.9 presents the evidence of thermal stratification in tank C, particularly at the start of the study, with a ten degree Celsius difference between the water in the upper and lower portions of the tanks. As the study progressed, the tank destratified (based on temperature data) when the ambient temperature cooled off and restratifed when it became warmer outside. Near the end of the study, the tank reached a steady state unstratified condition. Water quality data taken while the tank was thermally stratified (August 22nd) and while the tank was destratified (October 20th) are shown in Figures 4.10 and 4.11, respectively. Data used to create these charts, as well as other total chlorine measurements are presented in Appendix D.

Figure 4.10 shows a slight decrease in total chlorine concentration above the thermocline (approximately 0.25 mg/L less in the top of the tank compared to the bottom). However, a substantial chlorine concentration still remains in the upper reaches of the tank. Figure 4.11 shows that after the thermocline had disappeared, consistent concentrations were observed throughout the entire tank depth (slightly above 2.5 mg/L). Data used to explain this tank's ability to maintain chlorine concentrations under stratified conditions is presented in Figure 4.12.

Figure 4.12 shows that the temperatures in the lower levels of the tank were primarily influenced by the fill and draw cycles. The influence of filling water occurs when cooler water enters the tank during the fill cycle, decreasing the temperature of the lower level. During the subsequent draw cycle, warmer water is drawn from the upper elevations down to the lower reaches of the tank. Apparently, the thermocline was drawn down far enough to allow the next fill cycle to at least partially mix with the upper layer. Although the tank appeared stratified from a temperature standpoint, sufficient mixing occurs during the fill/draw operation to maintain adequate chlorine residuals, so it does not pose a substantial risk for water quality deterioration.

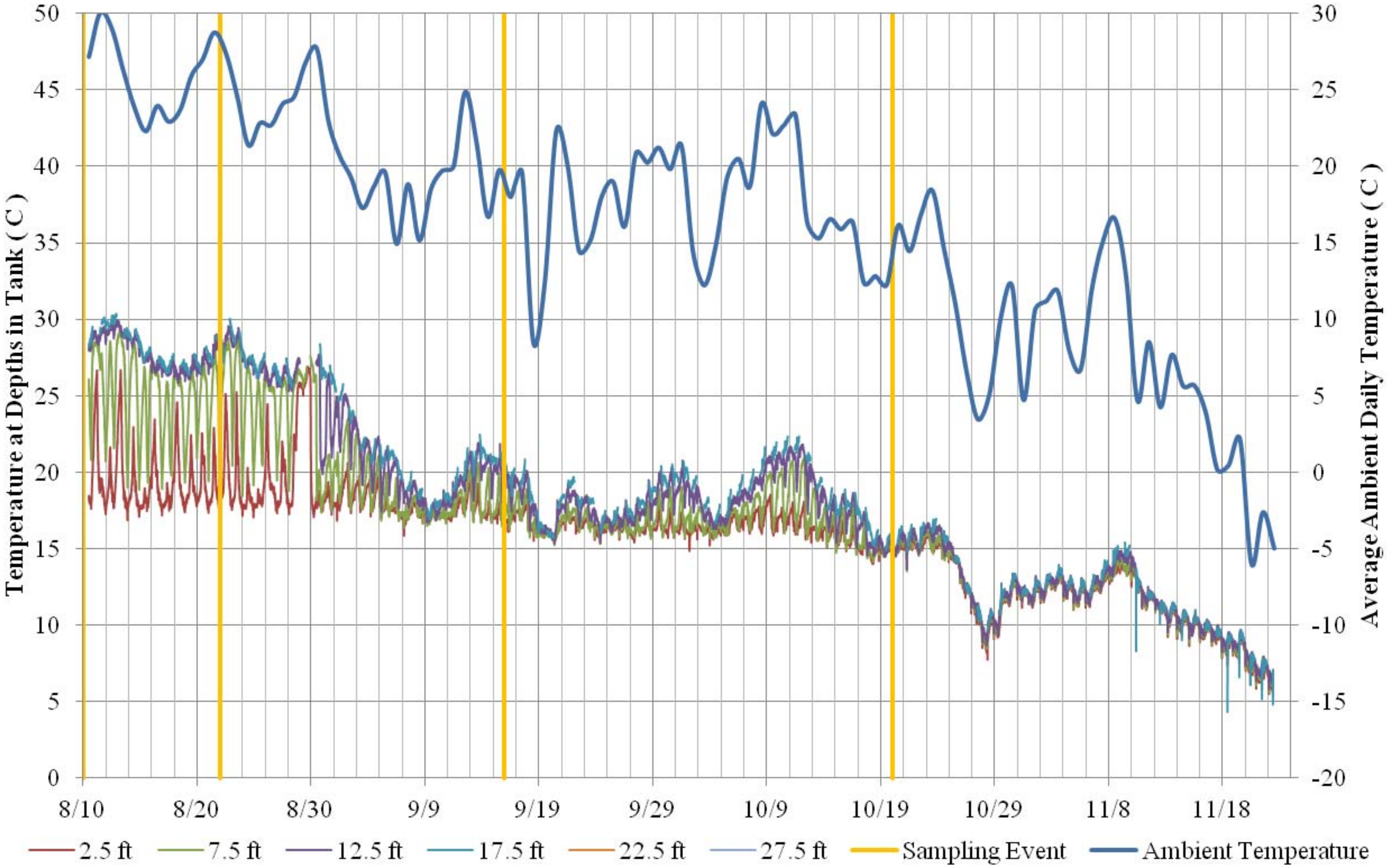


Figure 4.9. Long term tank C temperature profile (operational H:D = 0.88).

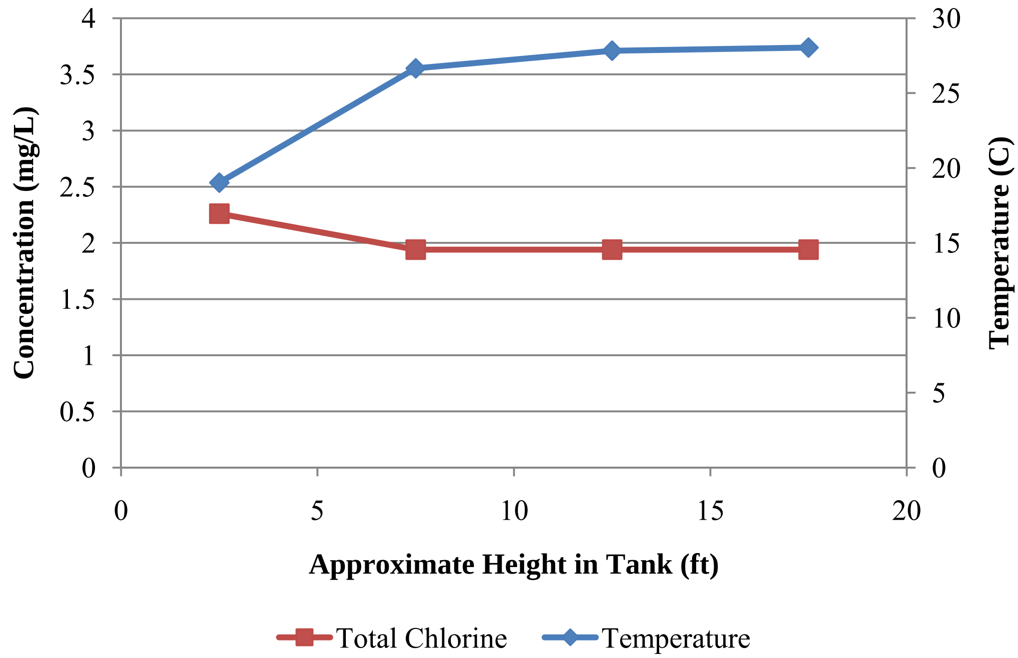


Figure 4.10. Water quality in long term tank C under stratified conditions.

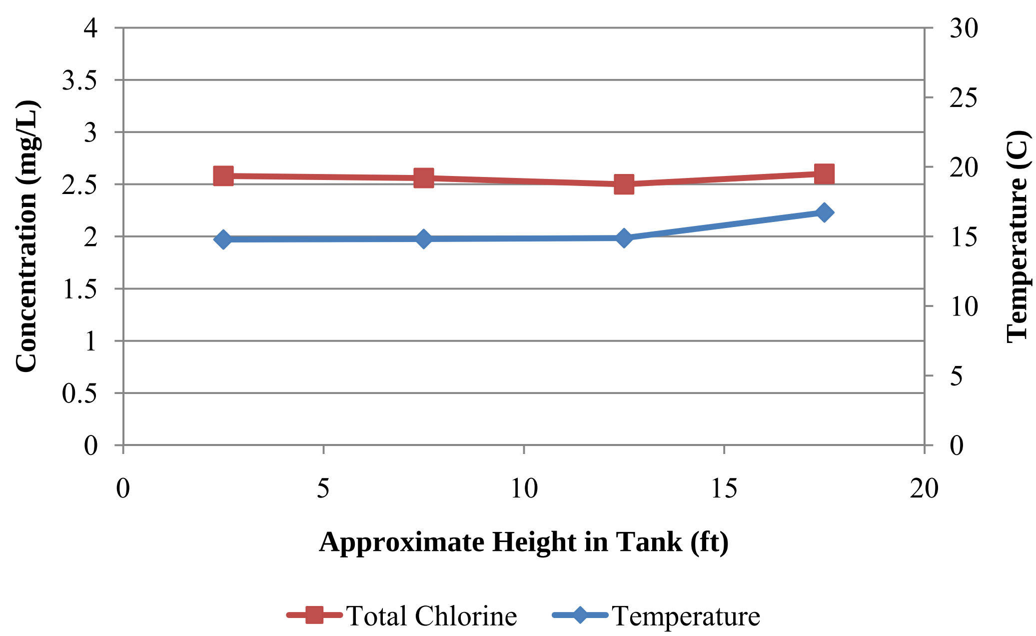


Figure 4.11. Water quality in long term tank C under unstratified conditions.

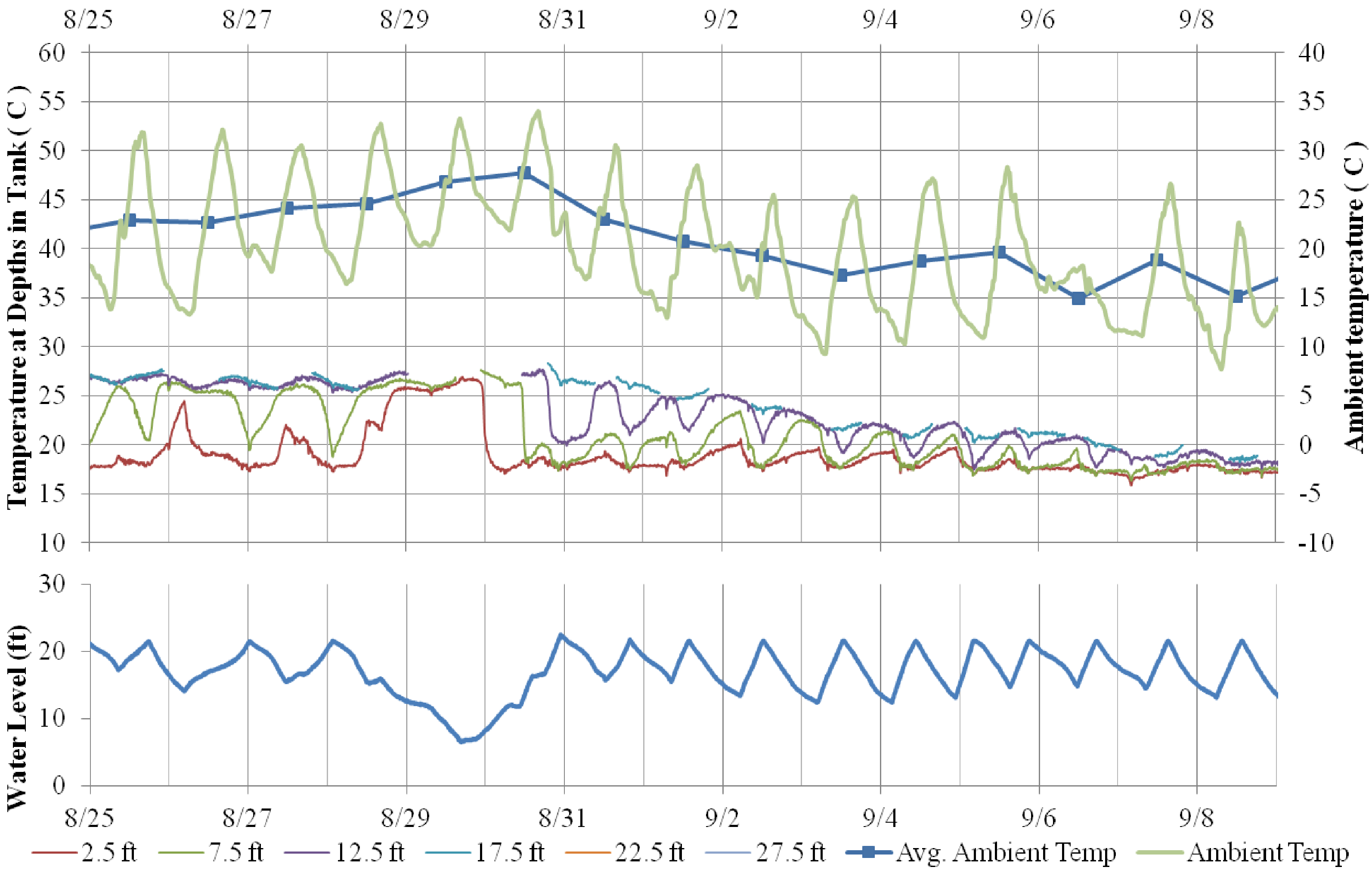


Figure 4.12. Long term tank C enhanced temperature profile.

4.3.3 Long Term Tank D

Temperature profiles measured in Long Term Tank D, as well as several operational and sampling events which occurred during the study are represented in Figure 4.13.

Figure 4.13 indicates that the tank experienced considerable thermal stratification during the warm period of the study (nearly 15 degrees difference is observed between the bottom and top of the water column during August). As the study progressed, this tank tended to destratify with regards to temperature when the ambient temperature dropped below 15 ^{o}C for several consecutive days. Water quality samples were collected during this time period to examine the impact of stratification on water quality. For example, total chlorine concentrations measured when the equipment was installed (August 11th) are shown in Figure 4.14.

A substantial drop in total chlorine concentration and ten degree increase in temperature occurred between 6.9 and 13.9 feet above the base of the tank. A total chlorine concentration of 0.92 mg/L was observed at the bottom of the tank, while the concentrations measured at the 13.9 ft. height was 0.065 mg/L. Chlorine concentrations were persistently low in the higher water temperature water above the 13.9 ft. height. These data indicate that the tank was stratified from both temperature and residual disinfectant perspectives.

The low chlorine residuals measured on August 11th were a concern for the water system, and the operator chose to drain the water from this tank to eliminate the low chlorine residual water. The chlorine residual was then restored in the upper zones of the tank by refilling it with water containing a high chlorine residual. Temperatures of tank depths and outside the tank, as well as water levels are shown in Figure 4.15.

When the tank was drained, the water level in the tank dropped below the system's water level sensor. The sensor was located 50 feet above the base of the tank, so from 8/13 until midday on 8/15 the actual level is unknown, but the data indicate 50 ft. Extrapolating level data slopes from before and after the water was below the transducer yields a level at the end of the deep draw of approximately 27.7 ft. After tank was refilled, the upper portion was still stratified. Over a six-day period, the center zone of the tank gradually increased in temperature until it reached a steady state condition uniform with the top of the tank. By the end of the six-day period, water in the tank had fully restratified with little to no mixing of water between the upper and lower sections of the tank. Water quality data collected 8 days following the complete refilling of the tank are presented in Figure 4.16.

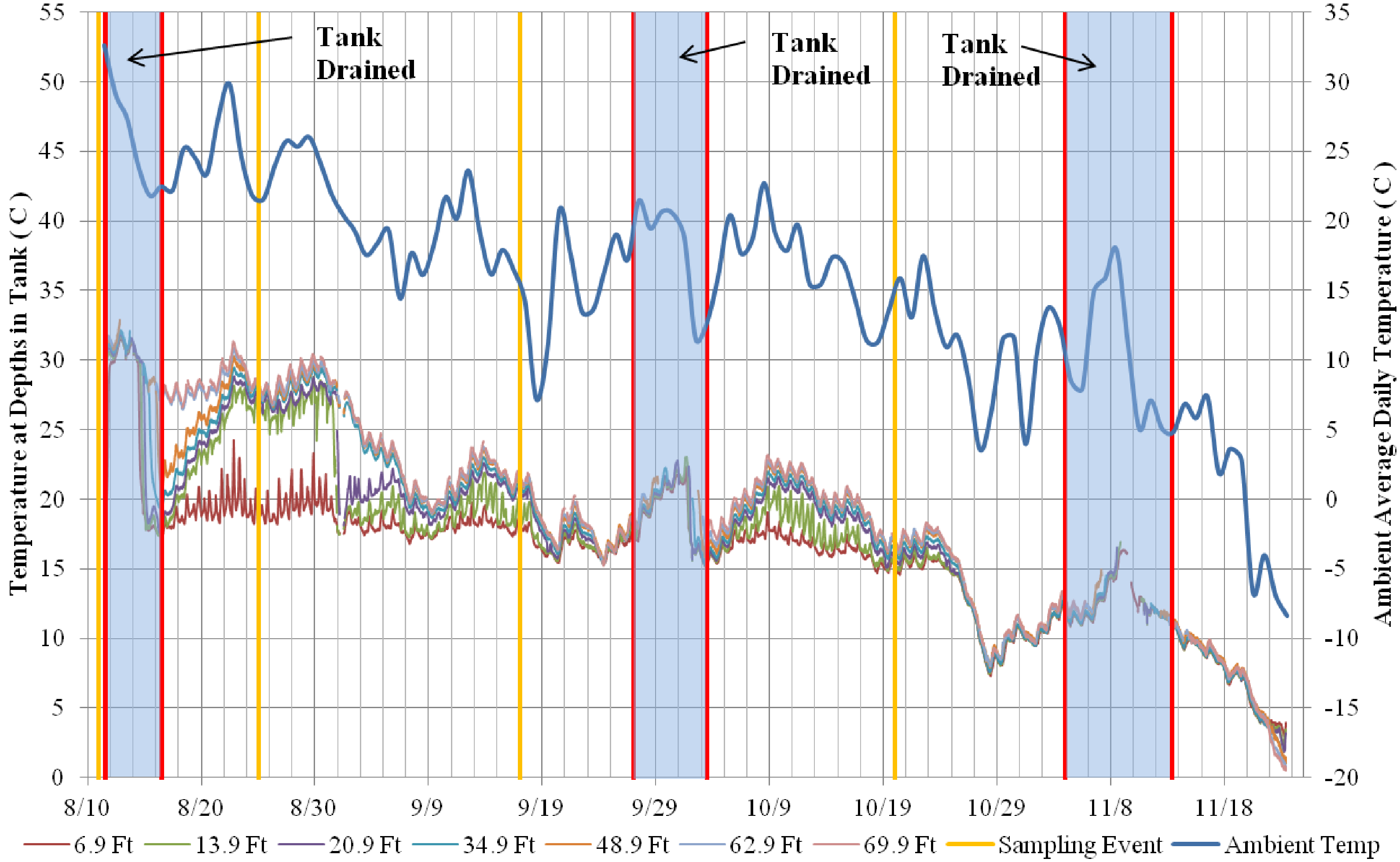


Figure 4.13. Long term tank D temperature profile, sampling events and operations (operational H:D = 3.55).

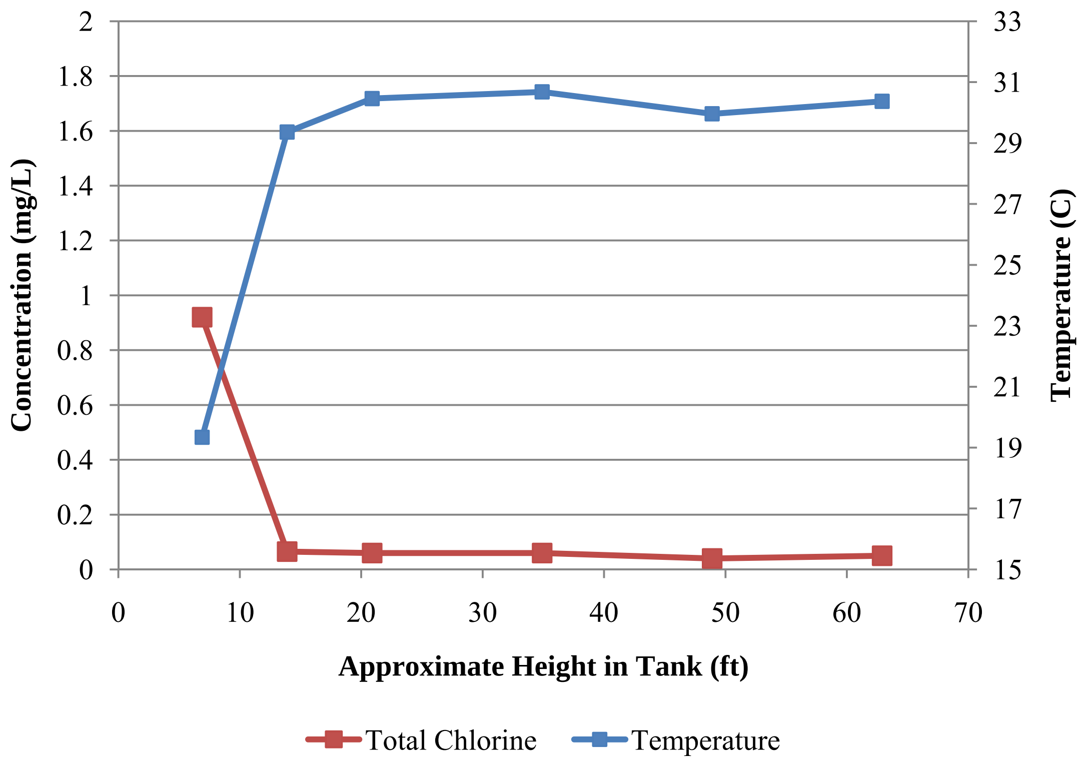


Figure 4.14. Long term tank D water quality data on August 11th.

Figure 4.16 still indicates stratified conditions within the tank, with a substantial drop in total chlorine and increase in temperature of samples collected between 6.9 and 13.9 ft. of tank height. In order to estimate the chlorine decay over time, a simple first order model was applied to the chlorine concentrations in the tank starting when the tank was refilled, and until the next time the tank was sampled. The calculations may be found in Appendix B, and they were conducted using the following parameters:

- Total chlorine decay constant 20 ^{o}C of 0.064 1/d at based on bottle tests conducted by Drews Nelson (2009) (Appendix B)
- Initial total chlorine concentration of 1.14 mg/L throughout the entire tank depth, calculated by mass balance between the water left in the tank after the drain (0.07 mg/L total chlorine at 27.7 ft of depth) and water filling the tank (1.83 mg/L and height of 73 ft – 27.7 ft)
- Eight day reaction time based on time from when the tank was refilled until the next site visit where total chlorine residuals were measured

The theoretical chlorine concentration in the upper reach of the tank is 0.68 mg/L following these assumptions. Instead, concentrations closer to 0.4 mg/L are observed. The difference between the theoretical and measured concentrations was likely due several factors:

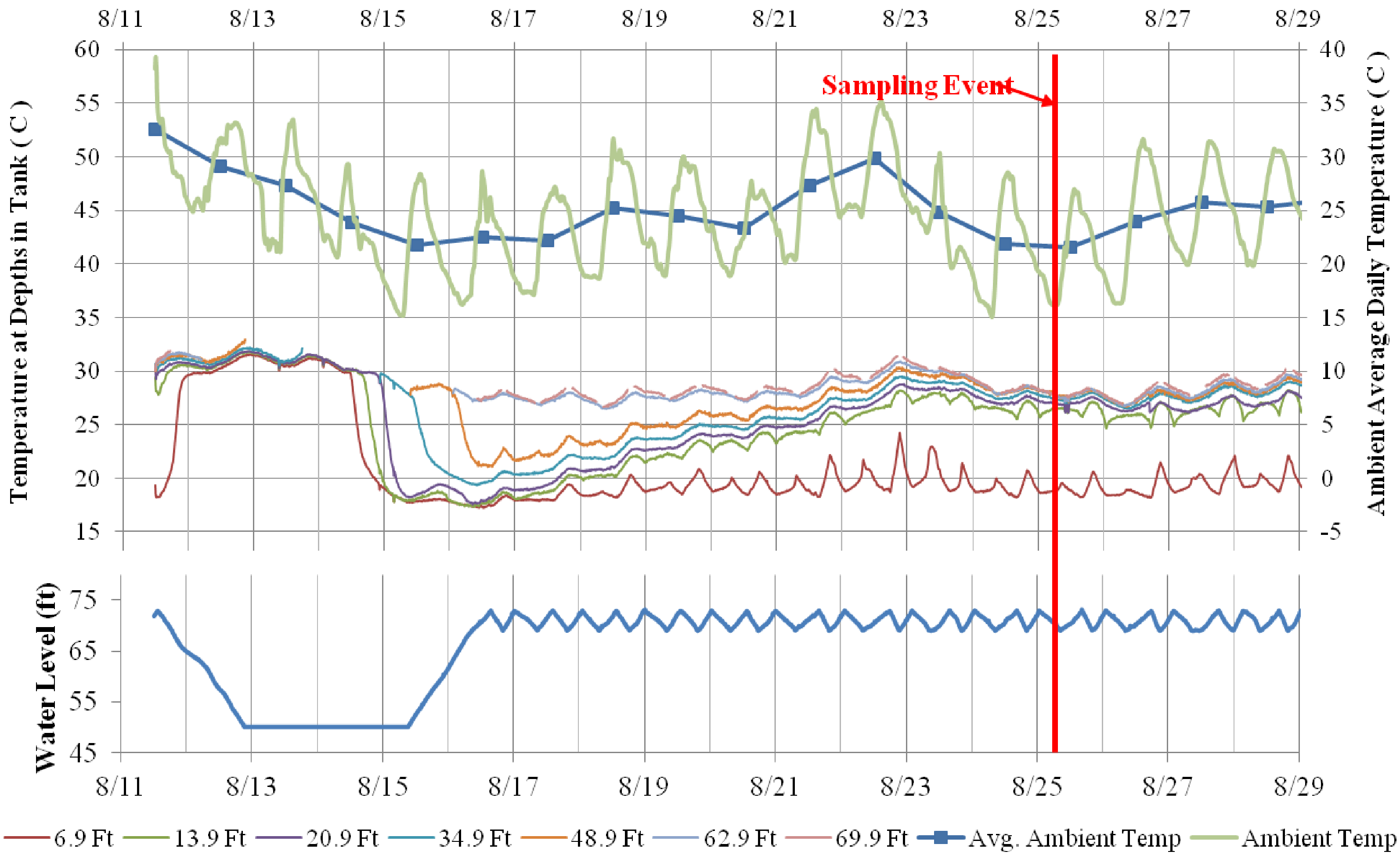


Figure 4.15. Long term tank D enhanced temperature profile during and after drain.

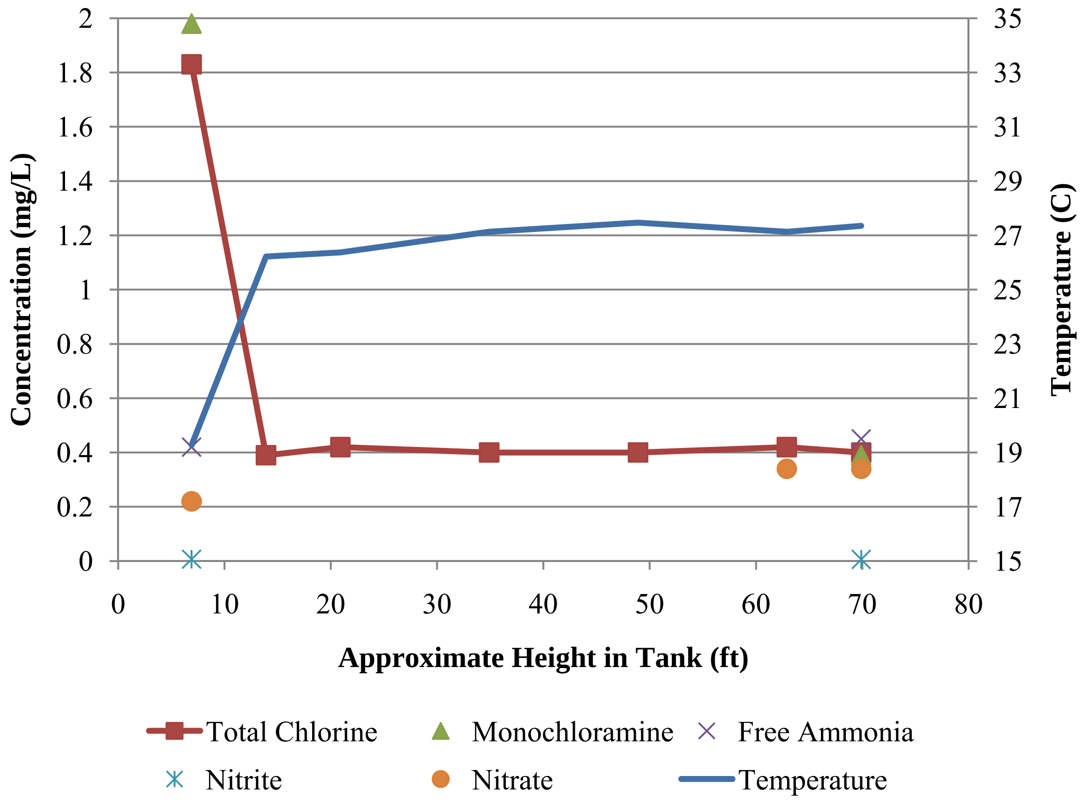


Figure 4.16. Long term tank D water quality data following the first drain of the tank.

Uncertainty in the decay constant, as the rate used is for 20 ^{o}C water, while the actual temperature in the tank was closer to 27 degrees (decay rate is faster at higher temperatures)

- Calculations do not take decay while the tank was filling under consideration, had decay during the filling been accounted for, the initial concentration would have been lower than 1.14 mg/L, leading to model results closer to the smaller measured value
- If nitrification had occurred in this tank, the presence of AOB, NOB, and possibly nitrite could increase chlorine demand
- Water filling the tank over the period of time may not have always been 1.83 mg/L

The system was still concerned that chlorine levels would continue to drop if the operation of the tank continued, and chose to drain the tank once again to regain chlorine in the upper zones of the tank. Approximately fifteen days following the second draining of the tank, water quality data were collected again, and are presented in Figure 4.17.

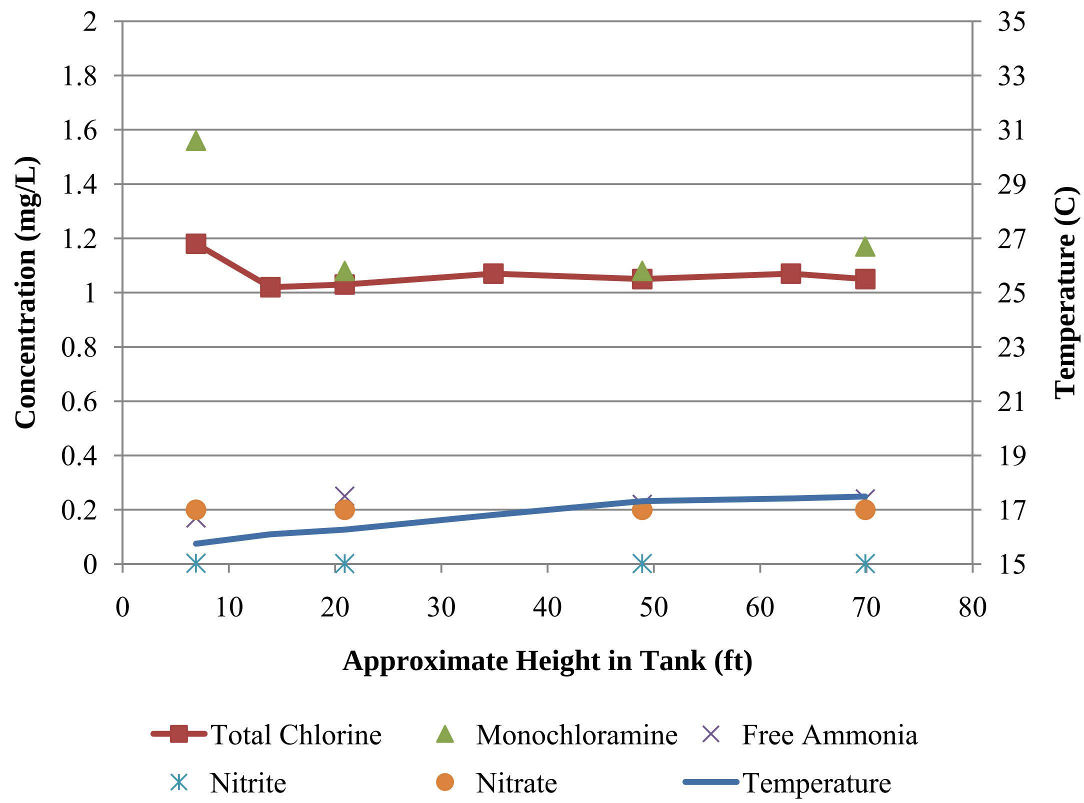


Figure 4.17. Long term tank D water quality data following the second drain of the tank.

Figure 4.17 presents consistent water quality throughout the entire depth of the tank. According to Figure 4.13, the ambient temperature several days leading up to the sampling date had been substantially cooler than had been in the early portion of the study. Cooler ambient temperatures led to cooling of the upper zone of the tank. When the upper zone of the tank cooled, it came closer to the temperature of the inflow. The more consistent temperatures in the tank led to smaller density differences, and subsequently a lower buoyant force. This smaller buoyant force caused water with higher chlorine residuals which was filling the tank to mix more easily with the tank contents. Additionally, when the temperature decreased, chlorine decay rates decrease. The smaller buoyant force allowing the tank to mix, as well as decreased decay rates allowed the chlorine concentration in the upper portion of the tank to be maintained. The behavior of this tank indicates that as ambient temperatures decrease, mixing improves and, in the case of this tank, chlorine concentrations became more consistent.

4.3.4 Long Term Tank E

Temperature data for the ambient and internal tank temperatures, as well as sampling and operational events which occurred during the study are presented in Figure 4.18.

Temperature variations between the bottom and top of the tank presented in Figure 4.18 show that thermally stratified conditions are present when the equipment was installed, similar to long term tank D. The tank destratified from a temperature standpoint when the weather outside cooled below 15 ^{o}C consistently, and restratified when the weather warmed up. To demonstrate the influence of stratification on water quality, data collected on August 16th are presented in Figure 4.19.

Between 8.5 and 22.5 feet above the floor of the tank a substantial decline in chlorine concentration, coupled with a seven degree increase in temperature is observed, indicating that both water quality and temperature stratification was occurring in the tank. Total chlorine experiences a decrease in concentration, and similarly nitrate experiences an increase between the lower two data points and the upper six. A mass balance on nitrogen species between the lowest and uppermost measurement points suggests that a nitrification episode had completely progressed to nitrate.

The water system was concerned with the loss of chlorine residual in the upper zone of the tank, and elected to start operating their ¾-hp ice-prevention mixer in an attempt to mix water from the top of the tank to the bottom. The tank was again sampled two days after the installation of the mixer yielding the results in Figure 4.20.

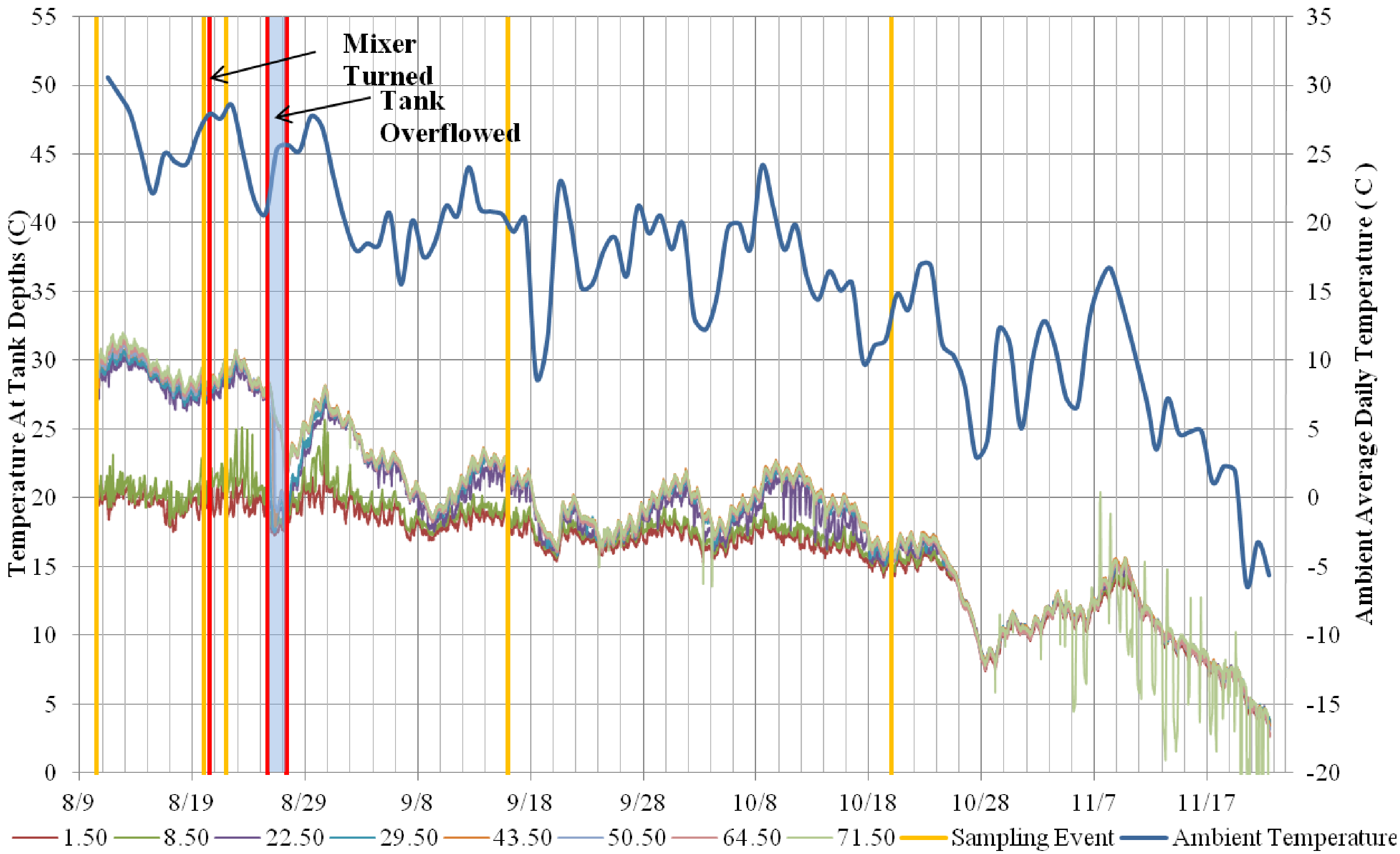


Figure 4.18. Long term tank E temperature profile (operational H:D = 4.80).

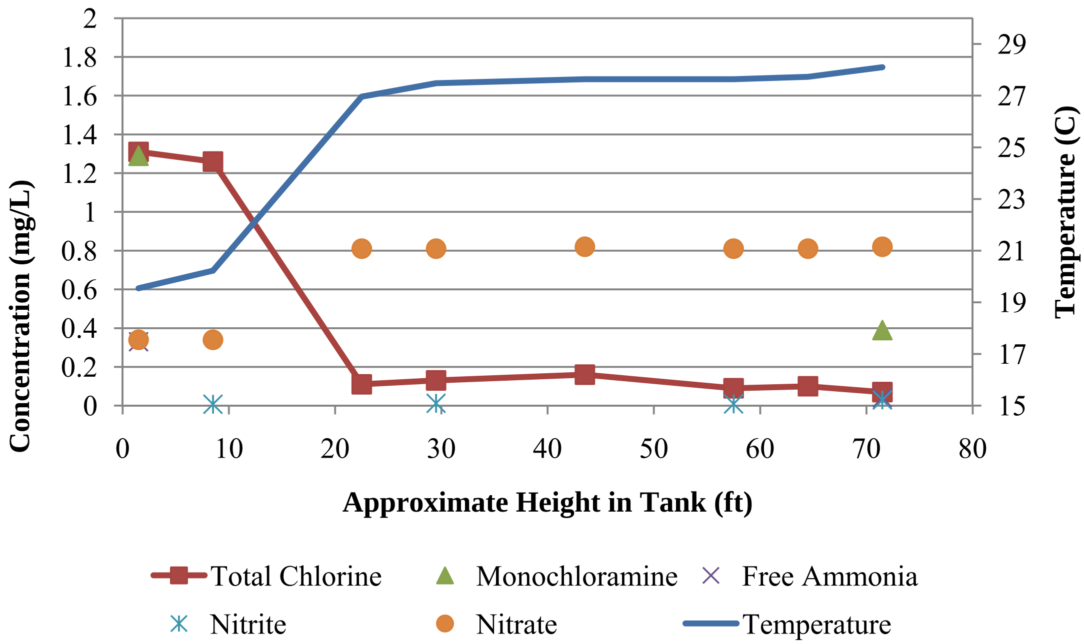


Figure 4.19. Water quality in long term tank E prior to any operational changes.

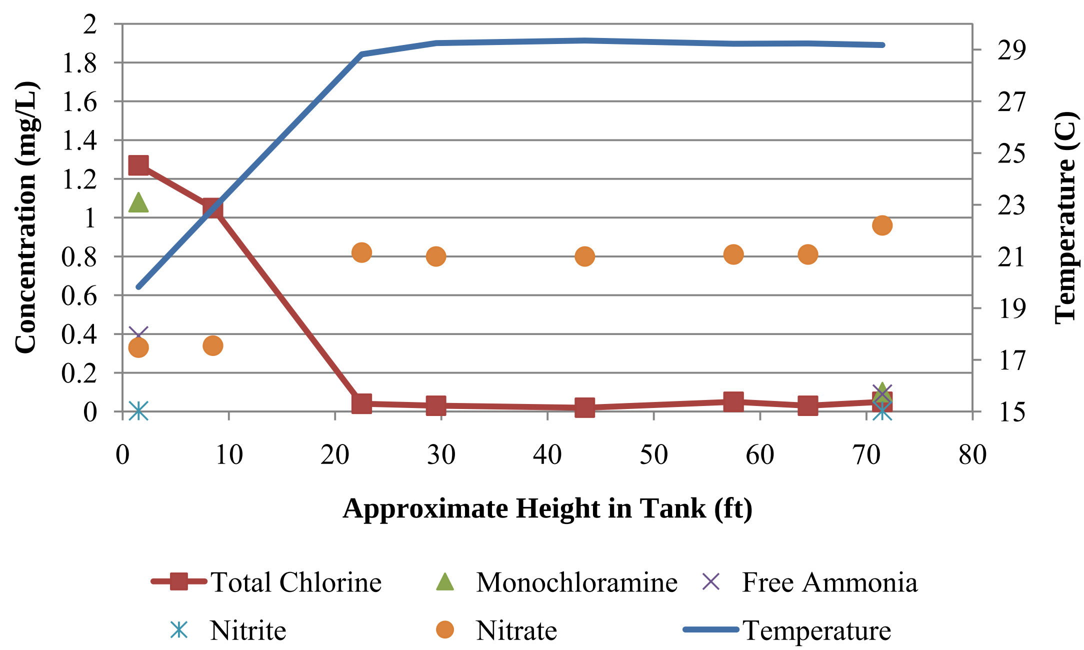


Figure 4.20. Water quality in long term tank E after ice prevention mixer installation.

If concentrations of the various water quality parameters became consistent throughout the tank depth, evidence would have shown that the mixer adequately mixed the tank. However, the drop in chlorine concentration and increase in nitrate and temperature with respect to height in the tank was still present after the installation of the ice prevention mixer, indicating that the mixer was insufficient at mixing the tank. The velocity gradient for the mixer when the tank is at its high water level of 85.5 ft is 30.1 s^{-1} (calculation shown in Appendix B). The literature review stated that velocity gradients of hydraulic recirculation systems of at least 10 s^{-1} can be used to promote mixing (Kirmeyer et al. 1996). In the case of this tank, the mixer is an impeller design, rather than the type of recirculation system described in the literature review. Because of the difference between the mixing systems in the literature review and the mixer in this tank, a comparison between velocity gradients calculated for this mixer and those presented in the literature review should be used with caution. The intended design of the mixer installed in this tank is recirculation of water in much shallower lakes and ponds. The manufacturer suggests that the mixer can be used to destratify ponds up to 18 feet deep, while the water level in the tank cycled between 77 and 85 ft. The use of this mixer in deeper water than it was designed for likely led to its inability to mix the entire tank depth.

Because mixing using the ice prevention mixer did not improve the water quality in the upper reaches of the tank, the system chose to dispose of the water in the tank by overflowing it. The tank was overflowed until a desired chlorine residual was measured in the overflow. The tank was again sampled approximately three weeks after the overflow completed, which yielded the results in Figure 4.21.

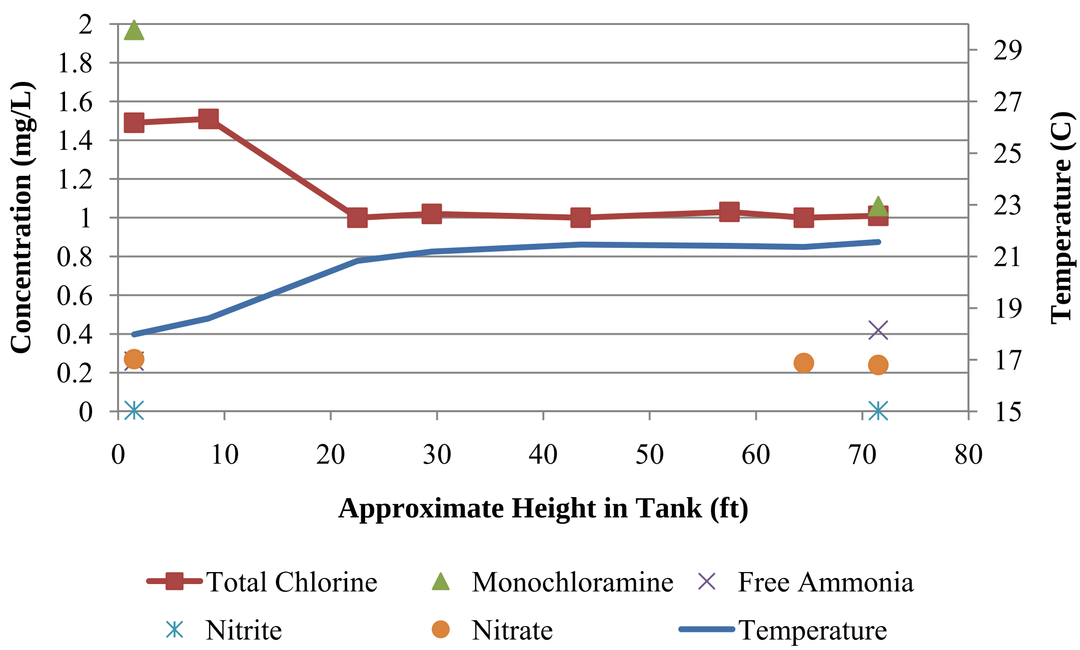


Figure 4.21. Water quality in long term tank E after overflow.

Figure 4.21 still shows a decrease in total chlorine from 1.5 mg/L at the bottom two sampling points to 1 mg/L at the top, however this is an increase from the negligible chlorine present in the upper zone prior to overflow. A first order model was used to estimate the chlorine concentration in the upper reach of the tank using the following parameters:

- Total chlorine decay constant 20 °C of 0.064 1/d at based on bottle tests conducted by Drews (2009) (Appendix B)
- Initial concentration of 1.5 mg/L assuming that the entire tank contents was replaced using water with a chlorine concentration the same as the bottom of the tank
- 21 day reaction time based on the time from when the overflow was completed until the tank was sampled again.

Using these parameters, the theoretical chlorine concentration was 0.39 mg/L. This theoretical concentration was considerably below the actual concentration, which is likely due to some degree of mixing of water from the bottom of the tank with the upper zone in response to density similarities resulting from lower ambient temperatures. If the tank were to remain in this stratified condition, however, chlorine concentrations would continue to decrease.

Water quality data collected on October 20th are presented in Figure 4.22. The ambient temperature leading up to October 20th illustrated in Figure 4.18 had been cooling, causing the tank to destratify. As a result the chlorine concentrations shown in Figure 4.22 are much more consistent, indicating a better mixed tank from a residual disinfectant standpoint. Long term tank D behaved similarly, by becoming more consistent from both water quality and temperature perspectives when the weather cooled.

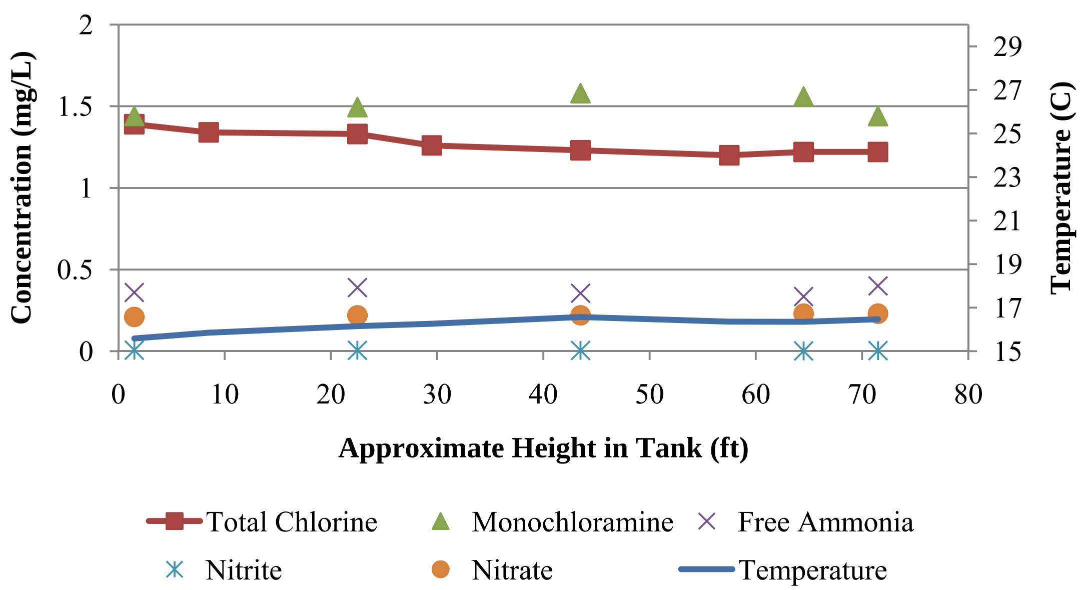


Figure 4.22. Water quality in long term tank E on October 20th.

Both long term tanks D and E fluctuate between stratified and unstratified conditions based on Figures 4.13 and 4.18. It is difficult to correlate the occurrence of stratification with the physical heat transfer process, as there are many unknowns in the equations which model heat transfer. However, according to Figures 4.13 and 4.18, both tanks tended to destratify when the temperature outside of the tank dropped below 15 ^{o}C consistently. The tanks became consistently destratified near the end of October.

4.4 Short Term Tank Studies

Tanks were selected for short term studies based on the interest of water systems both contributing funds to the study and in reasonable proximity to SDSU. Systems which fit that description were contacted and asked if any tanks were of interest. Using responses from these systems, several tanks were selected for further study.

Samples were collected from the top and bottom of most tanks and tested for residual disinfectant. Tanks whose residual disinfectant was free chlorine were tested for both free and total chlorine, while chloraminated tanks were tested for total chlorine. Water temperatures were measured at various depths in the tank, as well as on the surface.

4.4.1 Short Term Tank 1

Short term tank 1 was a 241,000 gallon standpipe, 107 ft tall and 20 ft wide, which corresponds to an aspect ratio of 5.35. The water in the tank was typically operated between 92 and 100 ft, however at one point the water level dropped to 82.6 ft. Temperature data collected for short term tank 1 are presented graphically in Figure 4.23.

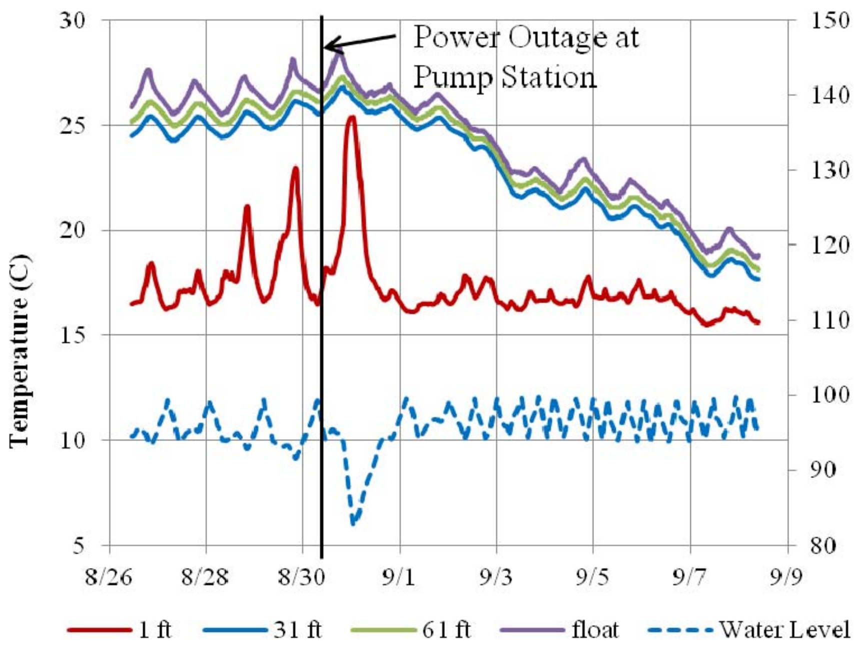


Figure 4.23. ST1 temperature profile and water level.

Temperatures of the water at and above the 31 ft sensor (upper zone) tended to fluctuate with time of day, while temperatures measured by the one foot sensor (lower zone) varied with the fill and draw cycles of the tank. As days passed, temperatures measured by the top three sensors began to move towards those measured by the one foot sensor. A power outage occurred on August 30th, which caused the water level to drop to 83 ft (typical operation ranged from 92 to 98 ft). As a result, temperatures at the one foot sensor increased substantially, indicating that water from the upper zone moved out of the tank and into the distribution system. The subsequent decrease in temperature of the one foot level indicates that the 15 ft of water lost during the power outage was replaced with fresh water. The water in the tank remained stratified after the power outage, as the temperatures of the upper three sensors continued to follow similar trends. Chorine residuals measured on the day when the temperature sensors were installed in the tank are presented in Figure 4.24.

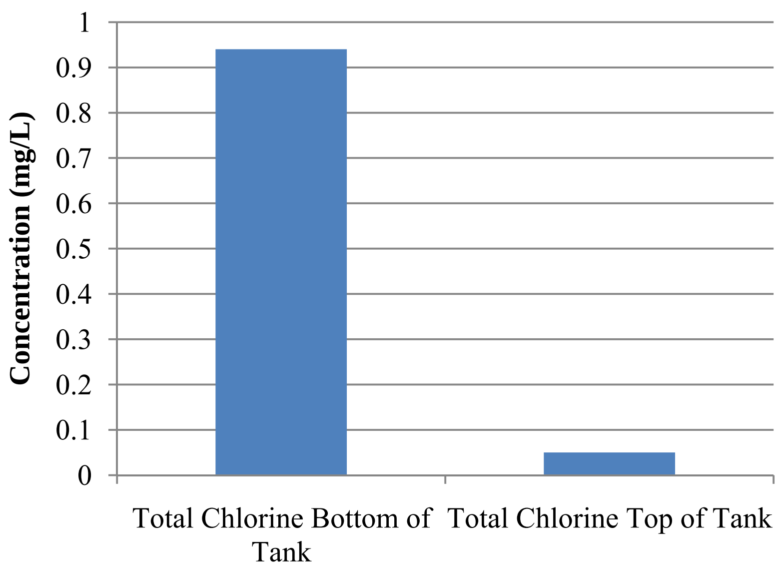


Figure 4.24. ST1 total chlorine concentrations.

A substantial difference in total chlorine between the top and bottom of the tank was observed. The difference in concentrations indicates that the tank was not well mixed from a residual disinfectant standpoint, which agrees with temperature data in that a thermocline was preventing good mixing in this tank.

4.4.2 Short Term Tank 2

Short term tank 2 was a 300,000 gallon elevated tower with a storage volume height of 26.4 ft and diameter of 44.7 ft. These dimensions correspond to a tank aspect ratio of 0.59. Water levels fluctuated between approximately 16.5 ft and 24.5 ft. Temperature data collected for short term tank 2 are presented graphically in Figure 4.25.

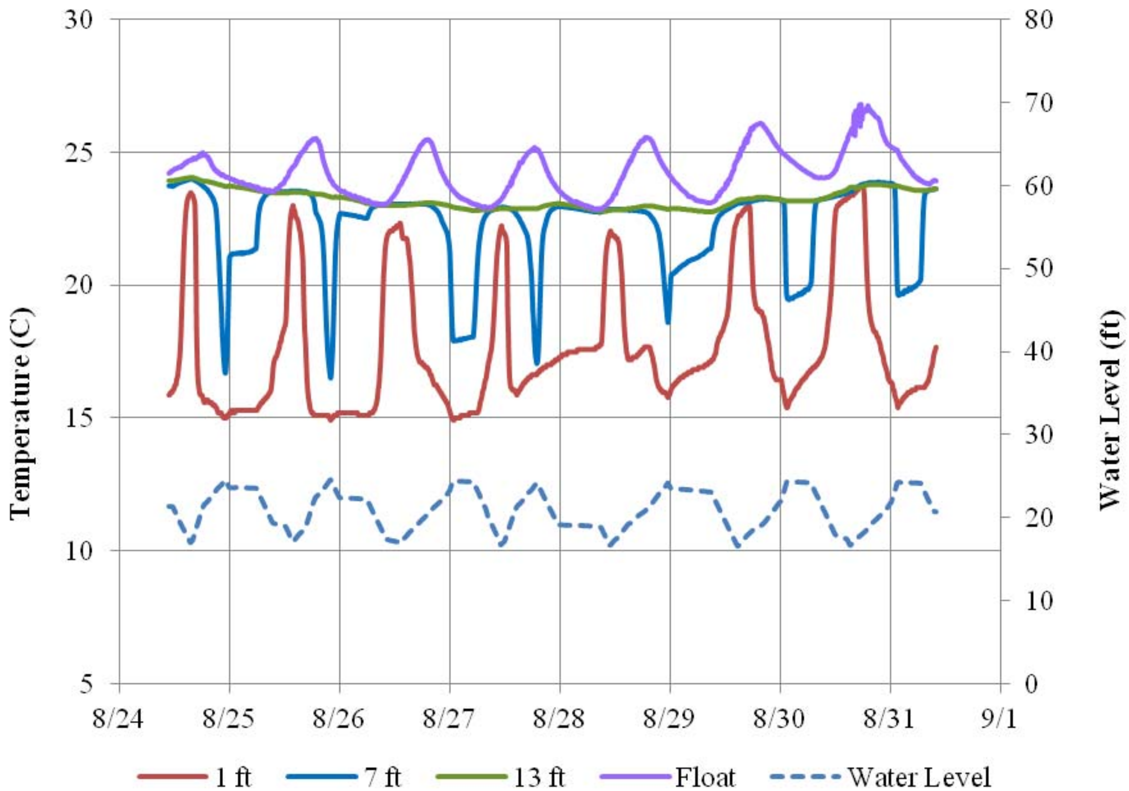


Figure 4.25. ST2 temperature profile and water level.

Temperatures at the one foot sensor (lower zone) were strongly influenced by the fill and draw cycle of the tank. The warming and cooling of the lower zone of the tank was the result of entering water being colder than water already in the tank, causing a decrease in temperature in the lower levels when the tank was filled. When the tank was drained, temperatures at the base increased as a result of warmer water being drawn down from the upper region of the tank. Water temperature at the surface (purple line) fluctuated as the temperature warmed and cooled outside (day to night). Temperatures 13 ft from the base of the tank (green line) remained fairly constant, indicating that the tank was stratified. However, the level fluctuates enough to remove some water from the stratified zone during the draw cycle, allowing filling water to mix with the stratified zone.

4.4.3 Short Term Tank 3

Short term tank 3 was a 440,000 gallon elevated tower with a storage height of 31 ft and diameter of 49 ft. These dimensions correspond to an aspect ratio of 0.63. Water levels in this tank fluctuated between 27 ft and 31 ft. Temperature data collected for short term tank 3 are presented graphically in Figure 4.26.

Temperature data in this tank indicate that stratification had occurred at the beginning of the study period. The recirculation pump was turned on approximately two days following the installation of equipment. Two days after the recirculation pump was turned on, the temperature of the bottom two measurement points gradually increased, while the temperature of the 15 ft point converged to meet the temperature of the lower points, indicating that some degree of mixing had occurred in the tank after the mixer was installed. Chlorine data collected at the installation (9/8) and removal (9/15) of equipment are shown in Figure 4.27.

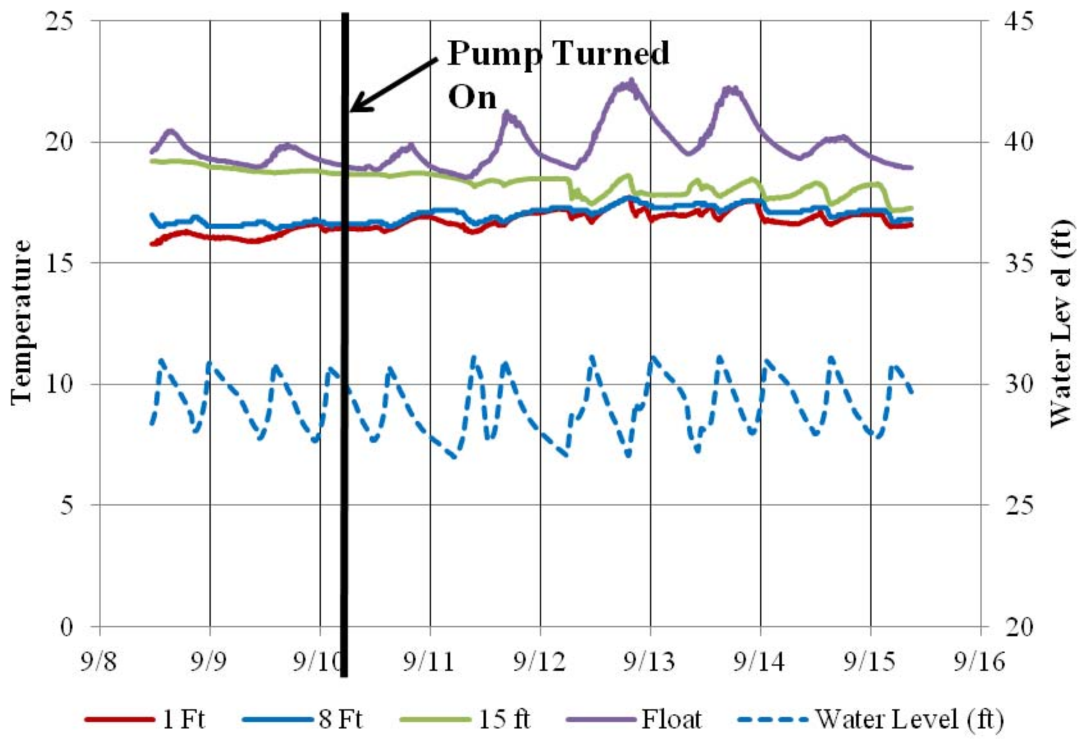


Figure 4.26. ST3 temperature profile and water level.

Before the recirculation pump had been implemented, the total chlorine at the top of the tank was 1.25 mg/L lower than the bottom. Following five days of operation with the recirculation pump employed, that difference had decreased to 0.83 mg/L. The decrease in variations of chlorine concentrations between the filling water and stored water, coupled with the convergence of temperature profiles shown in Figure 4.26 indicate that the recirculation pump may have improved mixing in the tank.

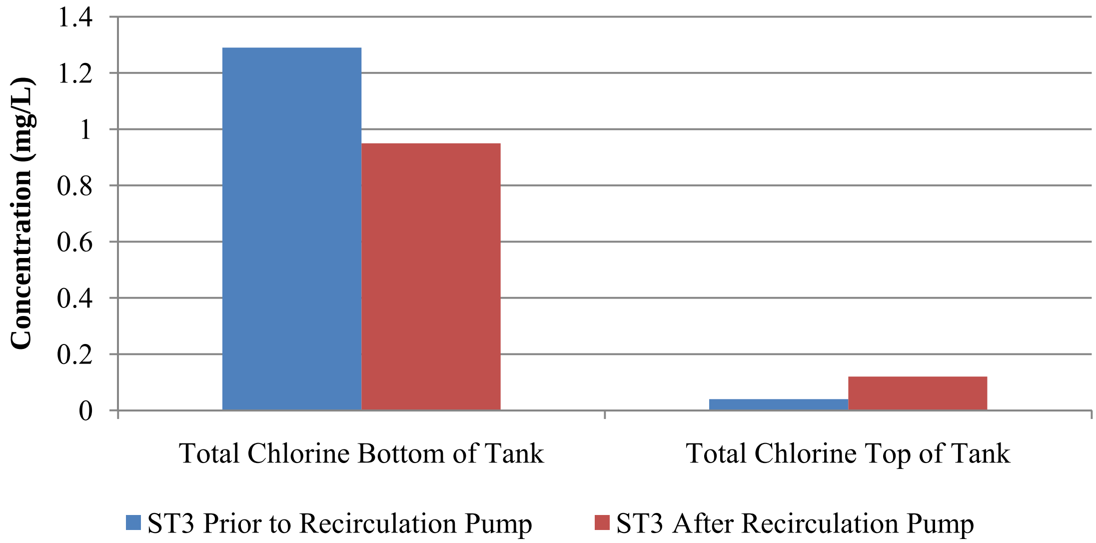


Figure 4.27. ST3 total chlorine concentrations.

4.4.4 Short Term Tank 4

Short term tank 4 was a 100,000 gallon standpipe, with a height of 120 ft and diameter of 12 ft. These tank dimensions correspond to an aspect ratio of 10.0. This tank was operated nearly full during the study, with water levels varying from 111.5 to 120.4 ft. The overflow level of was 119.6 ft, however, the tank was not overflowing during the study, indicating that the water level sensor was slightly deeper than 89 ft. Temperature data collected for short term tank 4 are presented graphically in Figure 4.28.

When the equipment was installed, there was not a defined thermocline in the tank, in spite of the fact that this was one of the tallest standpipes in the state. As time passed, temperatures at sensors in the upper zones started to diverge from that at the 10 ft water level. Temperatures at the 44 and 89 ft levels track with each other and seemed to follow the temperatures of the float sensor. On the other hand, the water temperatures at the ten foot level were affected by the inflow/outflow cycles mid-way through the test period. The ambient temperature was warming after a cool period when the study of this tank began, and this warming trend appeared to cause stratification somewhere between the 10 ft and 44 ft levels of the tank.

Water quality data collected when the equipment was installed is presented in Figure 4.29.

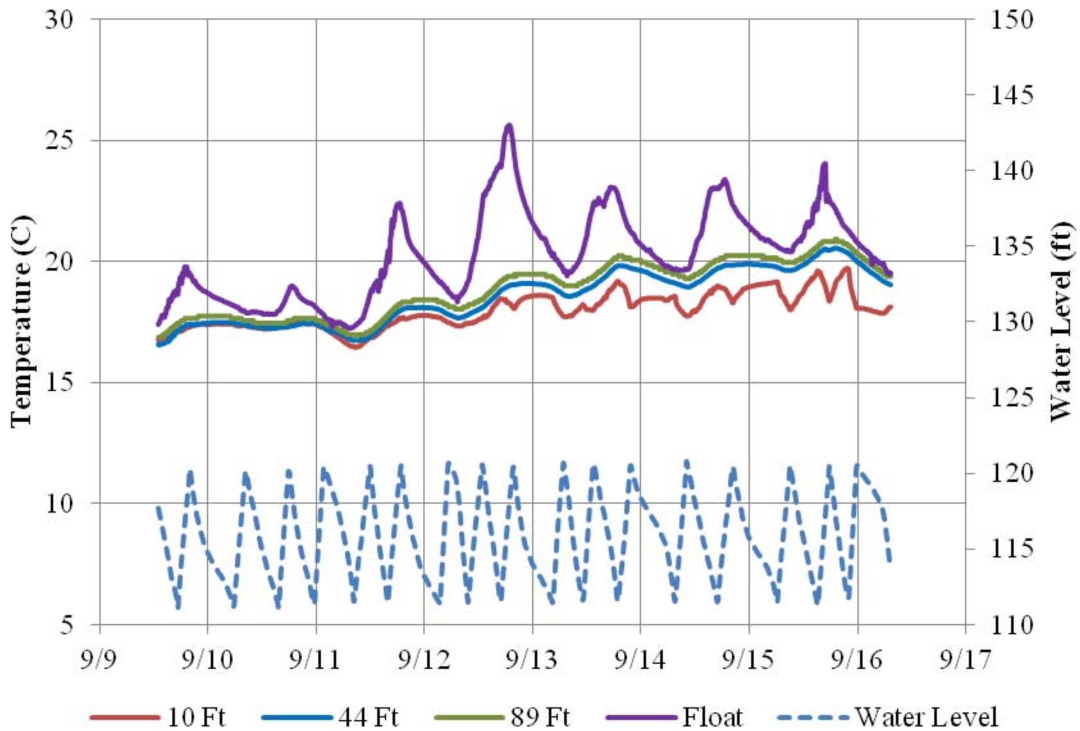


Figure 4.28. ST4 temperature profile and water level.

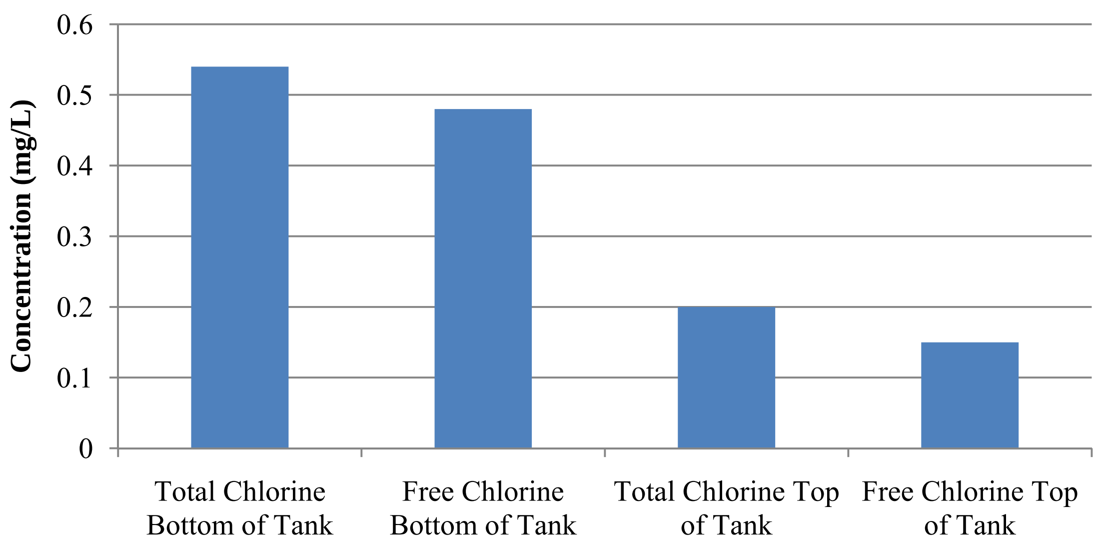


Figure 4.29. ST4 chlorine measurements.

Lower residuals were present in the top of the tank compared to the bottom. However, some chlorine was still present in the upper zone. Although the tank was not completely mixed from a residual disinfectant standpoint, temperature profiles indicate that the tank was well mixed when monitoring began. When the equipment was removed however, temperatures had diverged, causing more apparent stratification in the tank. However, chlorine residual measurements were not obtained and the end of the temperature measurement period to substantiate the impacts of stratification.

4.4.5 Short Term Tank 5

Short term tank 5 was a 500,000 gallon elevated tower. The operational head range for this tank was 40 ft (with ten feet of dead storage below the low water level) for a total water depth of 50 ft. Observed water levels during the study approximately ranged from 44 to 47 feet of total water depth. The tank's diameter ranged from 10 to 54 ft in a turnip shape. An average diameter was calculated as 32.7 ft. Water levels observed during the study were used to calculate an average aspect ratio of 1.40. Temperature data collected for short term tank 5 are presented graphically in Figure 4.30.

From September 27th through the 29th, the tank appeared to be stratified. During this time of stratification, temperatures at the 1 ft and 13 ft sensors were consistently 1.5 degree Celsius lower than those of the 25 ft sensor. Throughout the entire study period, the temperature measured from the point on the float tracked with time of day. The recirculation pump for short term tank 5 was turned on a few days after the temperature sensors were installed. The exact date and time when the pump started was unknown. On September 29th, the temperatures measured at the 1 ft and 13 ft levels increased and began to track with the 25 ft measurement point, effectively destratifying the tank. The tank destratification was likely the result of mixing by the recirculation pump, since the operational water levels remained unchanged. On October 4th the pump station which fills the tank lost power for a period of 22 to 27 hours, causing a drawdown approximately three times that of typical operation. The amplified drawdown caused temperatures measured by all three sensors within the tank body to become consistent with each other. Samples from the top and bottom of the tank were tested for free and total chlorine and the results may be seen in Figure 4.31.

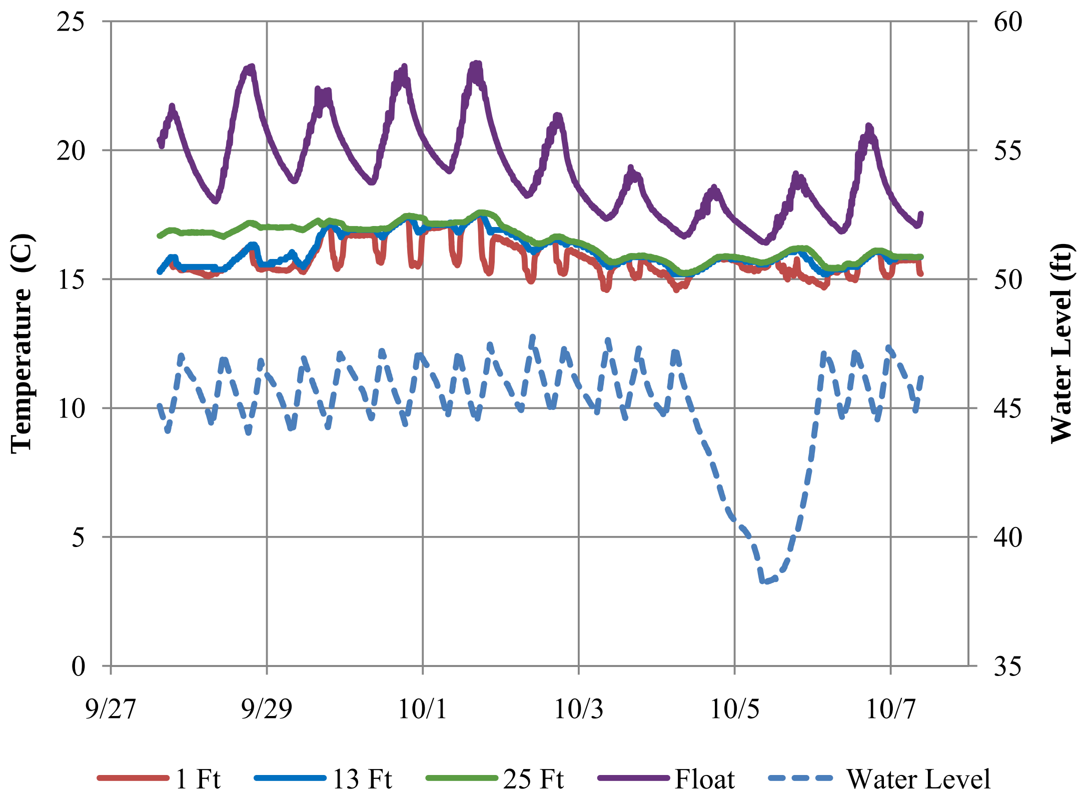


Figure 4.30. ST5 temperature profile and water level.

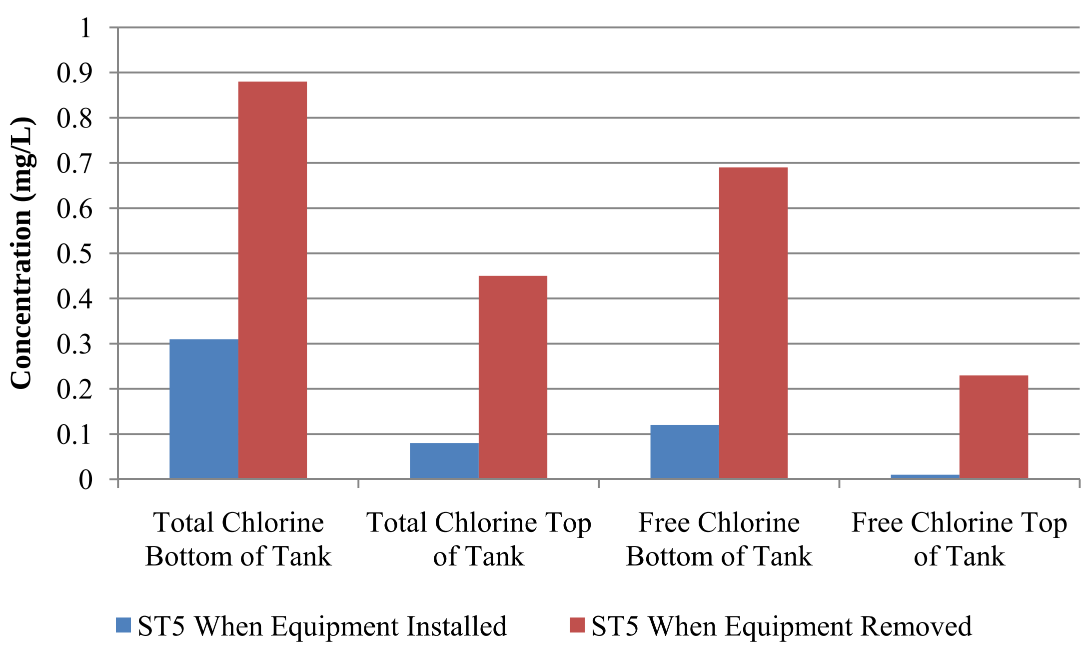


Figure 4.31. ST5 chlorine concentrations.

Differences in both free and total chlorine concentrations between the top and bottom of the tank suggest water quality stratification had been occurring in the tank when the temperature equipment was installed. There were considerable differences in chlorine concentrations measured between the installation and removal dates of the equipment, most likely due to the power outage, but also possibly due to the action of the recirculation pump. When the pump station lost power, more water drained than during normal fill and draw operations. When the tank was refilled, water with a higher chlorine residual filled the tank, effectively replacing the drained water which had lower residuals.

4.4.6 Short Term Tank 6

Short term tank 6 was a 125,000 gallon standpipe, 46 ft tall and 22 ft in diameter. These dimensions correspond to an aspect ratio of 2.09. Water levels fluctuated from 42 to 46 feet during the study. Temperature and water level data collected for short term tank 6 are presented graphically in Figure 4.32.

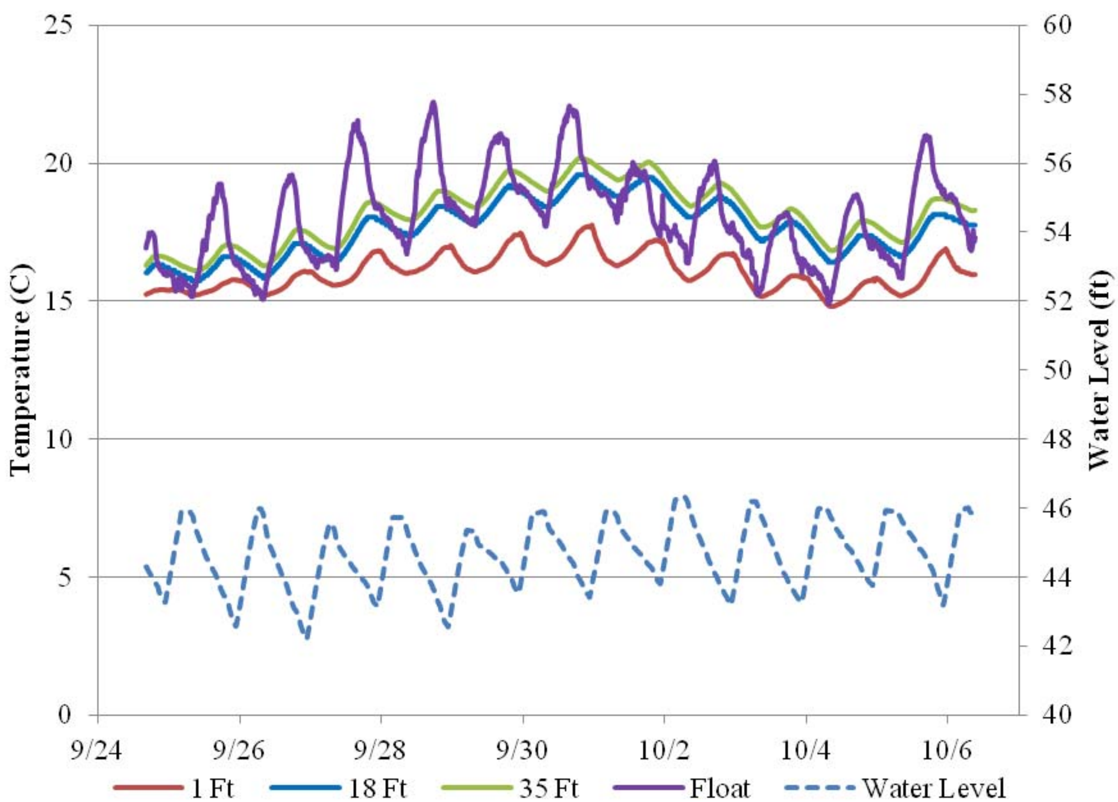


Figure 4.32. ST6 temperature profile and water level.

When the temperature equipment was installed in the tank, the tank appeared well mixed from a temperature standpoint. The 18 and 35 ft measurement points were approximately 1 degree Celsius warmer than the 1 ft level during the beginning of the study. As the study progressed, the 18 and 35 ft temperatures diverged from the one foot level, leading to some degree of thermal stratification. The cyclic fluctuations of temperatures at the one foot measurement point track well with the water level fluctuations in the tank. To further examine the relationships between temperatures, time of day, and operational cycle a plot of, water level, and temperatures measured at the one foot, 35 ft water levels and at the water surface (estimating ambient temperature) are shown in Figure 4.33.

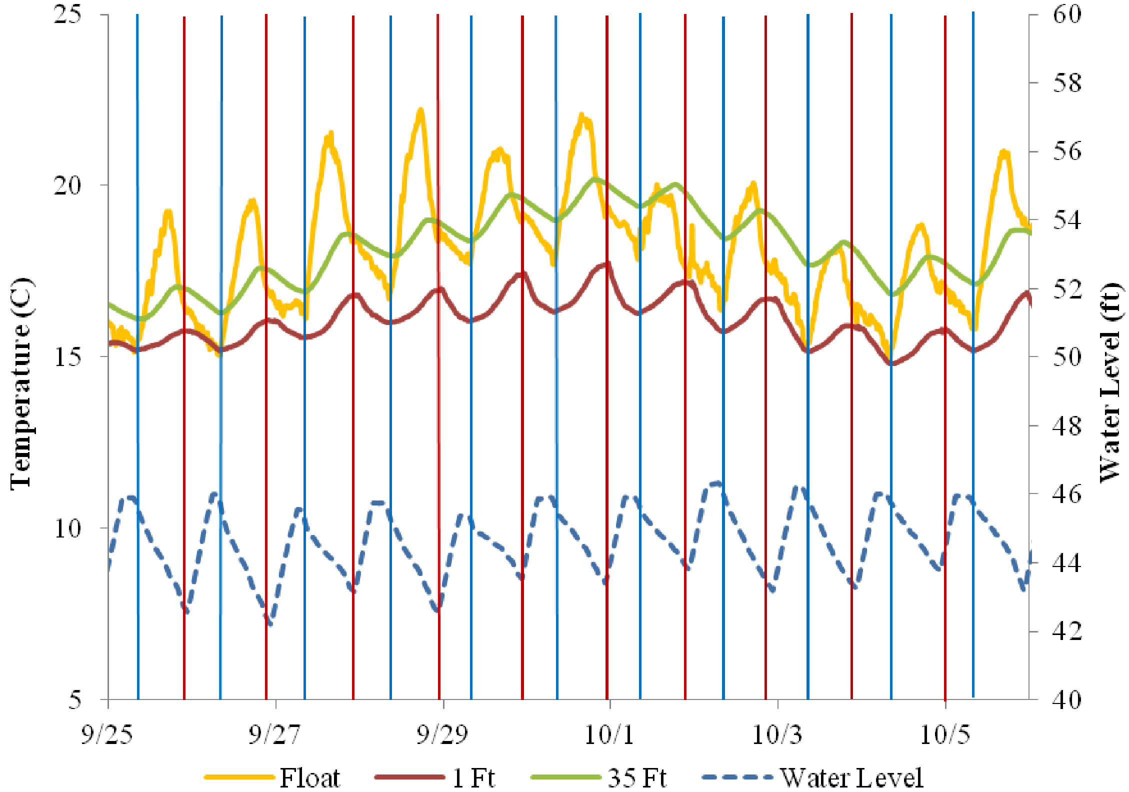


Figure 4.33. Water level, ambient temperature, and measurement points in ST6.

Vertical lines in Figure 4.33 were drawn at the high temperature (red lines) and low temperature (blue lines) for the one ft measurement point for each daily temperature cycle. The high temperature of the one foot measurement point occurs when the water level in the tank is lowest, while the low temperature occurs when the tank filling cycle finished. The daily fluctuation in temperature at the 35 foot temperature measurement point tends to track well with the temperatures of the float (similar to ambient temperature). When the temperature of the measurement point on the float is higher than that of the 35 foot measurement point, the temperature of the 35 foot level is increasing. Similarly, when the measurement point on the float is lower than that of the 35 foot measurement point, the temperature of the 35 foot level is decreasing. The tendency of the water temperature in the upper zone of the tank to track with the ambient temperature, while the lower level is influenced by the fill and draw cycles indicates the presence of thermal stratification in the tank.

Free and total chlorine data for ST6 are presented in Figure 4.34.

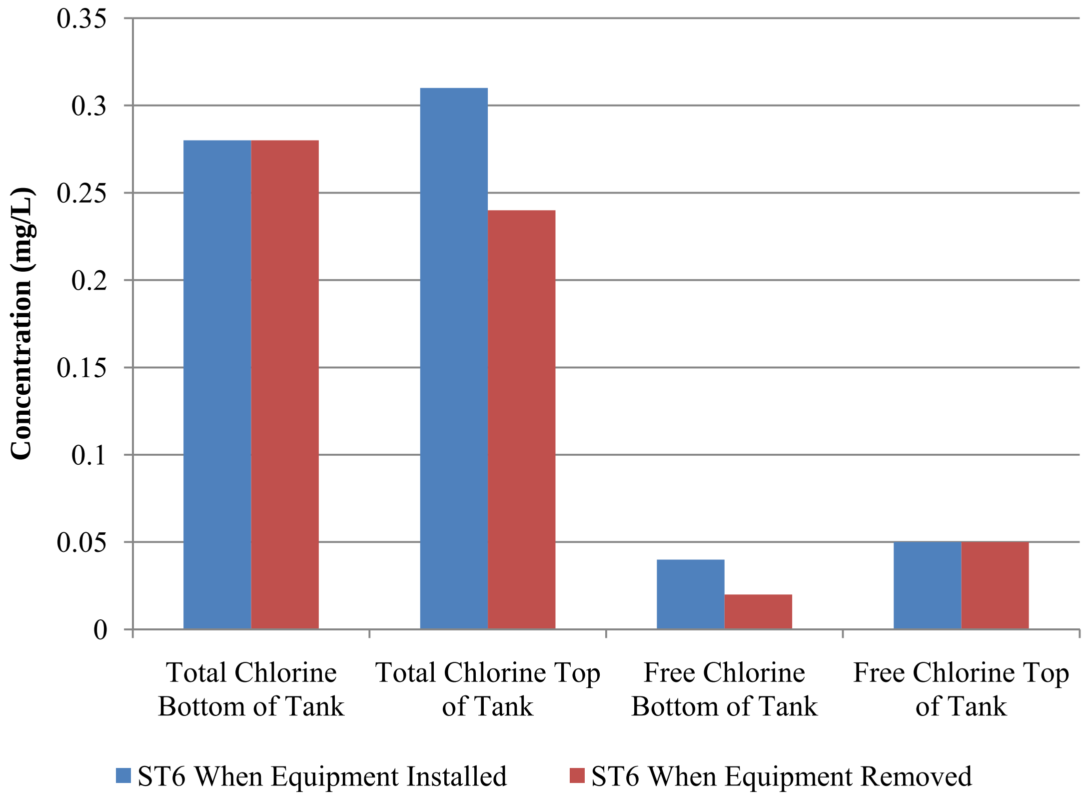


Figure 4.34. ST6 chlorine concentrations.

When temperature sensors were installed, there was slightly more total chlorine in the top of the tank than bottom. Free chlorine accounted for less than 0.05 mg/L in both the tank top and bottom, indicating the strong presence of combined chlorine filling, and within the tank. When temperature sensors were removed, a small drop in total chlorine was observed relative to when the equipment was installed. The degree of stratification in this tank increased throughout the study period, indicated by the increase in the difference of temperatures between the bottom and top of the tank. The part of the system served by this tank was a lakefront community, leading to substantial seasonal demand variations. The tank was studied from the end of September until the beginning of October when demands were low. These low demands led to a theoretical detention time of 16.45 days, considerably higher than even the longest recommended detention time presented in the literature review of seven days (Table 2.5).

4.4.7 Short Term Tank 7

Short term tank 7 was a 1.5 million gallon composite elevated tower. The storage volume was 83 ft in diameter, and the system estimates a height of 50 ft. Water levels were variable in the tank, typically fluctuating between 27 and 38 ft., with occasional spikes up to 40 ft and down to 22 ft. Temperature data collected for short term tank 5 are presented graphically in Figure 4.35.

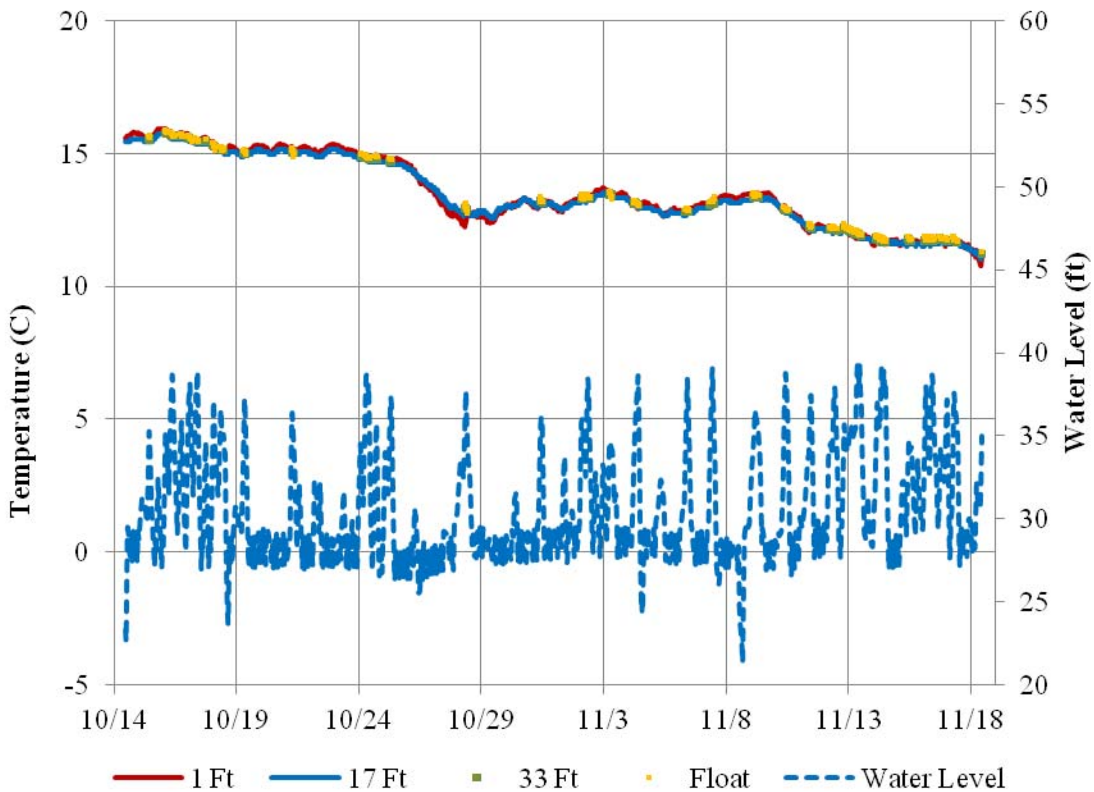


Figure 4.35. ST7 temperature profile and water level.

Temperature profile data in this tank do not present any evidence of stratification, likely as a result of the time period in which the tank was studied. This tank is on the mainline of the water system, and is filled directly by the high service pumps at the water treatment plant causing considerable movement of water through the tank. The treatment plant was undergoing upgrades during the study, which the system suggests as a reason for the seemingly random water level data. Total chlorine data collected for this tank are presented in Figure 4.36.

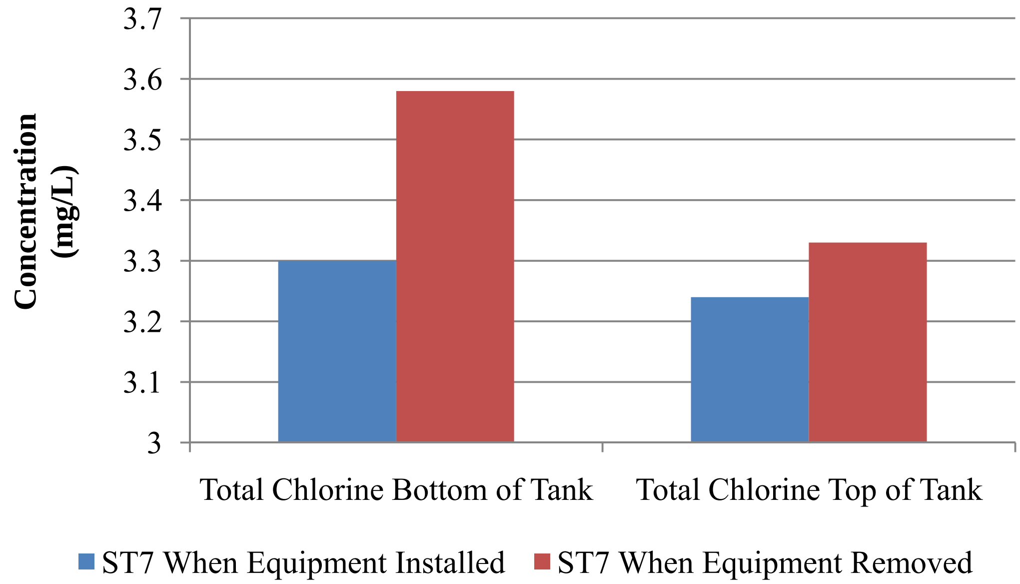


Figure 4.36. ST7 total chlorine concentrations.

Both times the tank was sampled, total chlorine concentrations were lower at the top of the tank than at the bottom; however, even at the lowest measured value, there was still 3.24 mg/L chlorine concentration in the tank. The high concentration indicates that during the time of study, the tank was able to maintain substantial chlorine residual. The high residuals measured in the tank supports the temperature data in concluding that this tank was well mixed. It should be noted that this tank was studied near the end of the study, when temperatures were coolest outside. Hence, it is possible that the tank was stratified during the summer and became destratified by the time the tank was studied.

4.4.8 Short Term Tank 8

Temperature data collected for short term tank 8 are presented graphically in Figure 4.37. Temperature profiles for this tank show little evidence of stratification, likely as the result of cool ambient temperatures during the study period in October and November. Total chlorine data collected from the top of the tank and from an underground pit below the tank are presented in Figure 4.38.

Similar chlorine concentrations are found at the top and bottom of the tank, both when the equipment was installed and removed. The substantial residual at the top of the tank, coupled with the unstratified temperature profile indicates that this tank was well mixed during the study period.

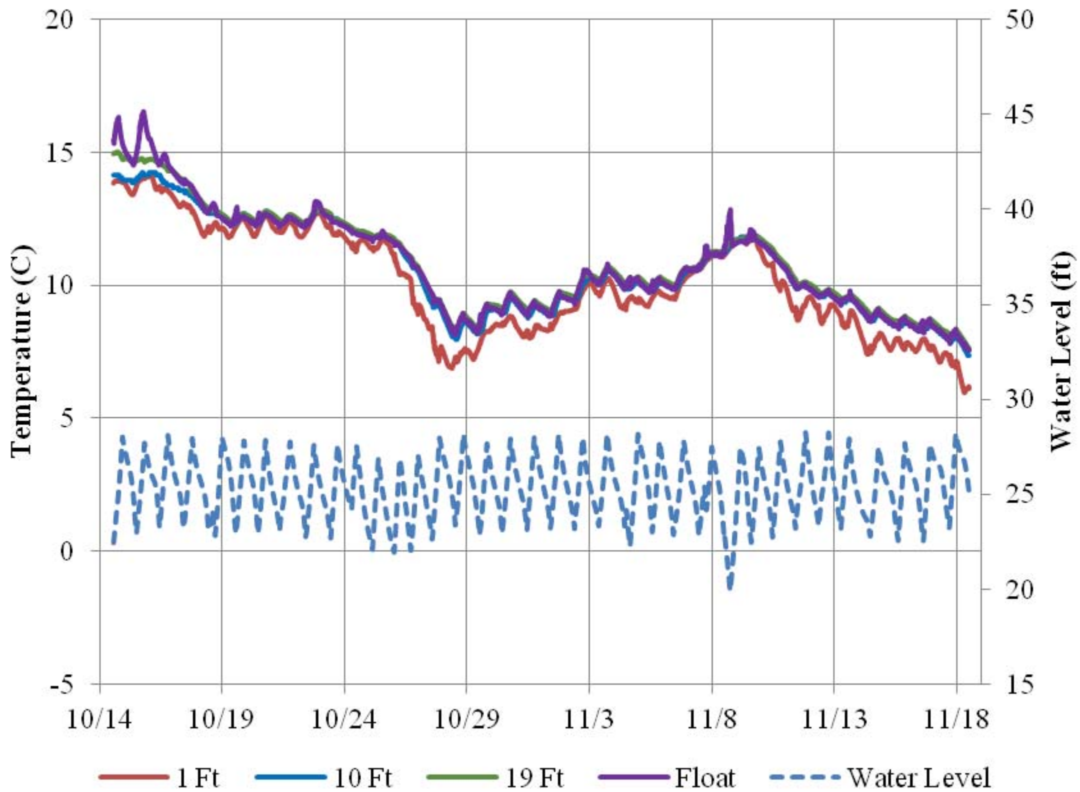


Figure 4.37. ST8 temperature profile and water level.

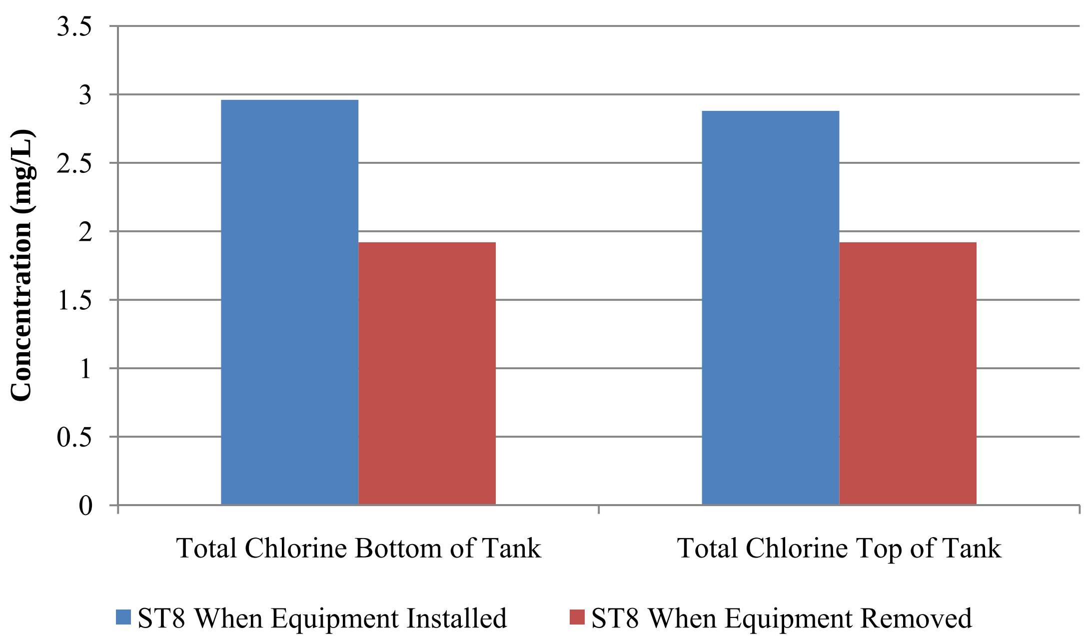


Figure 4.38. ST8 total chlorine concentrations.

4.5 Comparison of Long and Short Term Temperature Data

Standpipes in the long term studies tended to fluctuate between stratified and unstratified conditions based on ambient temperature. This leads to a degree of uncertainty in interpreting temperature profiles of the short term tanks since stratification events could have been missed due the brief timeframes in which the temperature sensors were installed in the short-term tanks. In order to compare data from the short-term tanks with the long-term tanks, temperature profiles for long and short term tanks operated under similar aspect ratios are plotted on the same charts.

Figure 4.39 presents the two tallest standpipes of the short term tanks, coupled with long term tank E. The average aspect ratios of the water column in the tanks presented in Figure 4.39 are as follows:

- Short term tank 1: 4.82
- Short term tank 4: 9.66
- Long term tank E: 4.80

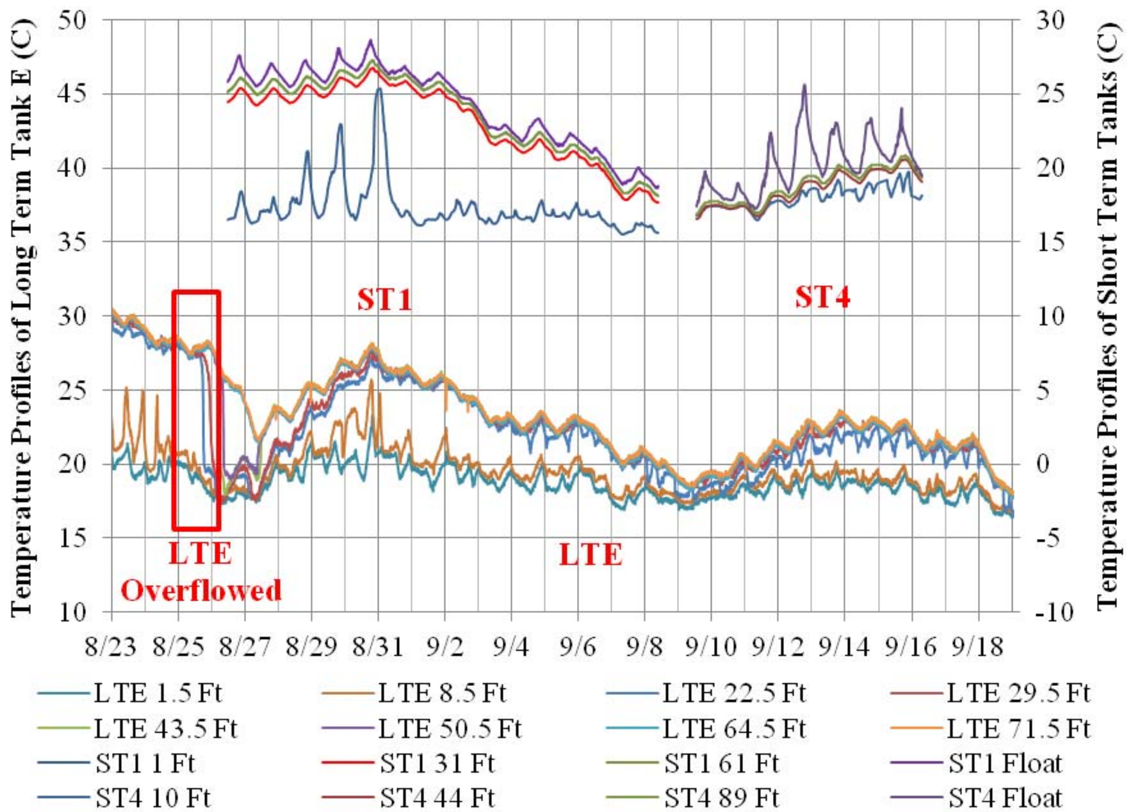


Figure 4.39. Comparison of short term tanks 1 and 4 with long term tank E.

When collection of temperature data began in short term tank 1, long term tank E was being overflowed. However, prior to and after that overflow, long term tank E was under stratified conditions. Short term tank 1 was stratified at the beginning of its study period with the bottom level temperature being approximately 8 ^{o}C lower than at the top of the tank; however, as the ambient temperature decreased, the difference in temperature between the top and bottom of the tank decreased to approximately 3 ^{o}C. During the time where short term tank 1 destratified, long term tank E also became less stratified. Short term tank 4 was largely unstratified when data collection began in the tank, but progressed to a stratified state. Long term tank E behaved in a similar manner by transitioning from unstratified to stratified conditions. The similar response of these tanks to external temperature variations indicates that standpipes have a tendency to stratify during hot weather, and destratify under cooler temperatures.

While tanks with high aspect ratios were compared in Figure 4.39, an example of two tanks of lower aspect ratios are (long-term tank B and short-term tank 2) presented in Figure 4.40. Long term tank B had an operational aspect ratio 0.54, while the operational aspect ratio of the short term tank 2 was 0.46. Long term tank B was a 50 ft tall ground storage tank operated between 25 and 35 ft, while short term tank 2 was a 26 ft tall elevated tank operated between 16.5 and 24.5 ft.

Figure 4.39 clearly shows ST2 under stratified conditions, while the long term tank C displays evidence of a well mixed tank. This indicates that the temperature profiles of tanks with low aspect ratios are less comparable to each other, and are likely more sensitive to operational or hydraulic parameters other than tank geometry. These parameters are discussed further in Section 4.6 of this report.

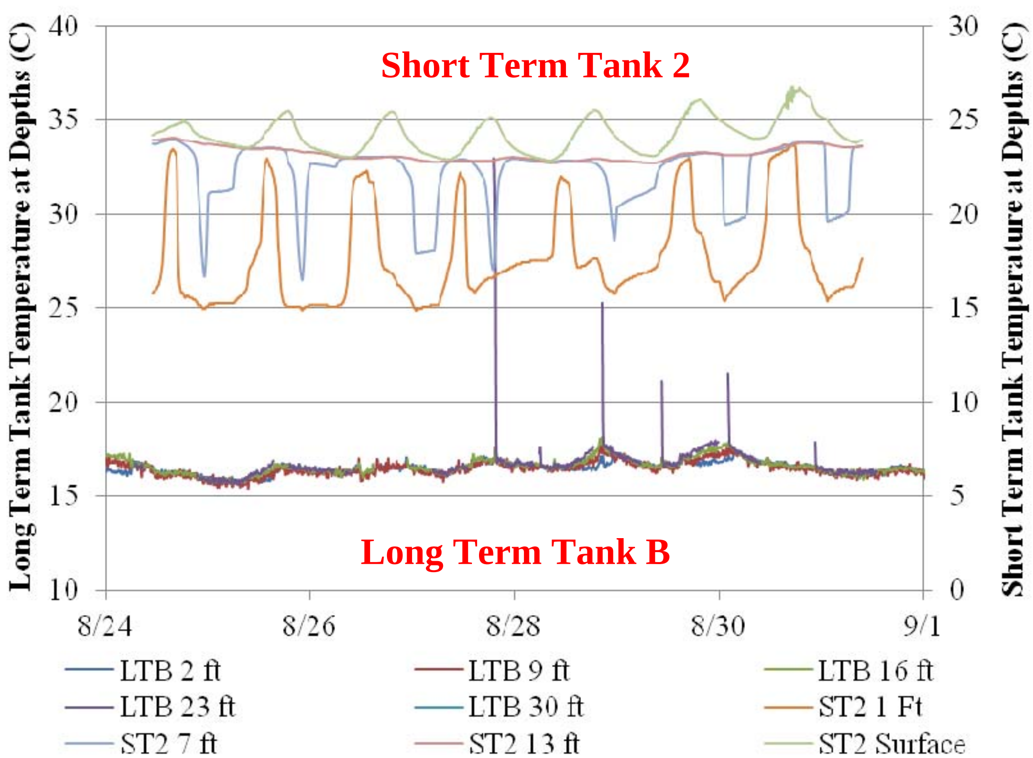


Figure 4.40. Comparison of short term tank 2 with long term tank A.

Each short term tank was compared to a long term tank based on the most similar aspect ratio. Comparison charts can be found in Appendix E, while a summary of these comparisons are presented in Table 4.1. Short term tanks of higher aspect ratios which were compared with long term tanks C and E tended to behave similarly (relative to temperature stratification), while only some tanks compared with long term tank B exhibited similar mixing characteristics. Because long term tank B was well mixed throughout the entire study period, any evidence of stratification found in tanks with similar aspect ratios would lead to dissimilarity between the two tanks. It is important to note that long term tank B also had a separate inlet/outlet, while all short term tanks it was compared with had a single inlet/outlet pipe.

Table 4.1. Comparisons of most similar long term tank to short term tank based on operational aspect ratio

Short Term Tank	**Aspect Ratio**	**Result**	**Long Term Tank**	**Aspect Ratio**	**Result**
1	4.82	Stratified Tank, degree of stratification reduced as weather cooled	E	4.80	Stratified Tank, degree of stratification reduced as weather cooled
2	0.46	Thermally stratified tank	B	0.54	Unstratified tank
3	0.60	Stratified tank, destratifies when mixer turned on	B	0.54	Unstratified tank
4	9.66	Unstratified at beginning, transitions to stratified	E	4.80	Unstratified at beginning, transitions to stratified
5*	1.40	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump	C	0.88	Unstratified at beginning, transitions to stratified
6	2.02	Unstratified at beginning, transitions to stratified	C	0.88	Oscillates between unstratified and stratified
7	0.35	Unstratified tank during cold weather	B	0.54	Unstratified tank during cold weather
8	0.63	Unstratified tank during cold weather	B	0.54	Unstratified tank during cold weather

*See appendix B for the estimate of the aspect ratio for short term tank 5.

Operational volumetric exchanges can also have substantial impacts on mixing, while the Table 4.1 comparisons were only evaluated based on aspect ratio. Long term tank B achieved 209% of its required volumetric exchange, while the short term tanks achieved between 30% and 86% of their required exchange. The use of a separate inlet/outlet pipe in long term tank B and the wide range of volumetric exchanges observed in these tanks of lower aspect ratios led to the dissimilarity found in these comparisons.

4.6 Analysis of Mixing Parameters

Various hydraulic mixing parameters were evaluated to relate experimental data to equations, design factors, and operational factors supplied in the literature review. If a tank's behavior relative to stratification can be predicted by hydraulic considerations, operators and engineers can use hydraulic characteristics to optimize the design and operation of the tank. Included in these parameters were:

- operational aspect ratio,
- Reynolds number,
- fill time (and volumetric exchange) required to meet a 90% mix,
- critical temperature difference between the filling water and water in the tank to cause stratified conditions,
- densimetric Froude number
- a dimensionless parameter illustrated in Roberts et al. (2006), and
- detention time.

The values for the above parameters that should be achieved to enable a tank to be mixed, as well as values obtained in the operation of the tank, are presented in the following sections. These values were compared with temperature and residual disinfectant measurements in various tanks to show the effectiveness of the parameters in predicting mixing.

4.6.1 Operational Aspect Ratios

Although the operational aspect ratio of the water column is not actually a measure of mixing in a tank, the interpretation of temperature and water quality data presented in this report may be used to estimate mixing in other tanks in the field (provided that the mixing conditions, inlet geometry, and tank type are also similar). Mixing characteristics of the tanks examined in this study are presented in Table 4.2, along with the minimum, average, and maximum operational aspect ratios.

Tanks exhibited operational aspect ratios ranging from 0.10 at the lowest, to 9.68 at the highest. Tanks which had high aspect ratios appeared to exhibit more signs of thermal and water quality stratification than those of lower aspect ratios. The long term standpipe tanks oscillated between stratified and unstratified conditions dependent on the temperature outside of the tank. When the two tallest long term standpipe tanks (aspect ratio > 3.55) were stratified, they experienced substantial loss of disinfectant residuals. As suggested by the comparison between long and short term tanks (Table

4.1), standpipes tend to be more relatable to each other than shorter, wider ground storage tanks.

Table 4.2. Operational aspect ratios of tanks studied.

Tank	Minimum	Average	Maximum	Summary of Mixing Characteristics
Long Term A	0.10	0.13	0.16	Well mixed tank
Long Term B	0.42	0.54	0.58	Well mixed tank
Long Term C	0.73	0.88	0.97	Stratified tank during warm season but maintained chlorine concentrations, destratified when the weather cools
Long Term D	3.45	3.55	3.60	Stratified tank during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
Long Term E	4.67	4.80	4.97	Stratified tank during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
Short Term 1	4.55	4.82	4.86	Stratified Tank, degree of stratification reduced as weather cooled
Short Term 2	0.46	0.46	0.47	Thermally stratified tank
Short Term 3	0.59	0.60	0.60	Stratified tank, destratifies when mixer turned on
Short Term 4	9.63	9.66	9.68	Unstratified at beginning, transitions to stratified
Short Term 5*	1.30	1.40	1.42	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump
Short Term 6	1.99	2.02	2.05	Unstratified at beginning, transitions to stratified
Short Term 7	0.32	0.35	0.44	Unstratified tank during cold weather
Short Term 8	0.59	0.63	0.65	Unstratified tank during cold weather

*See appendix B for the special consideration for short term tank 5.

Because the comparisons of long term to short term tanks indicated that standpipe tanks tended to behave similarly, conclusions for the long term standpipes can likely be extended to the short term standpipes. Because the tanks of lower aspect ratios were less relatable to each other, mixing in those tanks should be evaluated on an individual basis, taking into account factors other than aspect ratio.

4.6.2 Reynolds Number of Filling Jet

The Reynolds number of the filling jet was calculated to determine whether inflows are turbulent or laminar. According to section 2.2.2.1, laminar jets to not have sufficient momentum to establish strong mixing patterns within tanks. Fully turbulent jets have Reynolds numbers above 3,000, while laminar jets are below 1,000. Characteristics of the Reynolds numbers for jets filling each tank are presented in Table 4.3.

Table 4.3. Reynolds numbers of filling jets.

Tank	Minimum	Average	Maximum	Summary of Mixing Characteristics
Long Term A	2.33E+04	7.60E+04	2.15E+05	Well mixed tank
Long Term B	2.89E+04	9.57E+04	3.09E+05	Well mixed tank
Long Term C	7.21E+03	1.88E+04	2.96E+04	Stratified tank during warm season but maintained chlorine concentrations, destratified when the weather cools
Long Term D	4.45E+03	1.52E+04	2.56E+04	Stratified tank during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
Long Term E	1.36E+04	3.36E+04	6.51E+04	Stratified tank during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
Short Term 1	3.67E+03	2.04E+04	3.93E+04	Stratified Tank, degree of stratification reduced as weather cooled
Short Term 2	4.56E+03	6.01E+03	7.60E+03	Thermally stratified tank
Short Term 3	4.14E+04	5.14E+04	5.67E+04	Stratified tank, destratifies when mixer turned on
Short Term 4	1.72E+04	2.56E+04	3.83E+04	Unstratified at beginning, transitions to stratified
Short Term 5	2.85E+04	3.55E+04	4.21E+04	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump
Short Term 6	6.55E+03	9.15E+03	1.07E+04	Unstratified at beginning, transitions to stratified
Short Term 7	2.10E+04	1.22E+05	2.77E+05	Unstratified tank during cold weather
Short Term 8	9.94E+03	2.41E+04	3.41E+04	Unstratified tank during cold weather

All Reynolds numbers in Table 4.3 are above the threshold value (3,000) that maintains turbulent flow during the course of the study. Even though all of the inflows were able to meet fully turbulent conditions, those turbulent jets did not necessarily have enough momentum to fully mix the tanks. The presence of poor mixing in several tanks which met the Reynolds number to ensure turbulent flow indicates that there are more factors influencing mixing than just meeting turbulent flow conditions

4.6.3 Fill Time and Volumetric Exchange Ratio Requirements

The fill time required to maintain a 90% mix was calculated using Equations 10 and 11. The results of those calculations were compared with actual time that tanks took to fill. The volumetric exchange ratio associated with each fill cycle was plotted in charts, along with temperature profiles. According to section 2.2.2.1, the volumetric exchange ratio does not account for thermal variations between the tank volume and filling water. Because temperature differences between inflow and the tank body are not included in the volumetric exchange calculation, the presence of a thermocline could impede mixing and cause the calculated required exchange ratio to be underestimated.

In order to demonstrate relationships between volumetric exchange ratios and mixing in different tank geometries, the volumetric exchange ratios required and achieved for long term tanks A and E are presented in Figures 4.41 and 4.42, respectively. These two tanks correspond to the largest (tank E) and smallest (tank A) operational aspect ratios of the long term tanks studied. Long term tank A was a 948,000 gallon aboveground reservoir (24 ft tall, 81 ft diameter) generally operated between 9 and 16 ft of water level. Average operational aspect ratios for tank A ranged from 0.10 to 0.16. Long term tank E was a 140,000 gallon standpipe (86 ft tall, 14 ft diameter). Long term tank E was operated between 77 and 85 ft of water level from the beginning of the study period until the weather cooled in November, when the system changed the water level operations to range from 74 to 85 ft. Average operational ratios for tank E ranged from 4.67 to 4.97. Plots including temperature profiles, required volumetric exchange ratio, and achieved volumetric exchange ratios during the temperature sampling period for long term tanks A and E are presented in Figures 4.41 and 4.42, respectively. Similar plots for the remaining tanks which were studied may be found in Appendix F.

Long term tank A achieved on average 341% of the required exchange, while tank E only met 26% of the required value. High and low water levels in tank A varied approximately seven feet, while tank E varied 8 ft. Because tank A is much wider than tank E, (81 ft compared to 14 ft), those similar water level variations lead to much more water being exchanged in tank A compared to tank E. Tank A, on average exchanged 74% of its entire tank contents during a fill cycle, whereas tank E only exchanged about 10%.

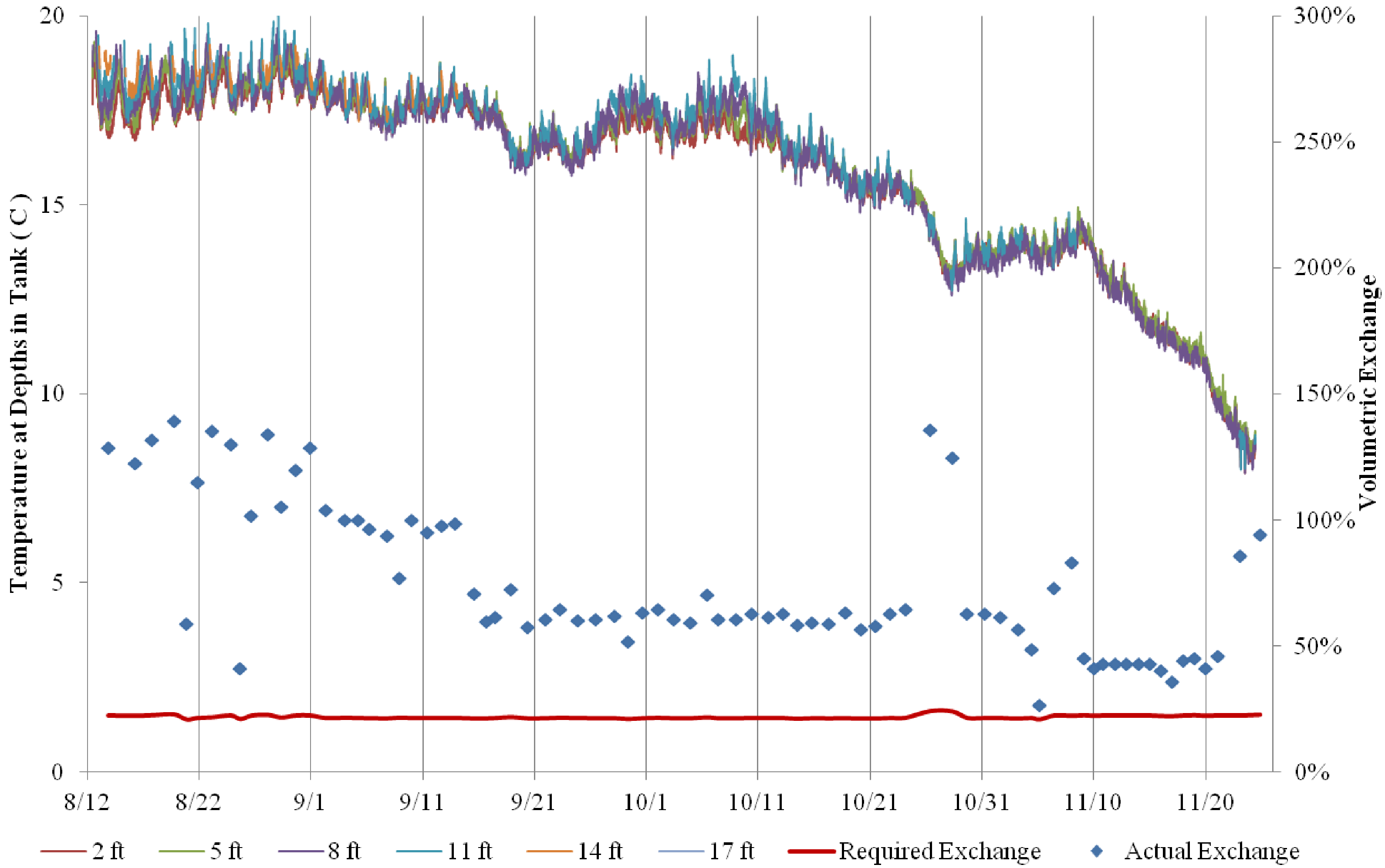


Figure 4.41. Temperature profiles, and actual and required volumetric exchange ratios for long term tank A.

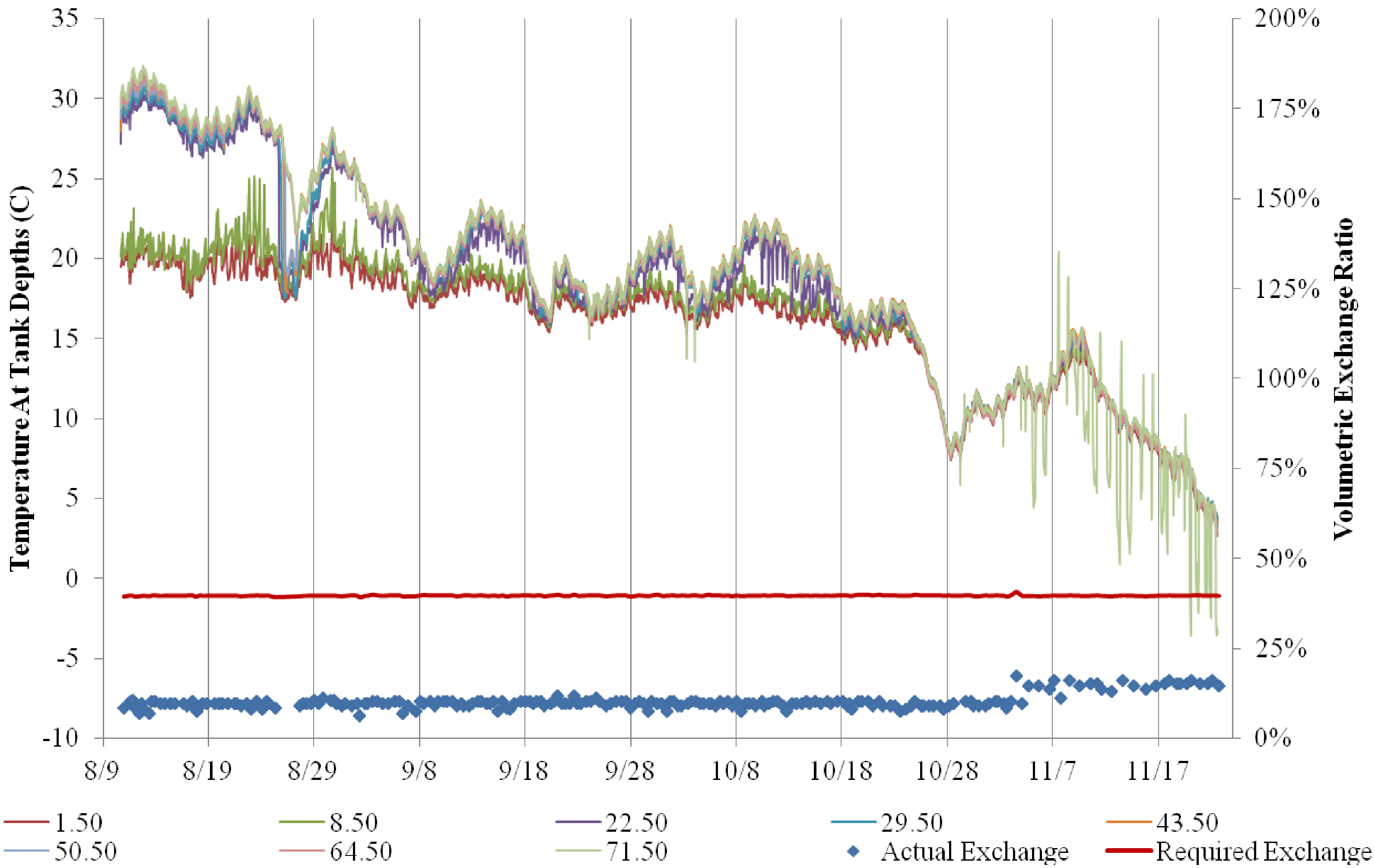


Figure 4.42. Temperature profiles, and actual and required volumetric exchange ratios for long term tank E.

The exchange which would be required to mix tank E was approximately 40% of the tank volume, which would require the water system to increase the operational water level fluctuations by a factor of four. Section 2.2.3 presented a case study of a tank whose water level fluctuations were increased to prevent nitrification by promoting mixing. The decreased low water level caused lower pressure in the system and led to several customer complaints. Similarly, according to the system which operated short term tank 1, the water level in that tank is drawn farther down in the winter than in the summer causing pressure problems. Because of pressure problems which can result from increasing the water level fluctuations, it is more difficult to match the required volumetric exchange in standpipe style tanks compared to tanks which are shorter and wider.

To summarize, actual filling time and volumetric exchanges for all of the tanks examined in this study, as well as filling time and volumetric exchange requirements, and the percentage of the required exchange (and fill time) which was actually attained for each tank are presented in Table 4.4.

The equations used to calculate the fill time (Equation 10) and volumetric exchange required to mix a tank (Equation 18) are related to the inlet diameter (smaller diameter requires less exchange). Short term tank 2 utilized a 60 inch riser pipe, while the next largest diameter used in any tank was 24 inches. Due to the large diameter of the riser pipe in short term tank 2, 149% of the tank contents would need to be added to adequately mix this tank compared to the next largest exchange ratio for the tanks studied of 77% (short term tank 4). If no other design or operational characteristics of short term tank 2 were changed, and the inlet diameter were reduced from 60 to 12 inches, the required exchange to mix this tank would be decreased from 149% to 30% showing that minimizing the inlet diameter would decrease the required exchange to mix a tank. By reducing inlet diameter, velocity of the inflow can be increased. If the velocity was increased and flow rate kept constant, the momentum of the inflow would increase, thus decreasing the required fill time calculated using Equation 10. Because the tank fill time to mix a tank is related to the volumetric exchange, reducing this fill time will decrease the required volumetric exchange.

Only three tanks met the required volumetric exchanges to be mixed. Long term tanks A, B, and C met their required volumetric exchanges by 341%, 209%, and 214%, respectively. These three tanks had maintained chlorine residuals throughout their tank depths, even during the warm season, indicating that if an adequate volumetric exchange is achieved, tanks would be well mixed.

Table 4.4. Average fill time and volumetric exchange data and requirements each tank.

Tank	Fill Time Required (hr)	Actual Fill Time (hr)	Exchange Required	Actual Exchange	Percent of Required Met	Summary of Mixing Characteristics
LTA	5.09	15.77	22%	74%	341%	Well mixed tank
LTB	4.20	7.95	17%	36%	209%	Well mixed tank
LTC	4.04	8.21	27%	59%	214%	Stratified during warm season but maintained chlorine residuals, destratified when the weather cooled
LTD	27.06	4.94	30%	6%	18%	Stratified during warm season with low chlorine residuals in the upper zone, destratified when the weather cooled
LTE	14.48	3.69	40%	10%	26%	Stratified during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
ST1	40.73	6.83	34%	6%	18%	Stratified Tank, degree of stratification reduced as weather cooled
ST2	32.92	10.03	149%	45%	30%	Thermally stratified tank
ST3	7.19	3.79	24%	12%	52%	Stratified tank, destratifies when mixer turned on
ST4	23.97	2.53	77%	8%	11%	Unstratified at beginning, transitions to stratified
ST5	12.10	4.56	20%	8%	37%	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump
ST6	25.60	6.80	24%	6%	27%	Unstratified at beginning, transitions to stratified
ST7	6.71	2.40	33%	13%	38%	Unstratified tank during cold weather
ST8	9.14	7.52	24%	21%	86%	Unstratified tank during cold weather

Long term tank D achieved 18% of the required exchange, and long term tank E met 26% of its required exchange. At the beginning of the study, these tanks experienced poor water quality in the upper reaches of the tank, but when the temperature outside of the tank decreased, the tanks became better mixed. When the temperature and chlorine profiles in the tank became consistent relative to depth, the volumetric exchange ratio that the tanks achieved still did not meet the required value. The evidence of well mixed conditions while the tank operation did not meet the required volumetric exchange indicates that for tall, unstratified standpipes, the required exchange could be overestimated. It is especially important to note that this overestimation is only relevant to unstratified tanks, as temperature (which is not accounted for with the volumetric exchange requirement) appears to strongly affect mixing in standpipes.

4.6.4 Critical Temperature Difference to Cause Stratification

The critical temperature difference between the water stored in the tank and the inflow which could cause a tank to stratify was calculated for each fill and draw cycle using Equation 4 presented in Section 2.2.1.1 for all tanks examined in this study. Results of these calculations are presented in Table 4.5.

The results of these calculations show that very little temperature difference is theoretically required to cause stratification in most tanks. As long term tanks become taller, the temperature difference between filling water and the tank volume to cause stratification decreases, as shown by tank A requiring a 2.19 ^{o}C, compared to tanks D and E, which were both below 0.01 ^{o}C. This relationship of tank geometry to critical temperature difference to cause stratification suggests that taller tanks are more susceptible to stratification than shorter tanks.

During the site visit to tank E on October 20th, total chlorine data varied relative to depth between 1.2 and 1.4 mg/L, indicating that the tank was well mixed from a disinfectant residual standpoint (see Figure 4.22). Theoretically, a 0.008 ^{o}C difference in temperature between the inflow and tank volume should have caused tank E tank to stratify; however, during that site visit while the tank was well mixed relative to chlorine residual, a 1 ^{o}C difference in temperature between the inflow and tank volume was observed. This higher measured difference in temperature between the inflow and tank contents than that which was calculated to cause stratification suggests that the actual temperature difference to cause stratification in these tanks is likely higher than Equation 4 predicts. It is also noteworthy that the equation calculating the critical temperature difference to cause stratification was proven for tanks whose aspect ratios were less than 1.0, which leads to some uncertainty when the applied to standpipe tanks.

Table 4.5. Characteristics of critical temperature difference to cause stratification.

	Average (H:D)	**Average Critical Temperature ^oC**	**Summary of Mixing Characteristics**
LTA	0.13	2.1959	Well mixed tank
LTB	0.54	0.8799	Well mixed tank
LTC	0.88	0.0720	Stratified during warm season but maintained chlorine residuals, destratified when the weather cooled
LTD	3.55	0.0021	Stratified during warm season with low chlorine residuals in the upper zone, destratified when the weather cooled
LTE	4.80	0.0079	Stratified during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
ST1	4.82	0.0023	Stratified Tank, degree of stratification reduced as weather cooled
ST2	0.46	0.0080	Thermally stratified tank
ST3	0.60	0.1396	Stratified tank, destratifies when mixer turned on
ST4	9.66	0.0021	Unstratified at beginning, transitions to stratified
ST5	1.40	0.0278	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump
ST6	2.02	0.0019	Unstratified at beginning, transitions to stratified
ST7	0.35	0.4051	Unstratified tank during cold weather
ST8	0.63	0.0571	Unstratified tank during cold weather

4.6.5 Densimetric Froude Number

Densimetric Froude numbers of each fill cycle were calculated using Equation 1 and compared with required values to overcome stratified conditions in tanks (Equation 3). The results for each tank are presented graphically in Appendix G. Two examples showing long term tanks A and E are presented in Figures 4.43 and 4.44, respectively.

Figure 4.43 shows that the calculated densimetric Froude numbers in long term tank A are frequently higher than would be required to overcome stratified conditions in the tank. As a result tank A (which has an aspect ratio of 0.13) was well mixed from both a temperature and water quality standpoint. Conversely, Figure 4.44 shows that very few calculated densimetric Froude numbers are greater than those required to overcome stratified conditions in long term tank E (aspect ratio 4.80). Nevertheless, near the end of the study, long term tank E became better mixed from a water quality standpoint. When long term tank E became better mixed at the end of October, the densimetric Froude numbers appeared to increase, however very few fill cycles were able to meet the required value.

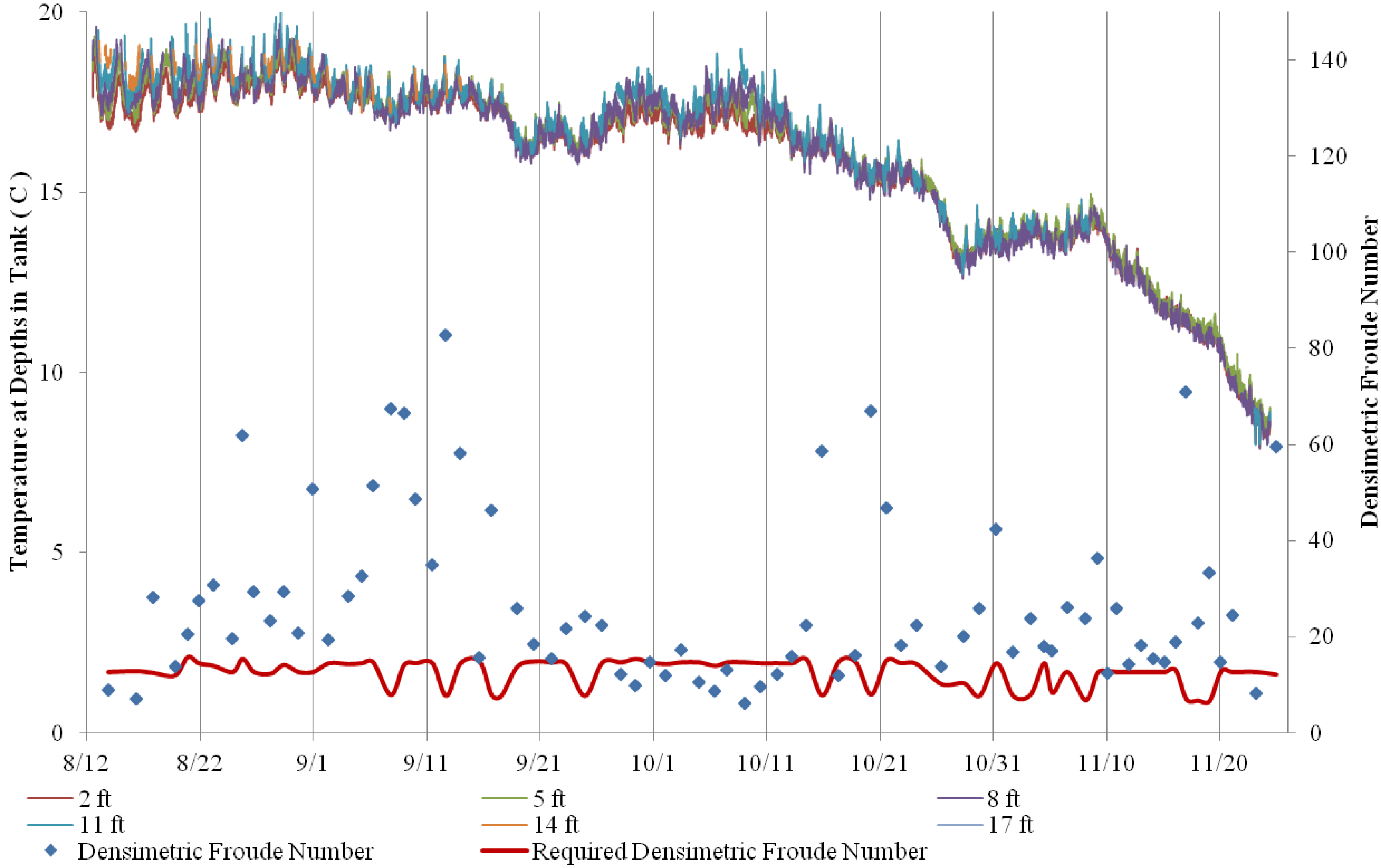


Figure 4.43. Densimetric Froude numbers for long term tank A.

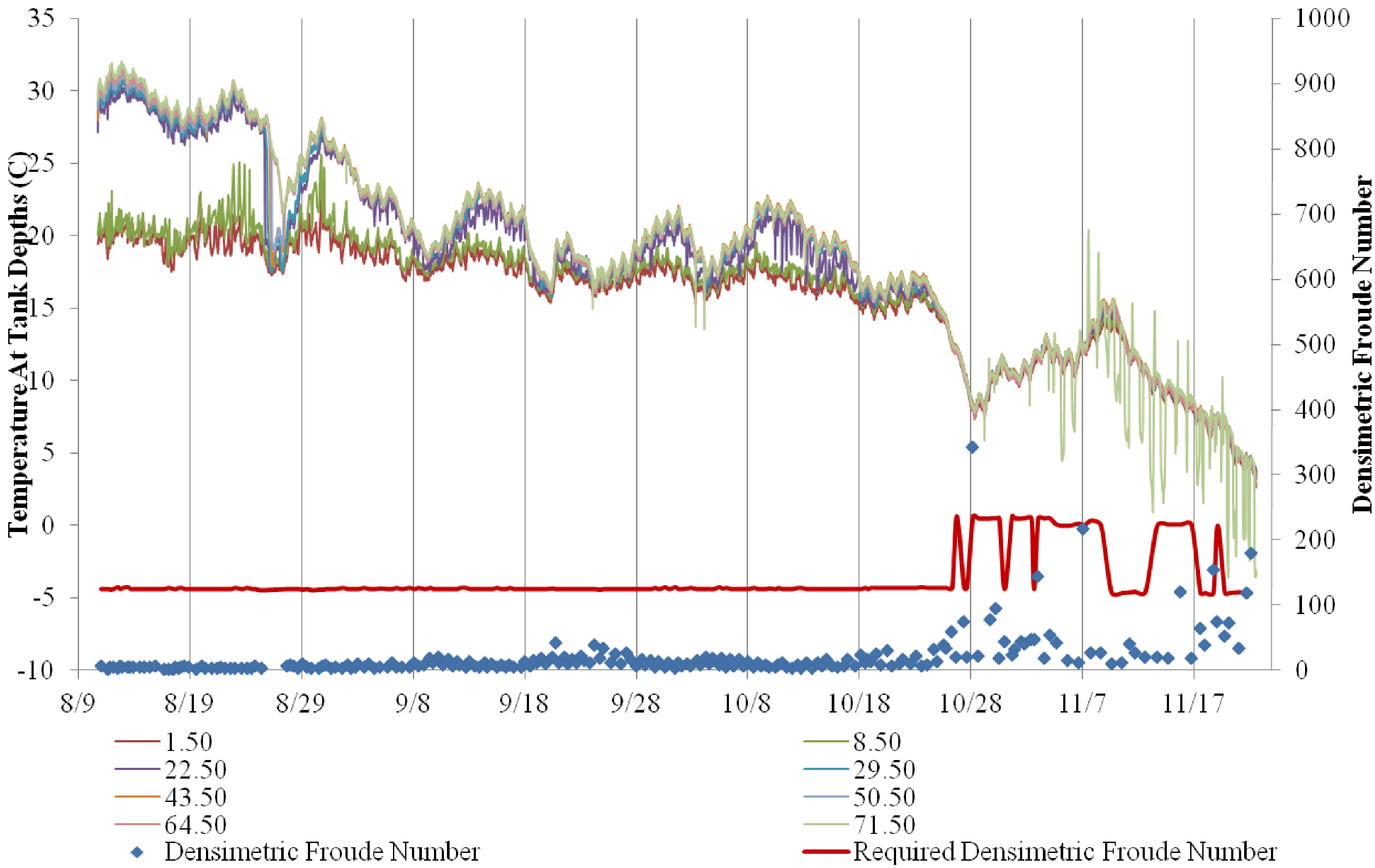


Figure 4.44. Densimetric Froude numbers for long term tank E.

The reason for the well mixed conditions in this tank (while the densimetric Froude numbers were below the required values) could be the result of the required densimetric Froude number being overestimated, or the tank behavior changing from a negatively buoyant jet (incoming water colder than the tank volume) to a positively buoyant jet (incoming water warmer than the tank volume).

Densimetric Froude numbers for long term tank C (aspect ratio 0.88) are plotted in Figure 4.45.

Figure 4.45 shows that long term tank C should not have overcome a temperature stratified condition based on dimensionless Froude numbers. However, the tank does mix on occasions when the densimetric Froude number met by the tank's operation comes closer to its required value. During August, temperature stratification was observed, however throughout the study, substantial chlorine residuals are found throughout the entire depth of the tank. The presence of high chlorine residual could have been the result of sufficient volumetric exchange during fill cycles (214% of the required to mix the tank attained on average), suggesting that although a tank may be stratified, if enough volumetric exchange is achieved, disinfectant residuals can be maintained.

Results for average attained and required densimetric Froude Numbers are presented in Table 4.6 for all tanks examined in this study

Table 4.6 shows that the average calculated densimetric Froude number for three tanks (LTA, LTB, and ST7 with aspect ratios of 0.13, 0.54, and 0.35, respectively) met the values required to mix the tank. Those three tanks are the most well mixed tanks in the study according to temperature data, indicating that maintaining the densimetric Froude number above the required values should fully mix a tank.

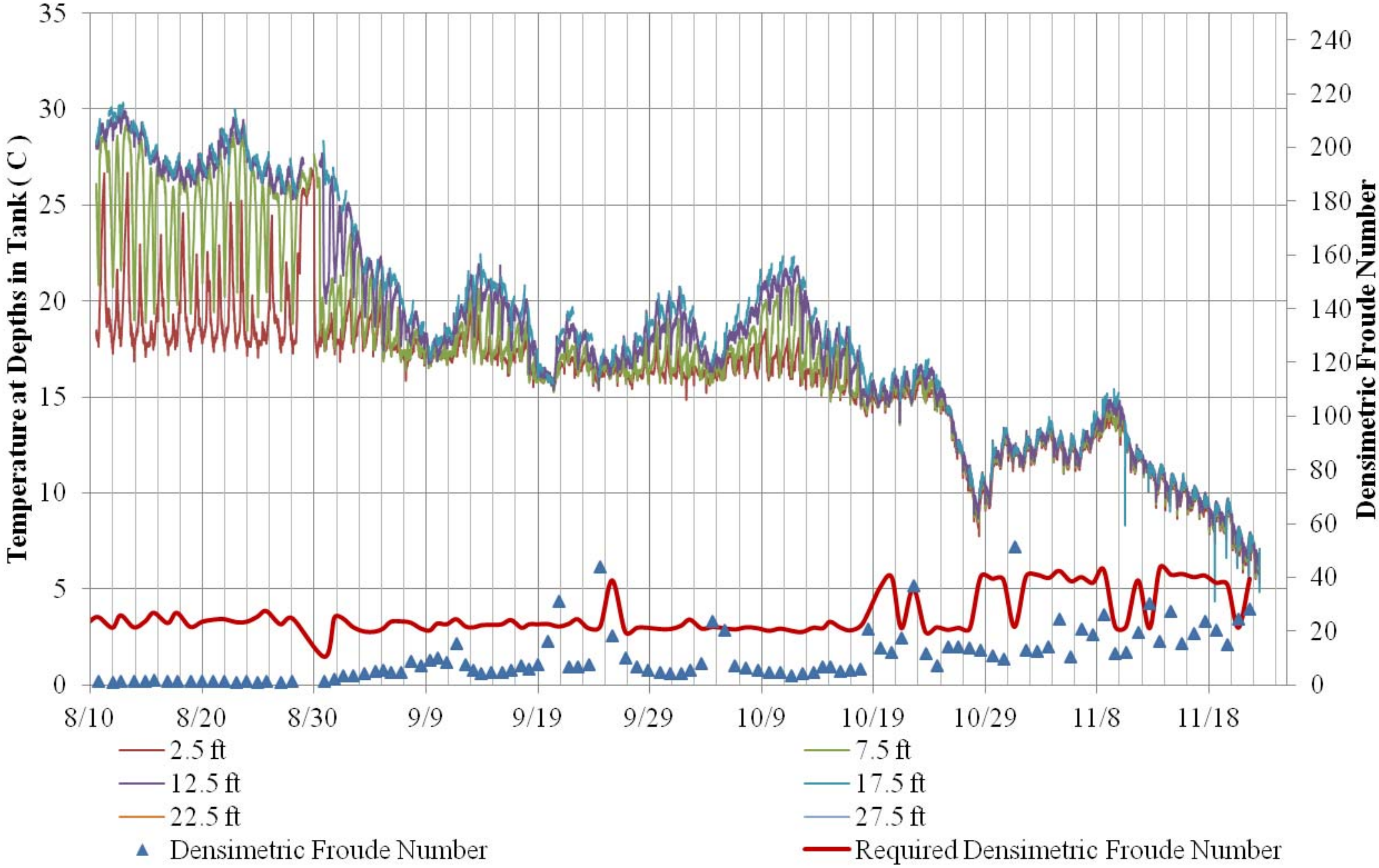


Figure 4.45. Densimetric Froude numbers for long term tank C.

The densimetric Froude number can be increased by increasing the inflow velocity, which is accomplished by either increasing flow rate or decreasing inlet diameter.

Table 4.6. Characteristics of densimetric Froude numbers for the various tanks.

Tank	**Average Densimetric Froude Number**	**Required Densimetric Froude Number**	**Percentage of required attained**	**Summary of Mixing Characteristics**
LTA	31.3	12.5	251%	Well mixed tank
LTB	78.2	39.9	196%	Well mixed tank
LTC	10.2	26.1	39%	Stratified during warm season but maintained chlorine residuals, destratified when the weather cooled
LTD	6.9	115.7	6%	Stratified during warm season with low chlorine residuals in the upper zone, destratified when the weather cooled
LTE	19.8	136.4	15%	Stratified during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
ST1	3.8	149.7	3%	Stratified Tank, degree of stratification reduced as weather cooled
ST2	0.03	2.7	1%	Thermally stratified tank
ST3	5.5	22.0	25%	Stratified tank, destratifies when mixer turned on
ST4	14.6	178.3	8%	Unstratified at beginning, transitions to stratified
ST5	6.9	42.3	16%	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump
ST6	2.7	69.1	4%	Unstratified at beginning, transitions to stratified
ST7	27.7	18.3	152%	Unstratified tank during cold weather
ST8	12.5	25.3	50%	Unstratified tank during cold weather

4.6.6 Dimensionless Mixing Parameter

A dimensionless mixing parameter ($M^{1/2}/(B^{1/3}H^{2/3})$) was calculated for each tank. This provides similar information to the study as the densimetric Froude number. If this parameter is maintained above a certain threshold as identified in Section 2.1.1.2 the tank should be well mixed. The dimensionless mixing parameter for each tank was plotted with the required value (based on inlet configuration and buoyancy type) and temperature profile for each tank. These plots may be found in Appendix H. Examples of these charts for long term tanks A and E are presented in Figures 4.46 and 4.47, respectively.

Comparing the dimensionless mixing parameters in Figures 4.45 and 4.46, long term tank A presents many fill cycles of the calculated parameter that are above the threshold to ensure that mixing occurs, while tank E does not. The parameter consistently attaining its required value indicates that tank A should be well mixed, while tank E should not. Temperature and water quality data support the notion that tank A was well mixed and tank E was not. As the study period progressed into mid October, the dimensionless mixing parameter for long tern tank E increased, and on October 28th and on six other occasions, the tank exceeded the dimensionless mixing parameter required to completely mix the tank. Average values of this parameter for each tank are presented in Table 4.7.

Only three tanks (LT1, LT2, and ST7) maintained average values of the dimensionless mixing parameter above those required to ensure that mixing occurs throughout the duration of the study. These are the same three tanks which met the required densimetric Froude number to be mixed. All three of these tanks were considered well mixed from both temperature and residual disinfectant standpoints. Because this dimensionless mixing parameter accurately predicted that these three tanks should be mixed, this parameter appears valid at full scale. Even with standpipes, this parameter increases when the temperature variation was minimized, further supporting the conclusion that this parameter appears valid at full scale.

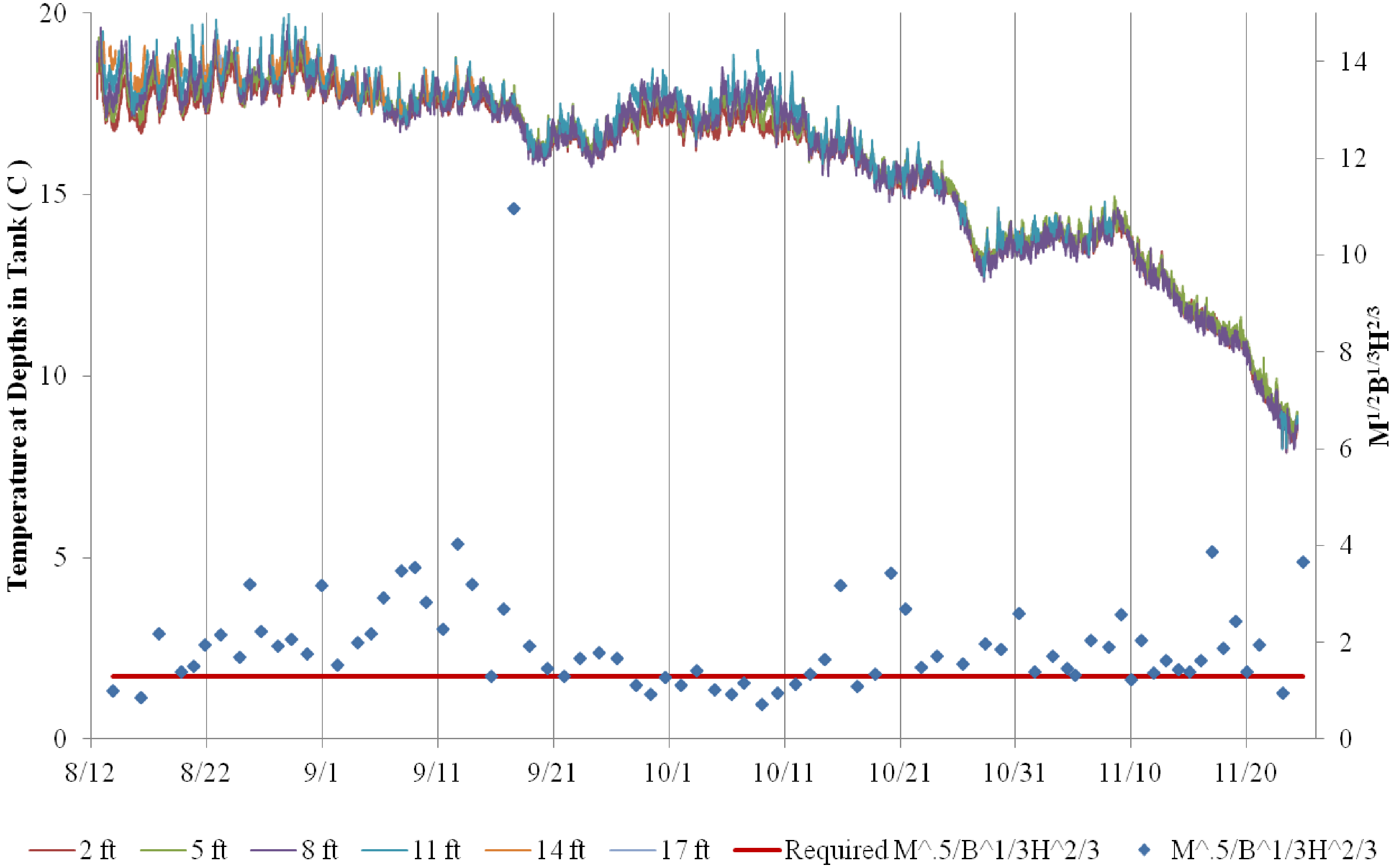


Figure 4.46. $M^{1/2}/(B^{1/3}H^{2/3})$ for long term tank A.

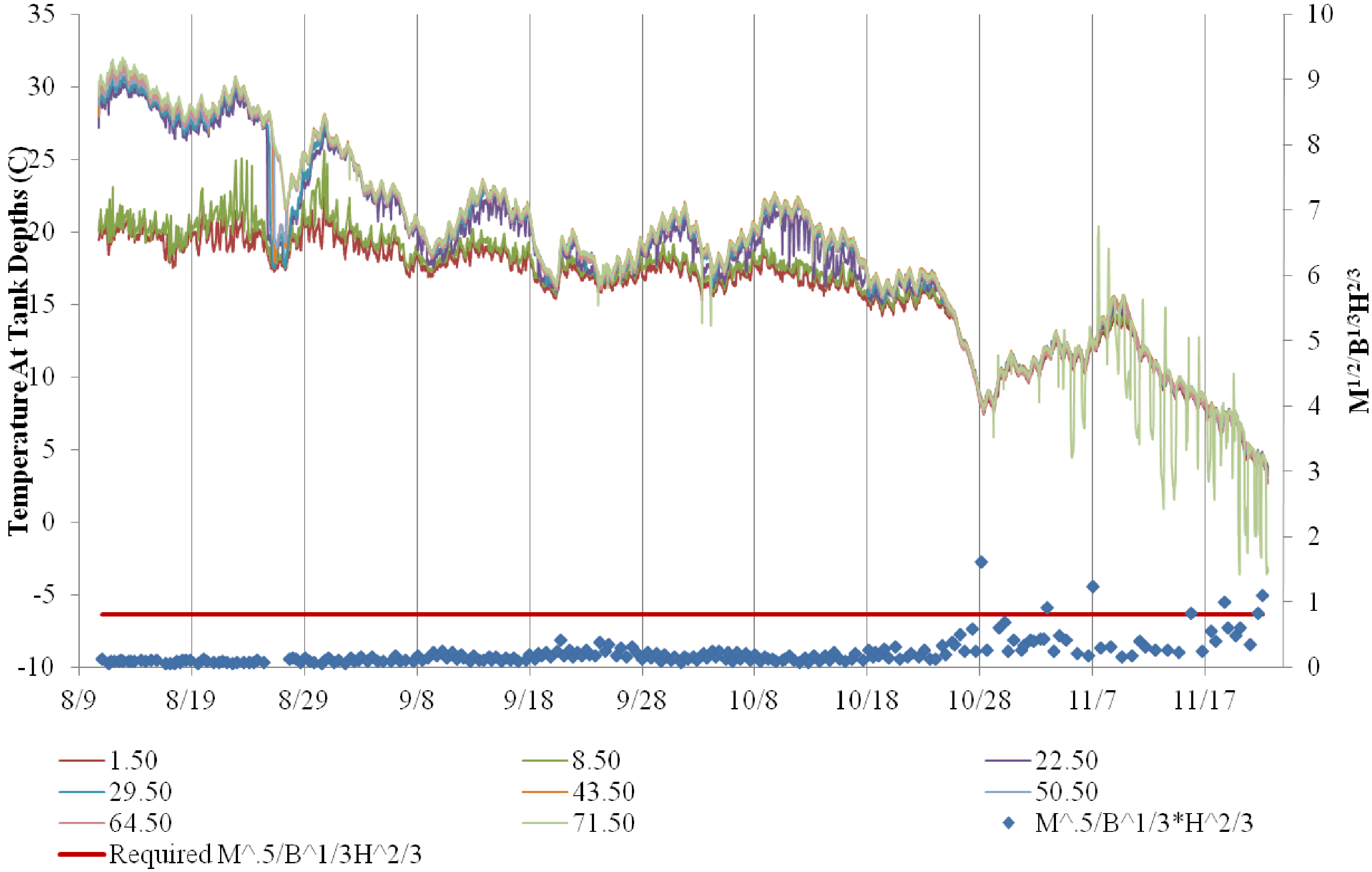


Figure 4.47. $M^{1/2}/(B^{1/3}H^{2/3})$ for long term tank E.

Table 4.7. $M^{1/2}/(B^{1/3}H^{2/3})$ required and actual values for each tank.

Tank	**Average $M^{1/2}/(B^{1/3}H^{2/3})$**	**Required $M^{1/2}/(B^{1/3}H^{2/3})$ to Ensure Mixing**	**Summary of Mixing Characteristics**
LTA	2.0	1.3	Well mixed tank
LTB	1.5	0.8	Well mixed tank
LTC	0.5	0.8	Stratified during warm season but maintained chlorine residuals, destratified when the weather cooled
LTD	0.1	0.8	Stratified during warm season with low chlorine residuals in the upper zone, destratified when the weather cooled
LTE	0.2	0.8	Stratified during warm season with low chlorine residual in the upper zone, destratified when the weather cooled
ST1	0.1	0.8	Stratified Tank, degree of stratification reduced as weather cooled
ST2	0.0	0.8	Thermally stratified tank
ST3	0.3	0.8	Stratified tank, destratifies when mixer turned on
ST4	0.2	0.8	Unstratified at beginning, transitions to stratified
ST5	0.2	0.8	Stratified at beginning, transitions to unstratified, likely the result of a recirculation pump
ST6	0.1	0.8	Unstratified at beginning, transitions to stratified
ST7	1.5	0.8	Unstratified tank during cold weather
ST8	0.5	0.8	Unstratified tank during cold weather

4.6.7 Tank Detention Time

The hydraulic retention time (detention time) of a tank is related to the fill and draw cycle lengths, as well as the volume at the start and end of each cycle (see Equation 14 from Section 2.2.3). Detention time was also described in the literature review as the turnover rate, or the average time that the entire tank contents spend in the facility. Table 2.5 in Section 2.2.3 provided guidelines for turnover rate in storage tanks, which recommend maximum detention times of one to seven days. The tank detention time can provide an estimate of water age in a well mixed tank. By reducing a tank's detention time, water age in a tank can be reduced as a result of younger water entering the tank at an increased rate. Characteristics of the detention times for the tanks in this study are presented in Table 4.8.

Table 4.8. Detention time characteristics for all tanks (hours).

Tank	Minimum	Average	Maximum	Standard Deviation
Long Term A	1.39	2.64	4.11	1.39
Long Term B	0.86	3.53	11.56	0.86
Long Term C	1.26	2.25	6.70	1.26
Long Term D	6.06	9.64	21.13	6.06
Long Term E	1.94	4.80	13.12	1.94
Short Term 1	5.42	10.38	39.96	5.42
Short Term 2	2.48	2.68	3.11	2.48
Short Term 3	2.12	4.92	7.06	2.12
Short Term 4	3.13	4.88	7.15	3.13
Short Term 5	3.74	8.61	21.73	3.74
Short Term 6	12.90	16.45	20.43	12.90
Short Term 7	0.48	1.94	10.40	0.48
Short Term 8	2.67	4.98	7.55	2.67

Although short term tank 7 was the largest tank (in terms of capacity) in the study, the location of this tank on the mainline of the system led to high demands from the tank (and thus high flow rate). These high flow rates led to the shortest average detention time of all of the study tanks (1.94 days). Occasionally, some fill and draw cycles are shorter or longer than typical for a tank, and as a result detention times inconsistent with the average values occur. This is especially true with short term tank 1, where a short fill and draw cycle accounts for a 39.96 day detention time. This is well outside what would be considered typical for this tank, with an average detention time of 10.38 days.

It is important to note that tank detention time is not actually a measure of mixing in a tank. Long detention times are caused by tanks which are too large for the demands they serve. Tanks can be operated such that their filling cycles can achieve a complete mix, but if demands are low long draw cycles can lead to excessive detention times. In the case of short term tank 6, the tank experienced substantial seasonal demands. Because temperature sensors were installed in this tank during low demand times, long detention times (16.45 days on average) were observed. Even though the tank was experiencing long detention times, similar total chlorine concentrations were observed at the top and bottom of the tank.

4.7 Relating Stratification to Ambient Temperature

When tanks D and E were stratified, temperatures in the upper zone of the tank appeared to be related to the ambient temperature (see Figures 4.13 for long term tank D and 4.18 for long term tank E). When the ambient temperature in those tanks decreased, the temperature of the upper zone also decreased, eventually converging to the temperature of the filling water. When the temperatures of the upper and lower zones of the tanks were similar, the buoyant force was minimized, allowing the residual disinfectant concentrations to become consistent throughout the tank contents. By relating ambient temperature to temperature in the tank, water systems can predict what times of year they should be most concerned with stratification in standpipes.

The processes required to accurately model heat transfer from the weather are quite complex, and would require data not collected in this study. Because of these limitations, empirical relationships between ambient temperature and internal temperature in the upper portion of the tank (rather than physical models) were developed to predict water temperature in the upper zones of tall standpipes. Two tanks (long term tanks 4 and 5) presented the most prevalent stratification, during which little to no mixing occurred in the upper zone. Due to this lack of mixing, temperatures in the upper reaches of the tank were not strongly influenced by the filling water, but were more affected by the weather outside the tank.

Linear regression analyses were performed by plotting water temperature in the upper zone of the tank with respect to outside temperature and adding linear trend lines. Linear regression lines were calculated to fit the plotted data using the least squares method. The temperatures utilized in these calculations were the average of the maximum and minimum temperatures for each day (the actual average daily temperature was not used, because the maximum and minimum do not occur at the same time each day, so an average could present additional error). The plot for long term tank 4 is presented in Figure 4.48 (both plots are found in Appendix I).

The linear regression between the temperature outside and inside the tanks was calculated using Microsoft Excel™. The standard error of the estimate was calculated to quantify the dispersion of the residuals (or differences between measured and predicted values). This standard error corresponds to the temperature in which 68% of the residuals are closer to the regression line than farther away. The regression equations for each of these tanks, as well as the coefficient of determination (R^2), and standard error, are presented in Table 4.9. The standard errors of the estimates for both tanks indicate that 68% of the observed values were less than three degrees Celsius away from the predicted regression equation.

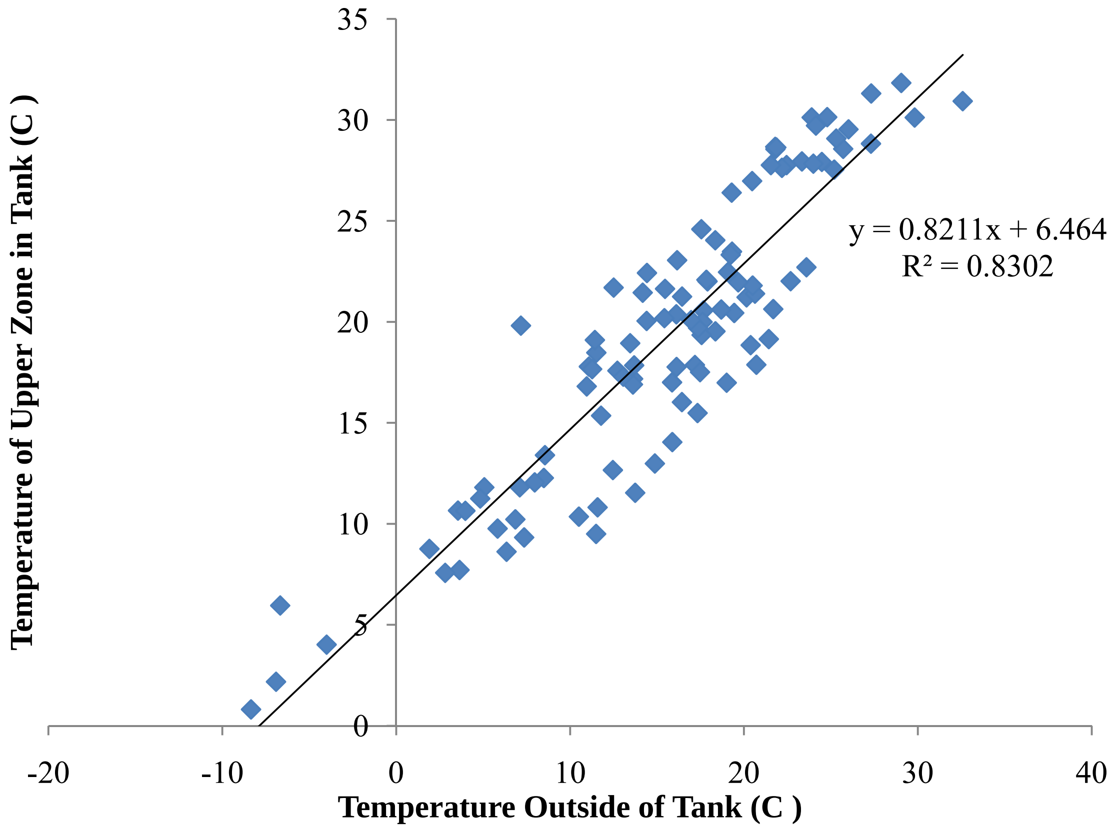


Figure 4.48. Relationship of temperature inside and outside of LT4.

Table 4.9. Empirical relationships between temperature inside and outside of tanks.

Tank	Regression Equation	Coefficient of determination	Standard Error of the Estimate (Degrees C)
LTD	$T_{tank} = 0.8211T_{outside} + 6.464$	0.830	2.94
LTE	$T_{tank} = 0.7755T_{outside} + 6.2074$	0.831	2.79

where: T_{tank}= temperature in the upper zone of the tank (Degrees C), $T_{outside}$ = temperature outside of tank (Degrees C) ((daily high – daily minimum) /2).

In order for a system to predict whether stratification is occurring in a tank, the system operating the tank would need to compare the temperature of the water filling the tank with the temperature calculated using these equations. The temperature of the water leaving the water treatment plant is relatively simple to monitor; however, particularly in rural systems, water can spend a considerable amount of time in pipelines and other reservoirs before it reaches the tank. The time which water spends in the system can have major impacts on water temperature before it reaches the tank. The water supply operating long term tank E provided temperature data for the water leaving their treatment plant (collected once a week), which were compared to measured temperatures at the bottom of the tank, as shown by Figure 4.49.

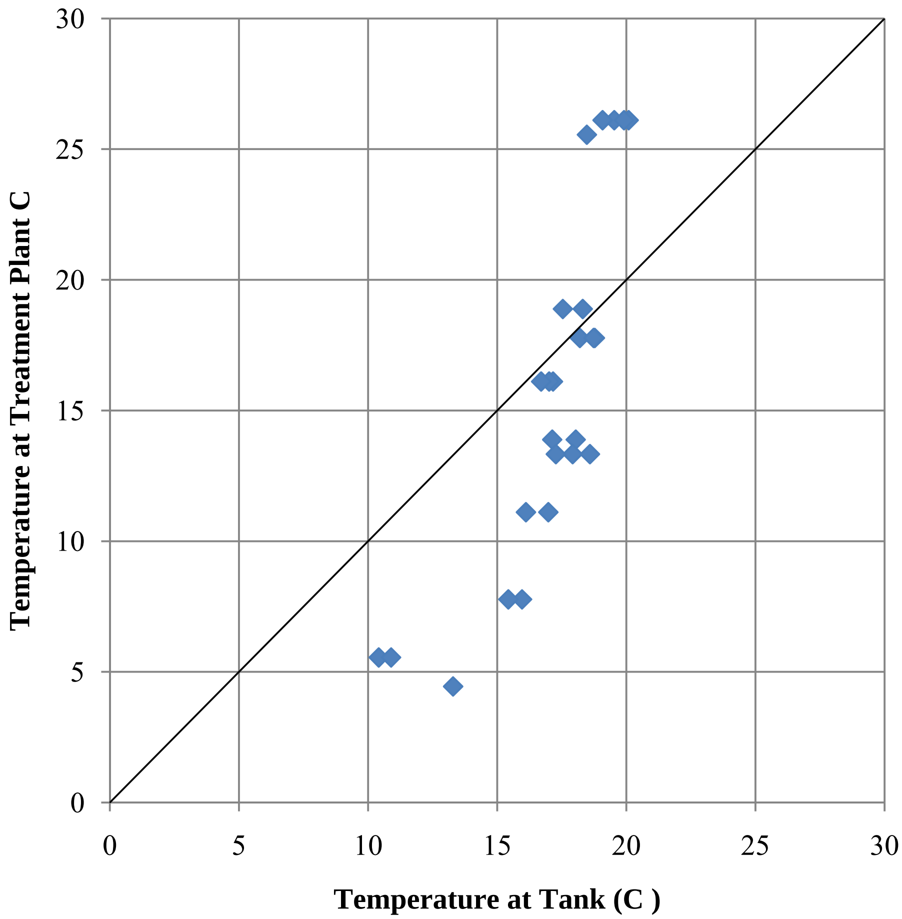


Figure 4.49. Comparison of temperatures of water leaving the plant and LT5.

A 45 degree angle is shown on this figure to compare temperatures at the tank and at the plant. If a point is above the line, water is warmer at the treatment plant, and cools off before arriving at the tank. Conversely, if a point is below the line, the temperature warms up as it moves to the tank. When the temperature of the water leaving at the treatment plant is greater than approximately 19 degrees C, the water cools before arriving to the tank, and conversely, when the water is cooler than 19 C, the water warms up. This shows that the water can experience substantial differences in temperature as it moves through the distribution system. If a water system has the capability to measure temperature at points in the system near the storage facility, prediction of the distribution system water temperature (filling the tank) is unnecessary, allowing comparisons between predicted temperatures in the tank and water filling the tank to be made. These comparisons could then be used to predict whether stratification is occurring.

In order to provide a general prediction as to what time of year stratification becomes a problem, Figures 4.50 and 4.51 were developed to illustrate the impacts of ambient temperature on stratification. Various operational actions which were taken in these tanks are also shown in these Figures.

Water temperatures in the upper zones of these tanks tended to move from stratified conditions to unstratified conditions following trends in ambient temperature from the beginning of the study in August until mid October. These tanks did not necessarily destratratify based on any single daily temperature value. Instead, they tended to move towards more well mixed conditions when the ambient temperature is cooler than the upper zone several days in a row. Both tanks destratified from a temperature standpoint near the middle to end of October, when ambient temperature was consistently below 15 ^{o}C (yellow line on Figures 4.50 and 4.51). It should be noted that these conditions may be different for various systems, primarily relating to the filling water temperature. This filling water temperature is a function of many factors including: source temperature, distance from the treatment facility, pipeline characteristics, and storage in the system prior to filling the tank.

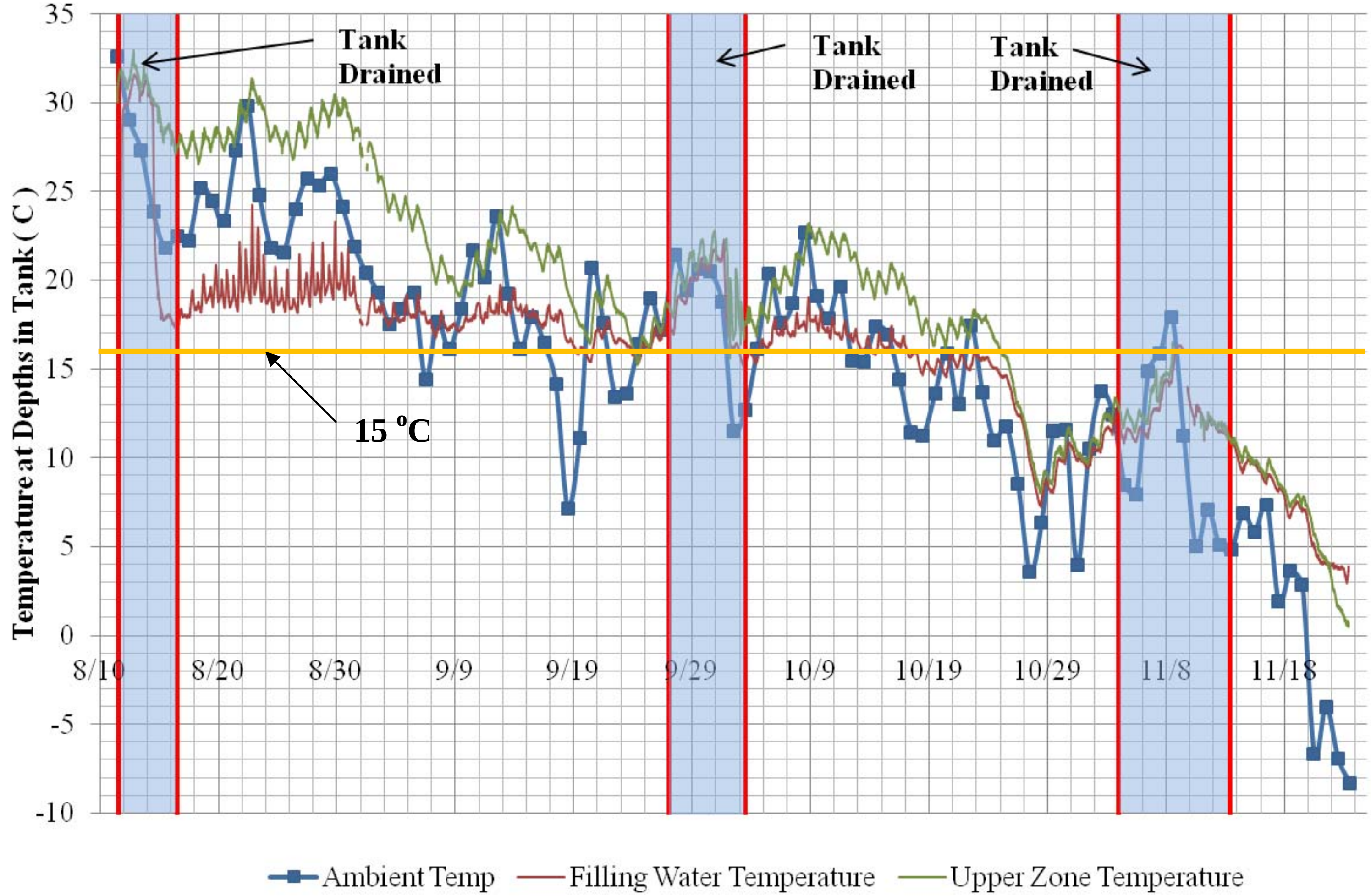


Figure 4.50. Long term tank D ambient, upper zone, and lower zone temperatures.

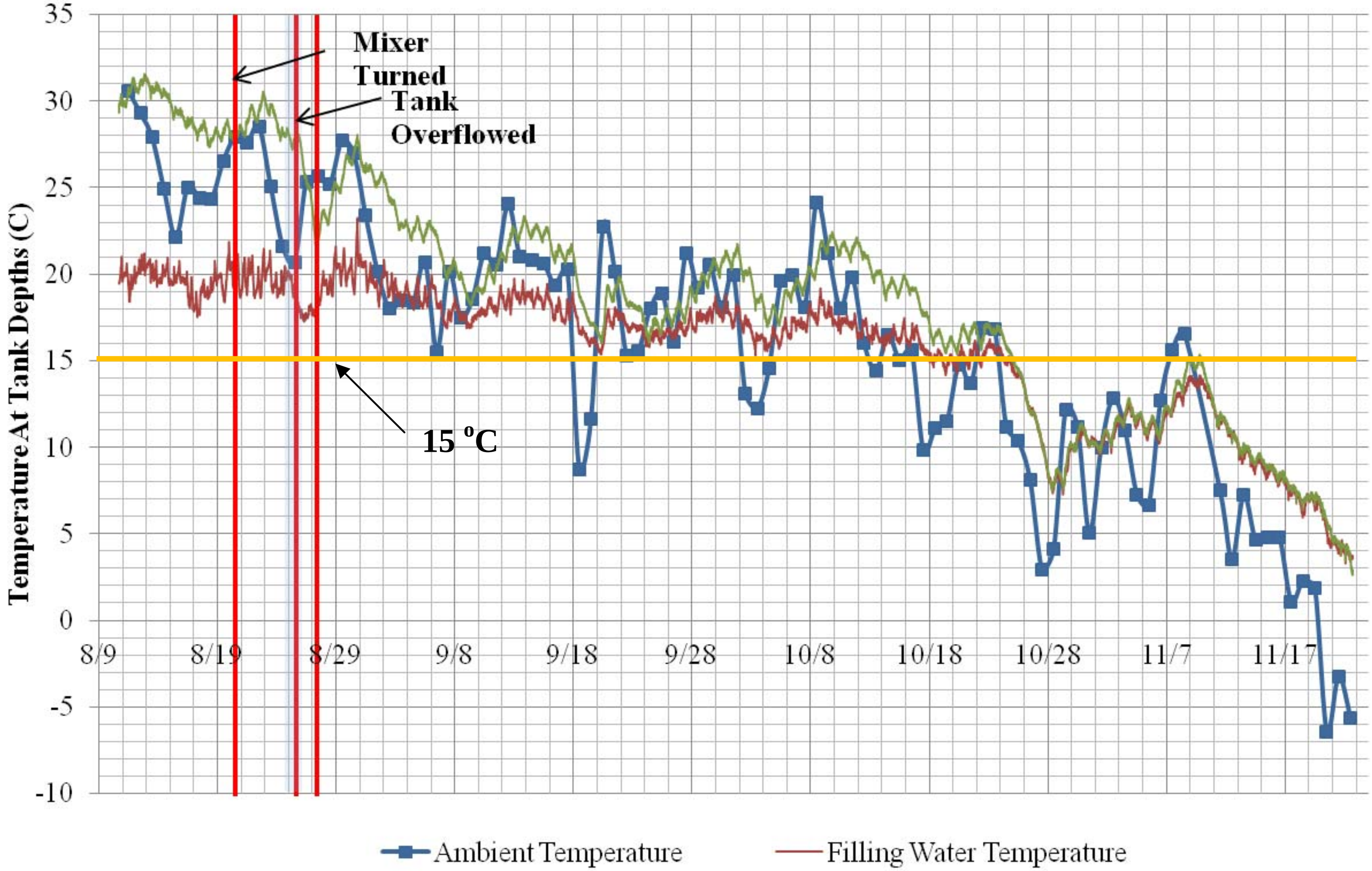


Figure 4.51. Long term tank E ambient, upper zone, and lower zone temperatures.

4.8 Disinfectant Decay Models in Long Term Tanks

Disinfectant decay was modeled for each of the long term tanks using the program CompTank. These models were created to describe disinfectant decay in tanks under completely mixed and fully stratified conditions. These models predict the time it would take for a fully stratified tank to deplete its chlorine residual. This understanding of chlorine decay in tanks allows water systems to know when appropriate actions to restore chlorine residuals in tanks should be taken.

4.8.1 Long Term Tank A

Temperature and water quality profiles for long term tank A indicated that this tank was well mixed, so this tank was modeled as completely mixed. CompTank model inputs included inflow rate, inflow concentration, and outflow rate. Inflow and outflow rates were calculated using water level data provided by the water system, and actual data for each fill and draw cycle were input into the model. Average flow rates and other model inputs are presented in Table 4.10.

Table 4.10. Inputs for the long term tank A model.

Model Input	Value
Initial tank volume	0.27 Mgal
Initial total chlorine concentration	0.17 mg/L
Decay coefficient	0.06 d^{-1} from 8/11 to 11/4 0.04 d^{-1} from 11/4 to 11/24
Average inflow rate	266 gpm
Average outflow rate	219 gpm
Inflow concentration	Extrapolated between site visits, ranged from 0.17 to 0.6 mg/L

The results of the model created for long term tank A are presented in Figure 4.52.

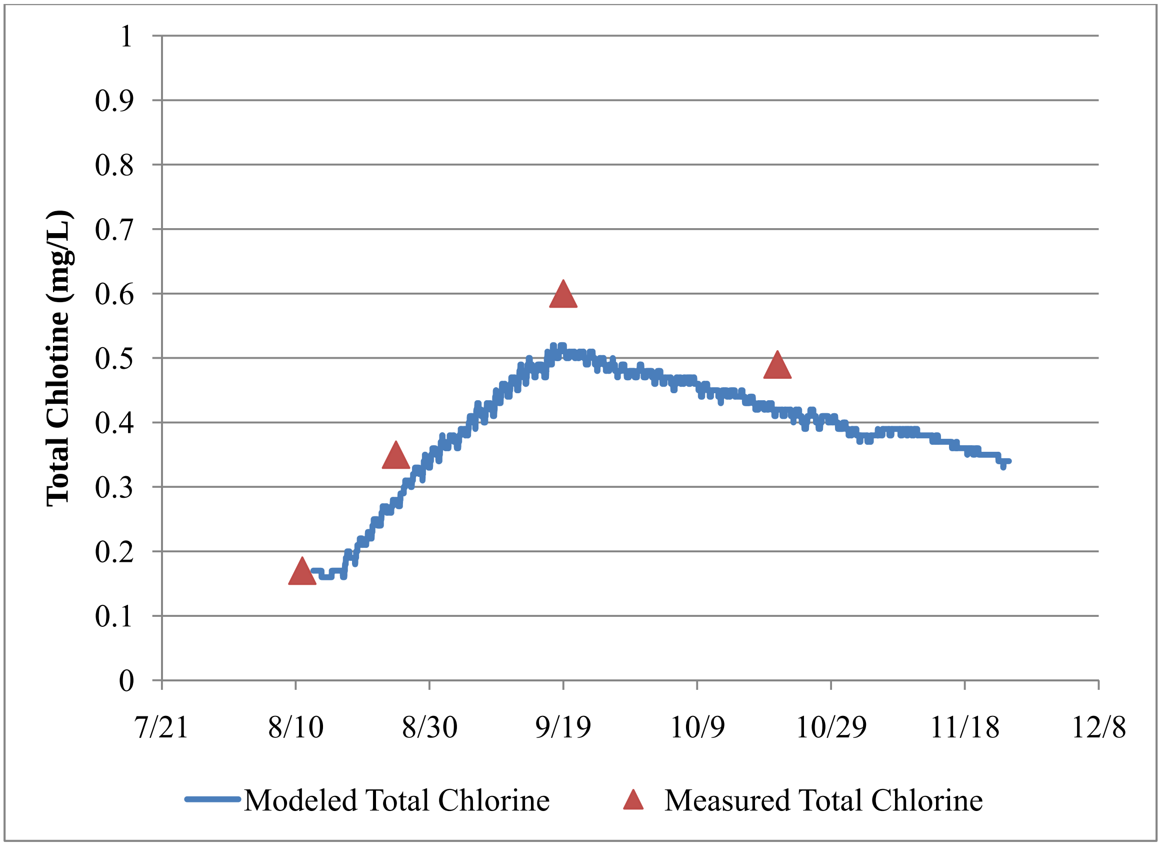


Figure 4.52. Completely mixed model for long term tank A.

This tank was modeled as a completely mixed tank under fill and draw conditions. As a result of changing the chlorine concentrations in the inflow, concentrations in the tank increased and decreased. The model responds well to changes in inflow chlorine concentrations, by closely following the measured values.

4.8.2 Long Term Tank B

Temperature and total chlorine profiles for long term tank B indicated that this tank was well mixed, similar to long term tank A. Model inputs included: initial tank volume, initial tank concentration, decay rate, inflow rate, inflow concentration, and outflow rate. Inflow and outflow rates were calculated using water level data provided by the water system, and actual data for each fill and draw cycle were input into the model. Average flow rates and other model inputs are presented in Table 4.11.

Table 4.11. Inputs for the long term tank B model.

Model Input	Value
Initial tank volume	0.36 Mgal
Initial total chlorine concentration	1.01 mg/L
Decay coefficient	0.06 d^{-1} from 9/19 to 11/16 0.04 d^{-1} from 11/16 to 12/3
Average inflow rate	278 gpm
Average outflow rate	177 gpm
Inflow concentration	1.01 mg/L

The results of the model for long term tank B are presented in Figure 4.53, along with field measurements.

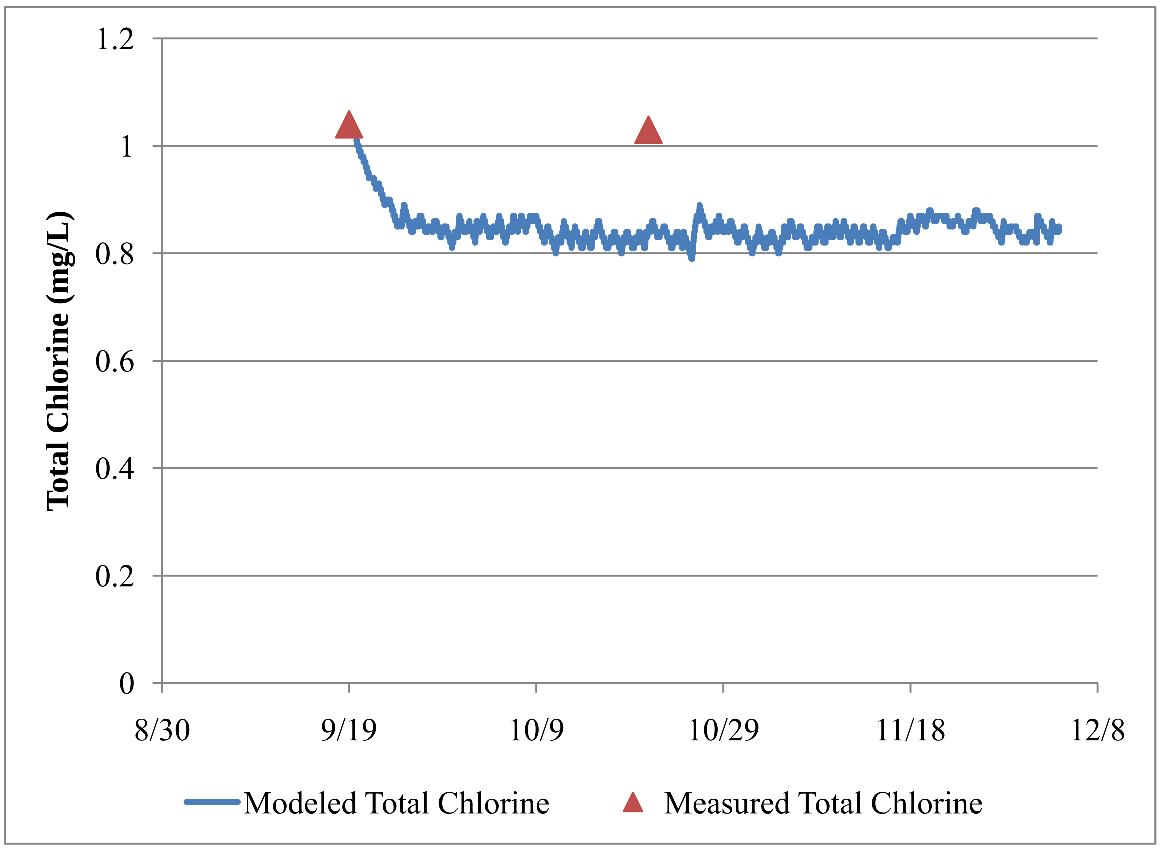


Figure 4.53. Completely mixed model for long term tank B.

The model for long term tank B presents an ideal case for a completely mixed tank, as the chlorine concentration filling the tank was assumed constant, rather than variable as in tank A. The initial chlorine concentration was taken as 1.01 mg/L, with the same concentration filling the tank. Initially, a drop was calculated by the model, but as the tank continued to operate, steady state conditions were observed with concentrations ranging from 0.8 to 0.9 mg/L. The model appears to underestimate the chlorine concentration in the tank, which was likely the result of the filling water concentration used in the model was measured in the field from the lowest measurement point within the tank volume, rather than from the pipe filling the tank. Filling water was likely diluted when it entered the tank, leading to the underestimation of the concentration of the filling water.

4.8.3 Long Term Tank C

Long term tank C was stratified at the beginning of the study from a temperature standpoint, but transitioned to completely mixed as the study progressed. Two models were created for long term tank C, one to simulate stratified conditions, and one to simulate unstratified conditions.

The stratified model was created for the time period from 8/9 until 8/28. Model inputs included: initial volume, total chlorine concentration, and decay rate for the main, inlet, and dead zones, as well as flow rates into the tank, out of the tank, and between zones. Inflow and outflow rates were calculated using water level data provided by the water system and actual data for each fill and draw cycles were used into the model. The total chlorine concentrations used in the model were taken from the August 22nd site visit, rather than August 10th visit due to uncertainty in data collected on the earlier visit (total chlorine concentrations measured were above the limit for the measurement equipment). On August 28th, the pump station filling the tank lost power, causing a deep drawdown in the tank, which caused the model to fail. This failure was caused by the water being drained to a level lower than the variable zone would allow. In order to model the tank for a period of longer than six days (August 22nd to August 28th), the flow rates starting August 9th were used in the model, along with total chlorine concentrations from August 22nd. Average flow rates and other model inputs are presented in Table 4.12.

Table 4.12. Inputs for the stratified long term tank C model.

Model Input	Inlet Zone	Main Zone	Dead Zone
Volume	0.01 Mgal	0.01 Mgal	0.02 Mgal
Initial total chlorine concentration	2.26 mg/L	1.94 mg/L	1.94 mg/L
Decay coefficient	0.06 d^{-1}	0.06 d^{-1}	0.06 d^{-1}
Average inflow rate	20 gpm		
Average outflow rate	21 gpm		
Inflow concentration	2.5 mg/L		
Flow rate between main and dead zone	10 gpm		
Flow rate between inlet and main zone	10 gpm		

The results of the stratified model for long term tank C are shown in Figure 4.54.

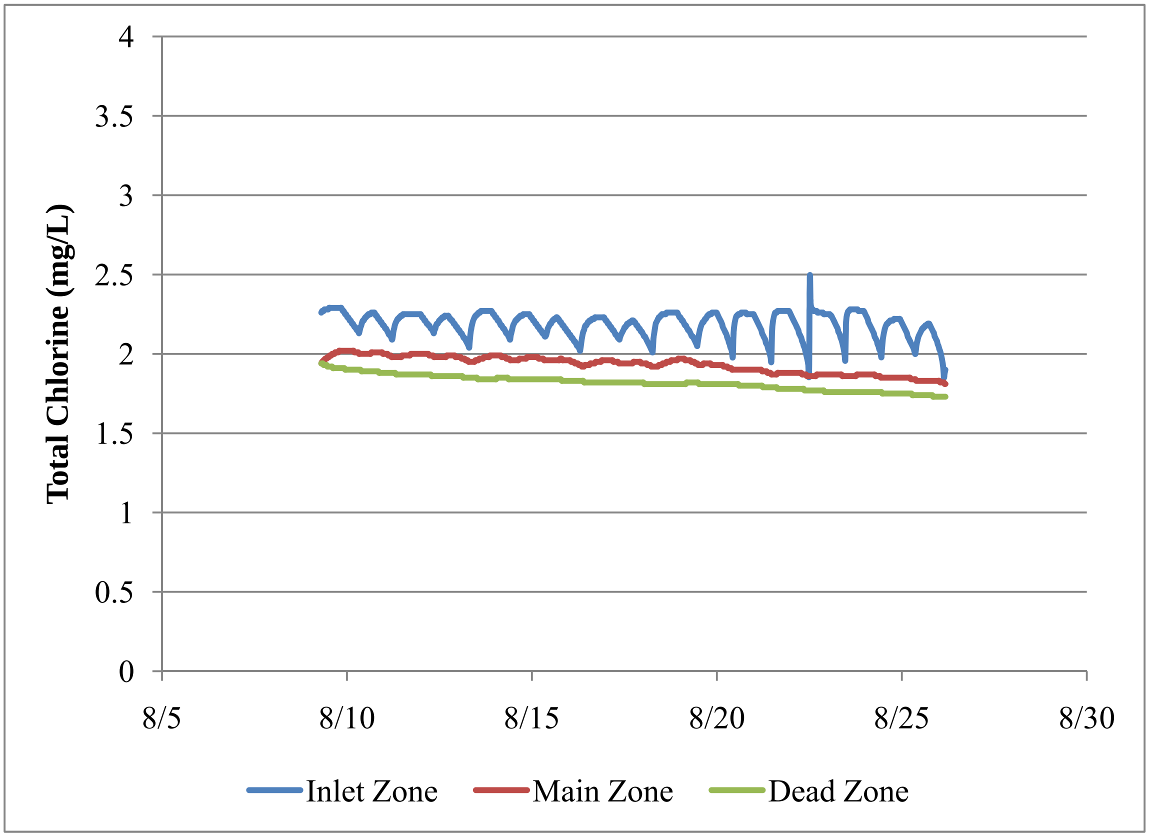


Figure 4.54. Stratified three compartment model results for long term tank C.

The model for long term tank C under stratified conditions assumes values for flow rates between compartments which cannot be validated by external data. The fact that there is chlorine in the upper zone of the tank indicates that there is mixing between compartments, but without a tracer study that value can only be assumed. The model shows that the chlorine concentrations oscillate between 2.0 and 2.25 mg/L in the inlet zone. The main and dead zones are decreasing in concentration, but not to levels of concern. The tank was not sampled between the date of the initial chlorine concentration and the date of the tank being fully drained, making comparisons with field measurements on any given day impossible. However, throughout the entire duration of the study measurements of total chlorine ranged between 1.94 and 2.6 mg/L, while the model results ranged from 1.7 to 2.5 mg/L.

Long term tank C became well mixed near the end of the study, and was modeled again under completely mixed conditions. Model inputs for the completely mixed conditions included: initial tank volume, initial tank concentration, decay rate, inflow rate, inflow concentration, and outflow rate. Inflow and outflow rates were calculated using water level data provided by the water system, and actual data for each fill and draw cycle were input into the model. Average flow rates and other model inputs are presented in Table 4.13.

Table 4.13. Inputs for the completely mixed long term tank C model.

Model Input	Value
Initial tank volume	0.03 Mgal
Initial total chlorine concentration	2.56 mg/L
Decay coefficient	0.04 d^{-1}
Average inflow rate	45 gpm
Average outflow rate	20 gpm
Inflow concentration	2.60 mg/L

The results of the model created for the completely mixed conditions of long term tank C may be seen in Figure 4.55.

The completely mixed model for long term tank C was set up assuming a lower total chlorine decay coefficient than the stratified model. This tank shows a gradual decline in total chlorine concentrations with time. The levels in the model do not drop to values of concern, and appear to have reached steady state conditions after 10/30. This, coupled with the stratified three compartment model indicates that this tank is able to maintain substantial chlorine residuals. The tank was not sampled after the October 19th visit to the tank, so no field measurements are available to validate this model.

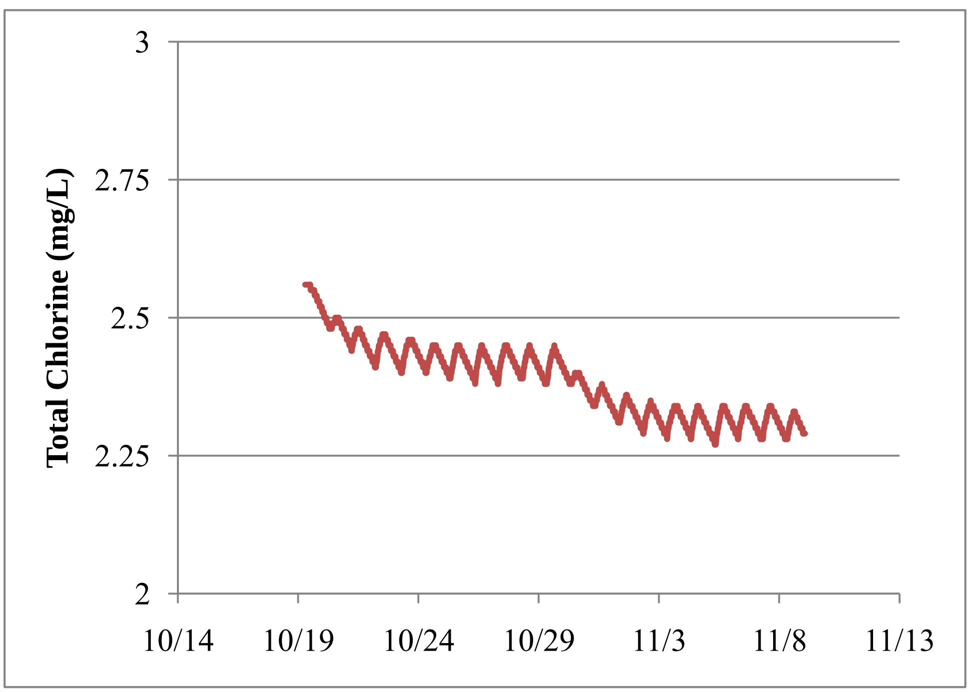


Figure 4.55. Completely mixed model for long term tank C.

4.8.4 Long Term Tank D

Long term tank D appeared to fluctuate between stratified and unstratified conditions and became well mixed near the end of the study. Two models were created for long term tank D, one under stratified conditions, and one under unstratified conditions.

The stratified model was created for the time period from 8/17 until 9/26. Model inputs included: initial volume, total chlorine concentration, and decay rate for the main, inlet, and dead zones, as well as flow rates into the tank, out of the tank, and between zones. Inflow and outflow rates were calculated using water level data provided by the water system and actual data for each fill and draw cycles were used in the model. Average flow rates and other model parameters are presented in Table 4.14.

Table 4.14. Inputs for the stratified long term tank D model.

Model Input	Inlet Zone	Main Zone	Dead Zone
Volume	0.02 Mgal	0.02 Mgal	0.12 Mgal
Initial total chlorine concentration	1.14 mg/L	1.14 mg/L	1.14 mg/L
Decay coefficient	0.06 d^{-1}	0.06 d^{-1}	0.06 d^{-1}
Average inflow rate	33.7 gpm		
Average outflow rate	24.0 gpm		
Inflow concentration	1.83 mg/L		
Flow rate between main and dead zone	0 gpm		
Flow rate between inlet and main zone	0 gpm		

The results of the stratified model for long term tank D are shown in Figure 4.56.

The model predicted a substantial decline in total chlorine in the dead zone which was modeling the concentrations in the tank above the thermocline. This corresponds with data collected; however the extent of the loss of residual is slightly underestimated on 8/25, and overestimated on 9/17. Reasons for the higher predicted concentration on 8/25 could be:

- Uncertainty in the decay constant, as the rate used is for 20 degrees C water, while the actual temperature in the tank was closer to 27 degrees (decay rate is faster at higher temperatures)
- If nitrification had occurred in this tank, the presence of AOB, NOB, and possibly nitrite could increase chlorine demand
- Water filling the tank over the period of time may not have always been 1.83 mg/L

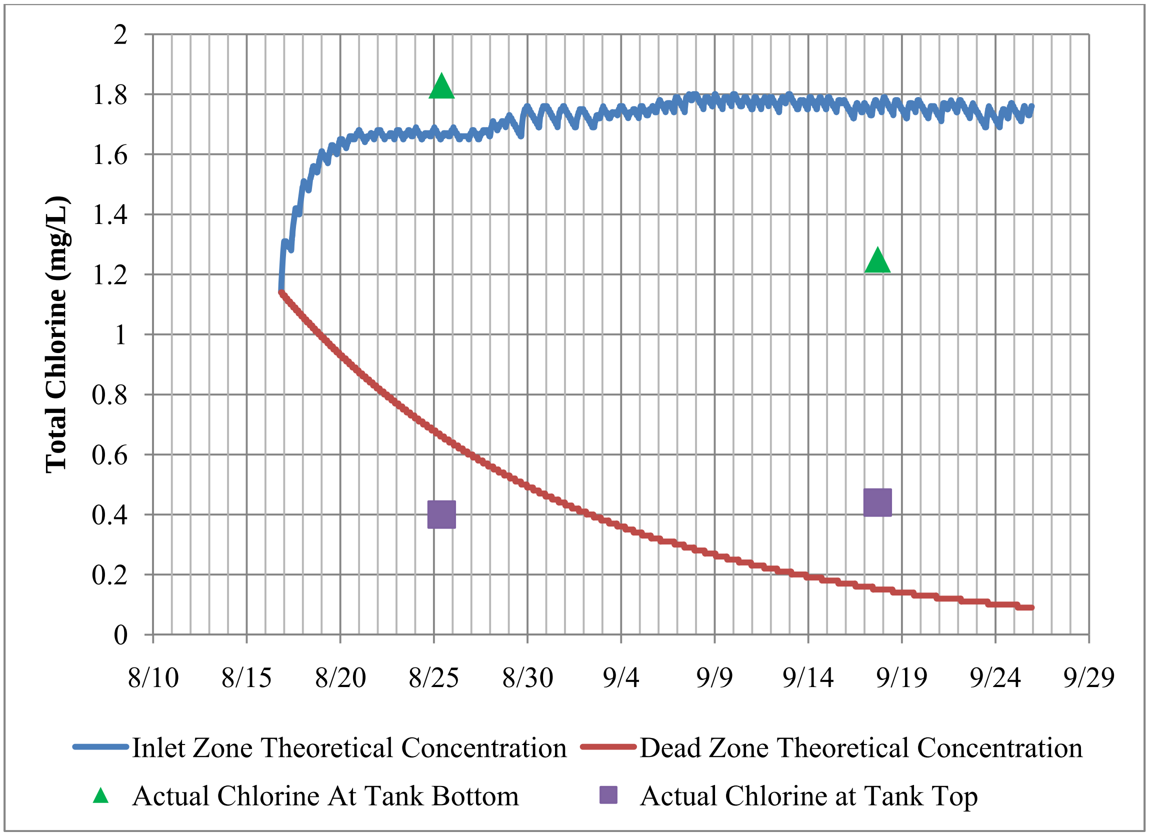


Figure 4.56. Stratified model for long term tank D.

The higher actual concentration than predicted on 9/17 is likely the result of some degree of mixing between the two compartments. Referring to the temperature profile of long term tank D (Figure 4.13), the temperature in the upper zone came closer to that of the inlet zone briefly between 8/25 and 9/17, which could have caused water from the inlet zone to mix with the dead zone. If this mixing had occurred, the inlet zone would decrease in concentration, and dead zone would increase, which coincides with data collected on 9/17.

Model residuals in the inlet zone increase in concentration, as a result of the filling water being higher in concentration than the initial concentration, and reach a steady state slightly below 1.8 mg/L, while the concentration of the filling water is 1.83 mg/L.

Long term tank D was modeled again under completely mixed conditions to represent the later portion of the study, when temperatures between the upper zone and inlet zone had had converged. Model inputs for the completely mixed conditions included: initial tank volume, initial tank concentration, decay rate, inflow rate, inflow concentration, and outflow rate. Inflow and outflow rates were calculated using water level data provided by the water system, and actual data for each fill and draw cycle were input into the model. Average flow rates and other model inputs are presented in Table 4.15.

Table 4.15. Inputs for the completely mixed long term tank D model.

Model Input	**Value**
Initial tank volume	0.16 Mgal
Initial total chlorine concentration	1.07 mg/L
Decay coefficient	0.04 d^{-1}
Average inflow rate	33.2 gpm
Average outflow rate	25.1 gpm
Inflow concentration	1.18 mg/L

The results of the model created for the completely mixed conditions of long term tank D may be seen in Figure 4.57. Under completely mixed conditions, the model reached a steady state total chlorine concentration of approximately 0.9 mg/L, which was a vast improvement over the stratified condition, where concentrations were modeled to drop to below 0.1 mg/L. The tank was not sampled after the October 20th visit to the tank, so no field measurements are available to validate this model.

The results of the modeling for long term tank D show that for stratified conditions, the tank can pose a risk for low residuals, but under completely mixed conditions, the risk is minimized.

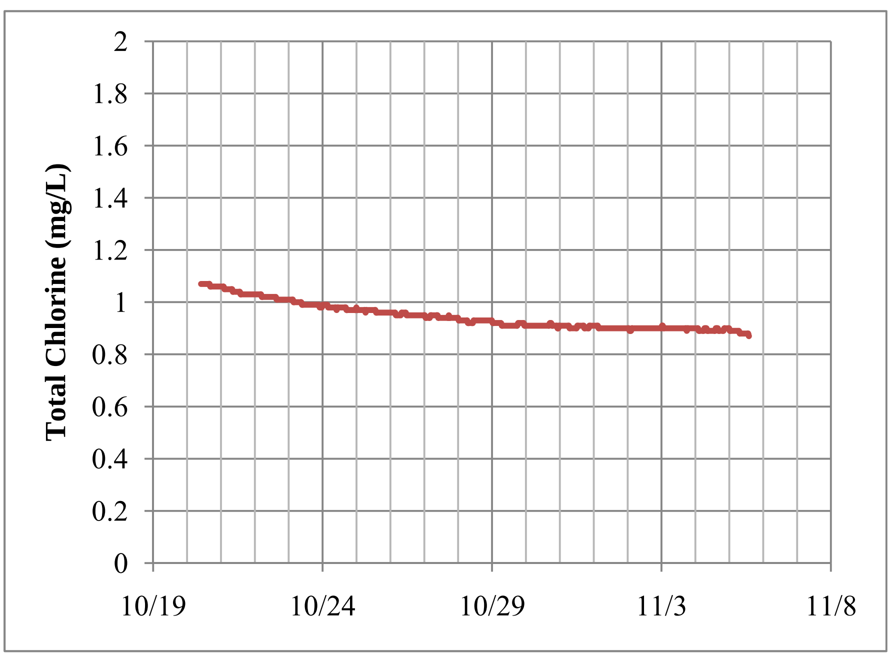


Figure 4.57. Completely mixed model for long term tank D.

4.8.5 Long Term Tank E

Similar to long term tanks C and D, two models were created for long term tank E, one under stratified conditions, and one under unstratified conditions.

The stratified model was created for the time period from 8/27 until 10/8. Model inputs included: initial volume, total chlorine concentration, and decay rate for the main, inlet, and dead zones, as well as flow rates into the tank, out of the tank, and between zones. Inflow and outflow rates were calculated using water level data provided by the water system and actual data for each fill and draw cycles were used into the model. Average flow rates and other model inputs are presented in Table 4.16.

Table 4.16. Inputs for the stratified long term tank E model.

Model Input	Inlet Zone	Main Zone	Dead Zone
Volume	0.03 Mgal	0.04 Mgal	0.07 Mgal
Initial total chlorine concentration	1.25 mg/L	1.25 mg/L	1.25 mg/L
Decay coefficient	0.06 d^{-1}	0.06 d^{-1}	0.06 d^{-1}
Average inflow rate	72.6 gpm		
Average outflow rate	37.5 gpm		
Inflow concentration	1.27 mg/L		
Flow rate between main and dead zone	0 gpm		
Flow rate between inlet and main zone	0 gpm		

The results of the model created for long term tank E under stratified conditions are shown in Figure 4.58.

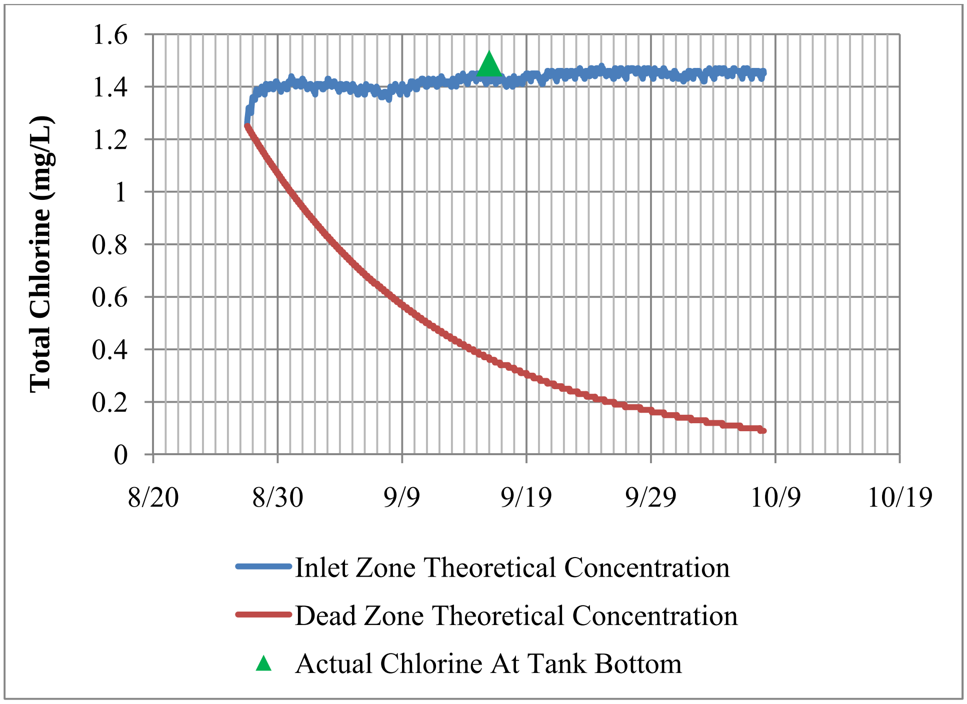


Figure 4.58. Stratified model for long term tank E.

The stratified model for long term tank E showed that the tank takes approximately one week for the total chlorine to decay from 1.24 mg/L to below 1.0 mg/L, and one presents similar results to tank D, in that should the tank remain in stratified conditions, the total chlorine residual will drop to levels of concern.

The tank was modeled again under completely mixed conditions to represent the later portion of the study, when temperatures between the upper zone and inlet zone had had converged. Model inputs for the completely mixed conditions included: initial tank volume, initial tank concentration, decay rate, inflow rate, inflow concentration, and outflow rate. Inflow and outflow rates were calculated using water level data provided by the water system, and actual data for each fill and draw cycle were input into the model. Average flow rates and other model inputs are presented in Table 4.17.

Table 4.17. Inputs for the completely mixed long term tank E model.

Model Input	**Value**
Initial tank volume	0.13 Mgal
Initial total chlorine concentration	1.27 mg/L
Decay coefficient	0.04 d^{-1}
Average inflow rate	70.7 gpm
Average outflow rate	35.6 gpm
Inflow concentration	1.39 mg/L

The results of the model created for the completely mixed conditions of long term tank E may be seen in Figure 4.59.

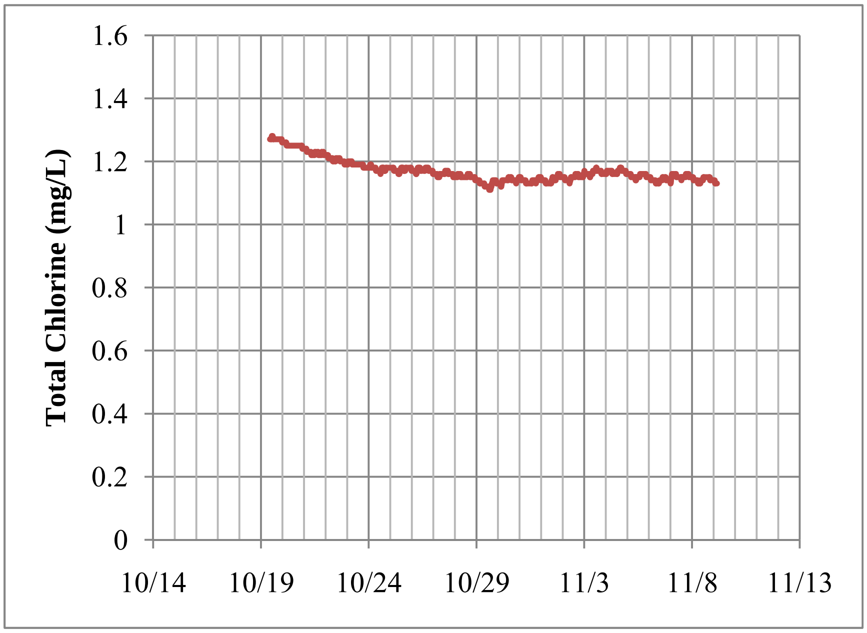


Figure 4.59. Completely mixed model for long term tank E.

Under completely mixed conditions, the tank reaches a steady state total chlorine concentration of just below 1.2 mg/L. This is a vast improvement over the stratified condition, where concentrations were modeled to drop to below 0.1 mg/L. The results of the modeling for long term tank E are similar to tank D by showing that for stratified conditions the tank can pose a risk for low residuals, but under completely mixed conditions, that risk can be mitigated.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary of Work Tasks

The results obtained from evaluations of storage facilities in regional water systems were evaluated to provide information to systems optimize their tanks. A survey was sent to rural water systems and representative above-ground tanks were selected for long term study. Additional tanks were chosen for short term study based on interest from sponsor systems. Apparatuses were constructed to draw samples from various depths in long term tanks as well as to measure temperatures at various depths in long and short term tanks. Water level data was provided by systems operating long term tanks, or from the apparatus itself in the case of short term tanks. Total chlorine and temperature data were plotted to show variations in chlorine residual and temperature relative to depth in tanks. Short term tank temperature profiles were compared to those of long term tanks to show whether tank water quality and mixing behavior can be associated with tank geometry.

Several parameters were calculated for each tank to provide information related to tank mixing including the operational aspect ratio, Reynolds number, fill time (and volumetric exchange) required to meet a 90% mix, critical temperature difference between the filling water and water in the tank to cause stratified conditions, densimetric Froude number, a dimensionless parameter illustrated in Roberts et al. (2006), and detention time.

Empirical relationships were developed to relate temperature in the upper zones of standpipes with aspect ratios greater than 3.5 to temperature outside of the tank. Systematic modeling of tanks estimated the residual disinfectant concentrations under stratified and unstratified conditions.

5.2 Conclusions

The following conclusions were made after evaluating data gathered in this project.

1. **Typical tank types in South Dakota's rural water systems**

Based on a survey sent to regional water systems in South Dakota, types of tanks were delineated into categories based on both number of tanks and total storage volume. Of these tanks, 22% were aboveground reservoirs and 29% standpipes. The 22% of tanks in the aboveground reservoir category accounted for 53% of the total storage volume, and the 29% in the standpipe category accounted for 13% of the total storage volume.

2. **Affects of tank geometry on mixing**

Long term tanks A and B (operational H:D = 0.13 and 0.54, respectively) both exhibited good mixing characteristics based on temperature and water quality profiles.

Long term tank A chlorine concentrations did not vary substantially with respect to depth, but changed on different dates (ranging from 0.14 to 0.6 mg/L). Tank B total chlorine concentrations did not vary substantially with respect to depth during both times the tank was sampled and were approximately 1 mg/L. Long term tanks A and B were in the aboveground reservoir (H:D < 1) category which would lead one to believe that all tanks in this category are well mixed. However, some short term tanks which had aspect ratios less than 1.0 exhibited stratification as a result of a lack of volumetric exchange and inflow momentum (especially short term tanks 2 and 3). Even though the geometry of low aspect ratio tanks promotes mixing, they should be designed and operated with appropriate volumetric exchange and inflow momentum to enhance mixing.

Long term tank C (operational H:D of 0.88) presented defined temperature stratification in August, with a 10 ^{o}C difference in temperature between the top and bottom of the tank. However the operations of tank C achieved sufficient volumetric exchange to mix the tank as indicated by chlorine residuals throughout the tank depth. Total chlorine residuals in tank C ranged from 1.94 to 2.56 mg/L, indicating that even thermally stratified tanks can maintain adequate chlorine residuals.

Long term tanks D and E (H:D > 3.55) presented substantial mixing issues in August as a result of warmer water in their upper zones compared to the lower zone (the upper zone was 15 ^{o}C warmer in tank D and 7 ^{o}C warmer in tank E). Before any operational attempts to destratify the tank, the water in the warmer, upper zone of tank E contained 0.07 mg/L of total chlorine, while its bottom zone contained 0.92 mg/L. Similarly, prior to any operational de-stratification attempts, total chlorine concentrations in the warmer, upper zone of tank E ranged from 0.11 to 0.16 mg/L, while the chlorine concentrations at the bottom zone ranged from 1.26 to 1.31 mg/L. These tanks were stratified from both temperature and water quality standpoints. Short term tank data for similar aspect ratio tanks reinforced the long term tank data. The water in the top zone of short term tank 1 (H:D of 4.82) was 8 ^{o}C warmer than the bottom zone, and chlorine residuals were 0.94 mg/L at the bottom compared to 0.05 mg/L at the top. The presence of thermal stratification and depleted chlorine residuals in the upper zones of these tanks indicate that tanks with aspect ratios greater than 3.5 are at risk for poor mixing and water quality.

Based on temperature and chlorine residual profiles from tanks examined in this study, shorter, wider tanks were less susceptible to poor mixing and stratification than standpipes. While tanks with smaller aspect ratios lends to better mixing, their design and operation must still be optimized to enhance mixing.

3. Impacts of ambient temperature on water quality in tall standpipes

A visual interpretation of long term temperature data indicates that the water temperature and water quality of standpipes with aspect ratios greater than 3.5 are strongly influenced by the ambient temperature (Figures 4.50 and 4.51). When the ambient temperature (outside the tank) is greater than approximately 15^{0} C, the water in these standpipes tends to stratify, resulting in increased rates of chlorine decay in the upper, warmer zone. When the temperature of the upper zones of tanks are similar to that of the water filling the tank, buoyant forces are minimized allowing tanks to mix more readily, enabling uniform chlorine residual throughout the tank depth. Stratified tanks examined in this study tended to destratify when the temperature outside of the tank reached 15 degrees C (average of the daily high and low temperatures) on a consistent basis.

4. Reynolds numbers of filling jets

The Reynolds of the water jets filling the tanks were all above the threshold of 3,000 to ensure that a mix-promoting turbulent jet occurs. The lowest Reynolds number recorded was 3,670, which occurred in short term tank 1, and the lowest average Reynolds number was 6,010 and occurred in short term tank 2. Maintaining the Reynolds number greater than 3,000 was not sufficient to mix all tanks examined in the study.

5. How fill time and volumetric exchange affects mixing

All tanks which achieved the required filling time and associated volumetric exchange ratio were well mixed from residual disinfectant standpoints. Long term tanks A, B, and C were all well mixed and achieved 341%, 209%, and 214% of their required volumetric exchange, respectively.

Long term tank C achieved more than twice its required volumetric exchange during filling cycles, and although it presented evidence of stratification, tank C maintained adequate disinfectant residuals within the tank (1.94 mg/L to 2.26 mg/L). During the warm summer months, tanks which did not meet the required volumetric exchange exhibited stratification.

It is easier to meet volumetric exchange requirements in a ground storage tank compared to a standpipe of the same volume. The water level change in a standpipe required to meet the required change in volume would draw the tank down much farther than for a ground storage tank. The increased drawdown for a standpipe may cause pressure problems and insufficient storage in the system.

6. Critical temperature difference to cause stratification

The critical temperature difference to cause stratification was higher for tanks which were well mixed, compared to that of poorly mixed tanks. For example, long term tank A would have required a 2.2 ^{0}C difference in temperature between the tank volume and filling water to stratify, while tank E would require a 0.0079 ^{0}C difference. Tank E, however appeared well mixed relative to its total chlorine profile (1.22 to 1.39 mg/L throughout the entire tank) when the filling water was 1 ^{0}C cooler than the tank contents. Tank E was mixed even though the measured temperature difference between the filling and stored water was considerably higher than the theoretical temperature to cause stratification, indicating that this parameter might be only suited for qualitative, rather than quantitative analyses. It should be noted that the equation which was used to calculate this parameter was proven using tanks whose aspect ratios were less than 1.0, which leads to uncertainty when using this parameter with standpipes.

7. **Densimetric Froude number**

The densimetric Froude number required to overcome stratified conditions in a tank was calculated for each tank. Long term tanks A and B, as well as short term tank 7 were all well mixed and achieved 251%, 196%, and 152% of their required densimetric Froude numbers, respectively.

With the exception of short term tank 8 (unstratified tank but only met 50% of its required densimetric Froude number), all tanks which did not meet the required densimetric Froude number experienced some degree of stratification, indicating tanks designed and operated to achieve the required densimetric Froude number would be well mixed. The densimetric Froude number can be increased by maximizing the velocity of the filling water, which can be accomplished by increasing flow rates or decreasing inlet diameters. Additionally, by drawing water levels to a low level, the required densimetric Froude number can be reduced.

8. **Dimensionless mixing parameter**

The dimensionless mixing parameter ($M^{1/2}/(B^{1/3}H^{2/3})$) presented in Roberts et al. (2006) was maintained above the required threshold in the tanks which did not present any evidence of stratification. Long term tank A required a dimensionless mixing parameter of 1.3 to be mixed, and achieved a value of 1.3. Long term tank B and short term tank 7 each achieved dimensionless mixing parameter values of 1.5, compared to 0.8 which was required to mix the tanks.

For all other tanks which were studied, the average value of the dimensionless mixing parameter was below the threshold required to ensure complete mixing. When the temperature of the upper zone of the tank became more consistent with that of the filling water, some values of the dimensionless mixing parameter for long term tanks C and E increased above the threshold to ensure complete mixing. When the value of the dimensionless mixing parameter was above the threshold, tanks C and E both appeared well mixed from a temperature profile standpoint. The occurrence of complete mixing in tanks which met the required value of the dimensionless mixing parameter indicates that designing and operating tanks to achieve the required value should result in well mixed tanks. The dimensionless mixing parameter can be increased by maximizing the inlet momentum or decreasing the initial water level prior to a fill cycle. Inlet momentum can be increased by either increasing flow rates or velocity (or both). Inflow velocity can be increased by decreasing inlet diameters.

9. **Tank detention time**

Tank detention time can be used as a measure of water age in tanks which are completely mixed. The literature review presented guidelines for optimizing detention time in water storage tanks, which recommended maximum detention times ranging from one to seven days. Average detention times for the tanks examined in this study ranged from 1.94 days (short term tank 7) to 16.45 days (short term tank 6).

10. Modeling

Models based on the CompTank software package were used to predict chlorine residuals in various zones of tanks, both stratified and completely mixed. The results of those models indicate that with more accurate representations of input parameters (from further studies), chlorine residual decay can be modeled.

CHAPTER 6: OPERATION AND DESIGN CONSISDERATIONS FOR TANKS

The following are operation and design considerations based on field data and data analyses performed in this study.

1. Tall standpipes appear to experience the most prevalent stratification, and therefore experience water quality problems. As a result these tank types should be avoided when new tanks are designed, unless supplemental mixers designed for use in storage facilities are provided.

2. Tanks which are found to experience water quality problems as a result of stratification may be drained into the distribution system before disinfectant residuals reach levels of concern, and then refilled with newer water, likely containing more disinfectant.

3. Of the hydraulic parameters, the densimetric Froude number, dimensionless mixing constant from Roberts et al. (2006), and volumetric exchange during fill cycles were found to be the most effective in predicting the potential for stratification. Tanks can be optimized to enhance mixing by reducing inlet diameters to increase the momentum of the inflow and by maximizing volumetric exchange during fill cycles. Designs incorporating a reduction in inlet diameter would require the modification of pump design to include the additional head loss associated with the inlet contraction.

4. Although not examined in this study, tanks with poor mixing and potential water quality problems can be mixed using commercial artificial mixers or check valve systems.

5. Systems desiring knowledge of storage tank water quality should collect samples from both the top and bottom of the tank to monitor water quality throughout the entire tank contents.

CHAPTER 7: RECOMMENDATIONS FOR FUTURE WORK

During the course of this research, opportunities for further study to improve the understanding of how tank behavior can impact water quality became apparent. Recommendations on how future work can to address these considerations are presented in this section.

1. Further study of the water quality issues associated with standpipes which lose their chlorine residuals during the warm seasons should be performed to examine impacts of chlorine loss on microbial water quality and disinfection byproduct formation.

2. The affects of mixing in the horizontal direction of shorter, wider tanks should be evaluated, as dead zones could persist at different points in the tank than just the vertical direction.

3. More detailed evaluations of the effects of changing tank operations on mixing should be performed. These evaluations should assess the effects of changing a tanks volumetric exchange ratio on mixing.

4. To improve the modeling of tanks, additional data should be gathered from tanks including:

- More frequent site visits should occur to collect total chlorine residual data enabling more accurate calculations of disinfectant decay coefficients
- Water samples should be taken from the inflow pipe and analyzed for temperature and water quality parameters, enabling the actual concentration of chlorine in the filling water to be used in the model
- If more accurate representations of compartment sizes are desired, a tracer study would be required.

REFERENCES

Baribeau, H., Kranser, S.W., Chinn, R., and Singer, P.C., (2005) “Impact of Biomass on the Stability of HAAs and THMs in a Simulated Distribution System.” *Journal of the American Water Works Association* 97(2), 69-81.

Boorman, G. A., Dellarco, V., Dunnick, J. K., Chapin, R. E., Hunter, S., Hauchman, F., Gardner, H., Cox, M., and Sills, R. (1999). “Drinking Water Disinfection Byproducts: Review and Approach to Toxicity Evaluation.” *Environmental Health Perspectives*, 107, Supplemental 1:207.

Boulos, P. F., Grayman, W. M., Bowcock, R. W., Clapp, J. W., Clapp., Rossman, L. A., Clark, R. M., Deininger, R. A., and Dhingra, A. K., (1996). “Hydraulic Mixing and Free Chlorine Residual in Reservoirs”. *Journal of the American Water Works Association*, 88(7), 48-59.

Chen, J.C., and Weisel, C.P. (1998). “Halogenated DBP concentrations in a Distribution System.” *Journal American Water Works Association*, 90(4), 151-163.

Clark, R. M., Abdesaken, F., Boulos, P. F., and Mau, R. E., (1996). “Mixing in Distribution System Storage Tanks: It’s Effect on Water Quality.” *American Society of Engineers Journal of Environmental Engineering*, 122(9), 814-821.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., and Tchnobanoglous, G., (2005). Water Treatment: Principles and Design, 2nd ed., John Wiley and Sons, Inc., New Jersey, 1543.

Drews Nelson, A. (2010). “Blending Chlorinated and Chlorminated Water in a Regional Water Supply System.” Masters Degree Thesis, South Dakota State University, Brookings, SD, 158-159.

Edwards, J., and Maher, J. (2008). “Water Quality Considerations for Distribution System Storage Facilities.” *Journal of the American Water Works Association*, 100(7), 60-65.

Fischer, H.B., List, E.J., Koh, R.C.Y, Imberger, J., and Brooks, N.H., (1979). Mixing in Inland and Coastal Waters. Academic, New York.

Giguere, R., and Fiske, P.S., (2010) “CFD Modeling and Assessment of Active Mixing in Large Volume Distribution Storage Facilities” *Proceedings of the American Water Works Association Annual Conference and Exposition Chicago Ill, June 20-24, 2010.*

Grayman, W. A., Rossman, L. A., Deininger, R. A., Smith C. D., Arnold, C. N., and Smith, J. F. (2004). “Mixing and Aging of Water in Distribution System Storage Facilities.” *Journal of the American Water Works Association*, 18(9), 70-80.

Grayman, W. A., Rossman, L. A., Arnold, C, Deininger, R. A., Smith, C., Smith, J. F., and Schniphe, R. (2000). “Water Quality Modeling of Distribution Storage Facilities.”, *American Water Works Association Research Foundation,* Denver.

Gyürék, L.L., and Finch, G.R., (1998) “Modeling Water Treatment Chemical Disinfection Kinetics.” *American Society of Engineers Journal of Environmental Engineering,* 124(9):783-793.

Hack, D. J., (1984), “State Regulation of Chloramine.” *Journal American Water Works Association* 77:1:4

Haestad Methods, (2003). Advanced Water Distribution Modeling and Management, 1st Ed. Waterbury, CT, Haested Press, pp 57.

Harrington, G., Noguera, D., Bone, C., Kandou, A., Oldenburg, P., Regan, J., Van Hoven D. (2003). “Ammonia From Chloramine Decay: Effects on Distribution System Nitrification.” *University of Wisconsin-Madison CEE Dept. and American Water Works Association Research Foundation*. Denver, CO.

Isaac R. A. and Morris, J. C. (1983), “Rate of Transfer of Active Chlorine Between Nitrogen Substrates.” *Water Chlorination: Chemistry, Environmental Impacts and Health Effect,* Col. 3
Ann Arbor Science Publ. Ann Arbor Mich.

Jones, J.B. (2002). “Mass Transfer Reactions and Decay Sinks for Disinfectants in Water Distribution Systems.” Ph.D. Dissertation, Old Dominion University, Norfolk Va.

Kasco Marine. Water Circulators. available online at: <http://www.kascomarine.com/products/water_circulators.html> (accessed April 3rd 2011).

Kennedy, M.S., Moegling, S., Sarikelle, S., and Suravallop, K. (1993). “Assessing the Effects of Storage Tank Design on Water Quality.” *Journal of the American Water Works Association*, 85:7:78.

Kirmeyer, G.J., Odell, L.H, Jacangelo, J.J, Wilczac, A., and Wolfe, R. (1995). “Nitrification Occurrence and Control in Chloraminated Water Systems” *American Water Works Association Research Foundation*, Denver.

Lee, J. H., and Jirka, G. H., (1981). “Vertical Round Buoyant Jets in Shallow Water.” *American Society of Engineers Journal of Hydraulic Engineering*, 107(12), 1651-1657.

Moran, M J., Shapiro, H N., Munson, B R., and DeWitt, D P., (2003). Introduction to Thermal Systems Engineering. Wiley, Hoboken, NJ.

Mahmood, F. et al. (2005) “Evaluation of Water Mixing Characteristics in Distribution System Storage Tanks.” *Journal of the American Water Works Association*, 97:3:74

Martel, K. D., Kirmeyer, G. J., Murphy, B. M., Noran, P. F., Kirby, L., Lund, T. W., Anderson (2002), Preventing Water Quality Deterioration in Finished Water Storage Facilities., *Journal of the American Water Works Association* 94:4, 139-148.

Mahmood, F., Pimblett, J., Hill, C., and Chowdhury, Z., (2009) “CFD Modeling and Spreadsheet Tool to Evaluate Mixing and Water Quality in Storage Tanks.” *Proceedings of the American of the Water Works Association Annual Conference San Diego CA, June 2009*.

Mau, R. E., Boulos, P. F., and Clark, R. M., (1995). “Multi-Compartment Models of Distribution Storage Water Quality.” *Proceedings of the American Water Works Association Computer Conference Norfolk VA, April 2-5 1995*, 147-179.

McNaughton, K. J., and Sinclair, C. G. (1966). “Submerged Jets in Short Cylindrical Flow Vessels.” *Journal of Fluid Mechanics*., Cambridge, U.K., 25(2), 367-375.

Mills, A.F. (1995).Basic Heat and Mass Transfer, Richard D Irwin Inc., Concord, MA.

Regan, J., Cho, A., Kim, S., Smith, C. (2007). “Monitoring Ammonia-Oxidizing Bacteria in Chloraminated Distribution Systems.” *American Water Works Association Research Foundation.* Denver, CO.

Reynolds, T., and Richards, P. (1992). Unit Operations and Processing in Environmental Engineering, 2nd Ed., PWS Publishing Company, Massachusetts, pp 181.

Roberts, J. W., Tian, X., and Sotiropoulos, F., (2006). “Physical Modeling of Mixing in Water Storage Tanks.” *American Water Works Association Research Foundation*., Denver.

Rossman, L. A. and Grayman, W. M., (1999) “Scale Model Studies of Mixing in Drinking Water Storage Tanks.” *American Society of Engineers Journal* of *Environmental*, 125(8), 755-761.

Sawyer, C. N., McCarty, P. L., and Parkin, G. F., (2003). Chemistry for Environmental Engineering and Science, 5th Ed., McGraw Hill, New York, NY.

Speight, V.L., and Singer, P.C. (2005). "Association Between Residual Chlorine Loss and HAA Reduction in Distribution Systems." *Journal of the American Water Works Association*,97(2), 82-91.

USEPA (2009) National Primary Drinking Water Regulations: Disinfectants and Disinfection Byproducts, Volume 74, Number 123, pages 31032-31033.

USEPA (1989) National Primary Drinking Water Regulations: Total Coliforms (Including Fecal Coliforms and E. Coli), Volume 54, Number 124, pages 31032-31033.

USEPA (1998) National Primary Drinking Water Regulations: Disinfectants and Disinfection Byproducts, Volume 63, Number 241, pages 27544-27568.

Valentime R. L., C.t. Jafvert, and S. W. Leung. 1988. Evaluation of a Chloramine Decomposition Model Incorporating General Acid Catalysis. *Water Research*, 22(9):1147-1153.

Valentine R. L., K. Ozekin, and P.J. Vikesland. 1998. Chloramine Decomposition in Distribution System and Model Waters. *American Water Works Association Research Foundation.* Denver, CO.

White, F M. (2008). Fluid Mechanics, 6th Ed. New York, NY: McGraw-Hill.

Wilczac, A., Jacangelo, J. G., Marcinko, J. P., Odell, L. H., Kirmeyer, G. J., and Wolfe, R. L., (1996) "Occurrence of Nitrification in Chloraminated Distribution Systems." *Journal of the American Water Works Association* 88(7), 74-85.

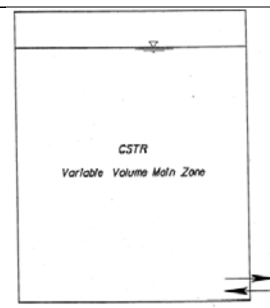
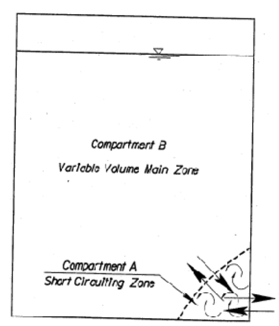
Wilczac A.J., Ardeshir, A., lai, H.H., Hoover, L.L, Smith, J.F., Berger, R., Rodigari, F., Beland, J.W., Lazzelle, L.J., Kincannon, E.G., Baker, H., and Heaney, C.T., (2003), "Formation of NDMA in Chloraminated Water Coagulated With DADMAC Cationic Polymer." *Journal of the American Water Works Association* 95(9), 94-106.

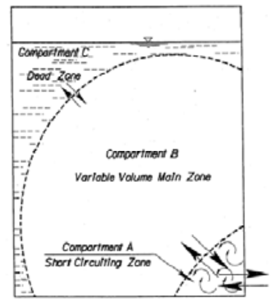
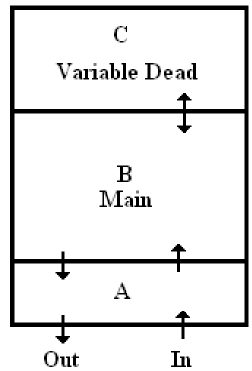
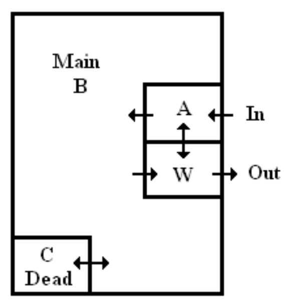
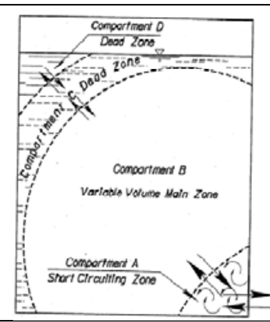
Wolfe, R.L.; Ward, N.R.,; and Olson, B H. (1985), "Interference in the Bactericidal Properties of Inorganic Chloramines by Organic Nitrogen Compounds." *Environmental Science and Technology.*, 19(12), 1192-1195

APPENDIX A

SYTEMATIC MODELS FOR MIXING IN STORAGE TANKS

Table A.1. Systematic Models for Mixing Characteristics in Storage Tanks.

Name of Model	Description of Model	Figure	Reference
Plug flow model	A Plug flow reactor (PFR) is also known as a first in-first out (or last in last out). In an ideal plug flow case, no mixing occurs within the tank, and each fluid particle remains independent of surrounding fluid particles. Plug flow reactors are most commonly found in treatment plants, rather than storage facilities in the distribution system.		
Mixed Flow Model	A mixed flow model assumes that the tank is constantly mixed at all times. It can be described as a continuously stirred tank reactor (CSTR).		Mau et al. (1995)
Two-compartment model	In a two-compartment model, the tank is divided into two regions, compartments A and B. Both of these compartments are modeled as individual CSTRs. The volume of compartment A is fixed, while B is variable. The inflow to the tank enters compartment A, while compartment B either increases in volume, receiving flow from A, or transfers water to A depending on the flow conditions.		Mau et al. (1995)

Three-compartment model	In a three-compartment model, a third region (compartment C) is added to the two-compartment model to represent a dead storage zone in the tank. The volume of compartments A and C are assumed to be constant, while B is variable. The addition of the third compartment adds a fixed flow between B and C to the model.		Mau et al. (1995)
Stratified three-compartment model	An additional three-compartment model was developed to better represent a study with stratified reservoirs. The only difference between this and the original three-compartment model is the variable zone is changed from compartment C to compartment A.		Mau et al. (1995)
Three-and-one half-compartment model	The three- and-one-half model was developed to represent a continuous inflow/outflow condition. The name for this model was created to prevent confusion with a four-compartment model developed by Mau et al. (1995). Compartment B is considered the variable zone, while all others are fixed, with the following image showing all the flows between compartments. Compartment C is set as the dead zone.		Grayman et al. (2000)
Four-compartment model	The four-compartment model was developed to provide a representation for tanks containing extreme dead storage. This is represented by adding an additional compartment as a buffer zone between the main compartment and the dead zone.		Mau et al. (1995)

APPENDIX B

CALCULATIONS

Data points used in several following calculations are presented in Table B.1.

Table B.1. Data points used in sample calculations for mixing parameters.

	Time	**Water Level**
Start of fill	T_{SF} = 8/9/10 07:20	L_{SF} = 14.60 ft
End of fill	T_{EF} = 8/9/10 20:05	L_{SF} = 21.50 ft
End of draw	T_{ED} = 8/10/10 07:40	L_{SF} = 15.80 ft

Temperature at top of tank: 28.39^{O} C
Temperature at bottom of tank: 18.21^{O} C
Tank diameter = 20 ft
Inlet diameter = 6 inches

Aspect ratio of water column

$$Aspect\ ratio = \frac{(L_{SF} + 0.5(L_{EF} - L_{SF})}{(D_T)}$$

$$Aspect\ ratio = \frac{(14.6\ ft + 0.5(21.5\ ft - 14.6\ ft)}{(20\ ft)}$$

$$Aspect\ ratio = 0.90$$

Flow Rate

$$Q_{fill} = \frac{(L_{EF} - L_{SF}) * \frac{\pi D_T^2}{4}}{(t_{EF} - t_{SF}) * 86{,}400}$$

$$Q_{fill} = \frac{(21.5\ ft - 14.6\ ft) * \frac{\pi 20^2}{4}}{(8/9/10\ 20{:}05 - 8/9/10\ 07{:}20) * 86{,}400}$$

$$Q_{fill} = 0.047\ cfs$$

Velocity of inflow

$$v = \frac{Q_{fill}}{\left(\frac{\pi d_i^2}{4}\right)}$$

$$v = \frac{0.047\ cfs}{\frac{\pi \left(\frac{6\ in}{12}\right)^2}{4}}$$

$$v = 0.24\ ft/s$$

Reynolds Number

$$Re = \frac{\rho V d_i}{\mu}$$

$$\rho = \frac{1}{515.379}(1000 - 0.0178(T-4)^{1.7})$$

$$\rho = \frac{1}{515.379}(1000 - 0.0178(18.21-4)^{1.7})$$

$$\rho = 1.9372\ \frac{slug}{CF}$$

$$\mu = 1.201 * 10^{-3} e^{-1.704 - 5.306\frac{273}{273+T} + 7.003\left(\frac{273}{273+T}\right)^2}$$

$$\mu = 1.201 * 10^{-3} e^{-1.704 - 5.306\frac{273}{273+18.21} + 7.003\left(\frac{273}{273+18.21}\right)^2}$$

$$\mu = 7.12 * 10^{-4}\ \frac{ft * s}{lb}$$

$$Re = \frac{\left(1.9372\frac{slug}{CF}\right)\left(32.2\ \frac{lb}{slug}\right)\left(0.24\ \frac{ft}{s}\right)(0.5\ ft)}{1.72 * 10^{-4}\frac{ft*s}{lb}}$$

$$Re = 1.05 * 10^4$$

Detention time

$$DT = \left[0.5 + \frac{V}{\Delta V}\right](t_{Draw} + t_{Fill})$$

$$DT = \left[0.5 + \frac{(14.6\ ft)\frac{\pi 20^2}{4}}{(21.5\ \text{ft} - 14.6\ \text{ft})\frac{\pi 20^2}{4}}\right](8/10/10\ 07{:}40 - \ 8/9/10\ 07{:}20)$$

$$DT = 2.64\ days = 63.4\ hr = 2.64\ days$$

Time to reach 90% mix

$$t = \tau_m \frac{V^{2/3}}{M^{1/2}}$$

$$\tau_m = 10.0\ because\ aspect\ ratio = 0.90$$

$$V = \frac{\pi D_T^2}{4} H = \frac{\pi 20^2}{4} 14.6 = 4856.7\ ft^3$$

$$M = Qv = (0.047\ cfs)\left(0.24\frac{ft}{s}\right) = 0.0113\frac{ft^4}{s^2}$$

$$t = 10.0\frac{(4856.7\ ft^3)^{2/3}}{\left(0.0113\frac{ft^4}{s^2}\right)^{1/2}} = 26979\ s = 7.49\ hr$$

Derivation of Volumetric Exchange Required to Achieve a 90% Mixed Tank

The actual time that a tank takes to fill is characterized by the relationship t = ΔV/Q where ΔV is the change in tank volume during the fill cycle, and Q is the flow rate of the inflow. This time value must be greater than the result of Equation 10; so the result is:

$$\frac{\Delta V}{Q} = \tau_m \frac{V^{2/3}}{M^{1/2}}$$

Because the momentum is flow rate * velocity; the following applies:

$$\frac{\Delta V}{Q_{fill}} = \tau_m \frac{V^{2/3}}{(Q_{fill} v)^{1/2}}$$

substituting the equation for the velocity of the inlet,

$$\frac{\Delta V}{Q_{fill}} = \tau_m \frac{V^{2/3}}{\left(Q_{fill}\frac{Q_{fill}}{\left(\frac{\pi d_i^2}{4}\right)}\right)^{1/2}}$$

Q_{fill} cancels, and the following applies:

$$\Delta V = \tau_m \frac{V^{2/3}}{\left(\frac{\pi d_i^2}{4}\right)^{1/2}}$$

dividing each side by the volume yields

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2}\tau_m d_i}{2V^{1/3}}$$

For Long term tank C:

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2}(10)0.5\,ft}{2(4856.7)^{1/3}}$$

$$\frac{\Delta V}{V} > 0.26$$

Compared to the actual volumetric exchange ratio:

$$\frac{\Delta V}{V} = \frac{(21.5\,ft - 14.6\,ft)\frac{\pi 20^2}{4}}{(14.6\,ft)\frac{\pi 20^2}{4}} = 0.47$$

so the percentage of the required volumetric exchange attained is:

$$\frac{0.47}{0.26} = 1.8 = 180\%$$

Velocity gradient calculation for long term tank E

$$G = \sqrt{\frac{P}{(V\mu)}}$$

$$P = 0.75\ hp = 412.5\ ft * lb/s$$

$\mu = 2.344 * 10^{-5} lb * s/ft^2$ at 20 degrees C

$V = 19{,}406\ ft^3$ (17 ft diameter, 85.5 ft tall cylindrical tank)

$$G = \sqrt{\frac{412.5\ ft * lb/s}{\left((20{,}714\ ft^3) * (2.344 * 10^{-5} lb * \frac{s}{ft^2})\right)}} = 30.1\ s^{-1}$$

Special consideration for short term tank 5

Given: Water level ranges from 38 ft to 48 ft at outliers.

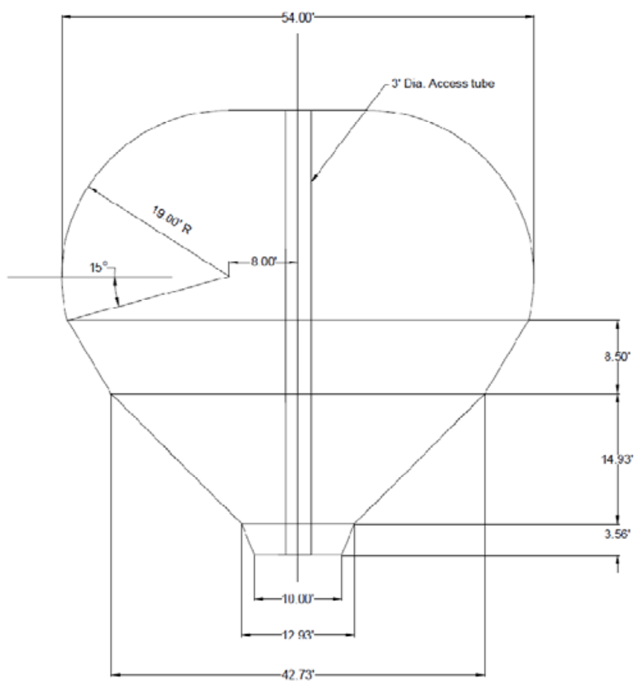
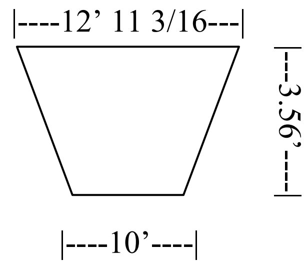


Figure B.1. Schematic of short term tank 5.

Find: Volume of tank related to water level in the tank.

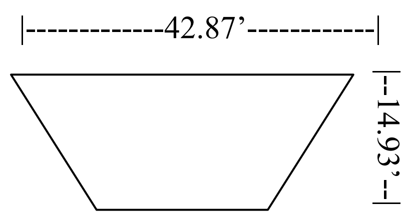
- Split the tank into five sections and calculate the volume of the bottom four
- Write an equation relating height above the widest diameter to volume in the top section
- Add all volumes together and subtract the tube through center

- Section A



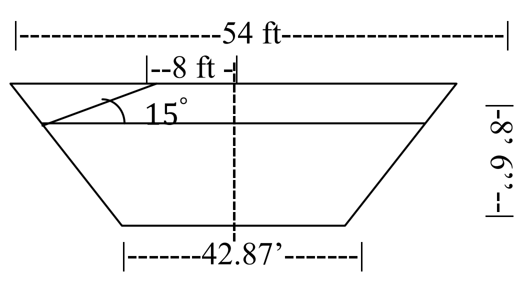
$$V = \frac{\pi \cdot h}{3} \cdot (R^2 + R * r + r^2)$$
$$= \frac{\pi \cdot 3.56}{3}\left[\left(\frac{10}{2}\right)^2 + \left(\frac{12.93}{2}\right) \cdot \left(\frac{10}{2}\right) + \left(\frac{12.93}{2}\right)^2\right]$$
$$= 363.3\ ft^3$$

- Section B



$$V = \frac{\pi \cdot h}{3} \cdot (R^2 + R * r + r^2)$$
$$= \frac{\pi \cdot (14.93)}{3} \cdot \left(\left(\frac{12.93}{2}\right)^2 + \left(\frac{12.93}{2}\right) \cdot \left(\frac{42.87}{2}\right) + \left(\frac{42.87}{2}\right)^2\right)$$
$$= 10003.57\ ft^3$$

- Section C



Top radius needs to be calculated.

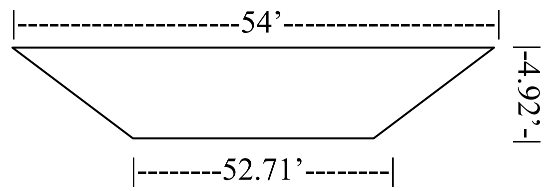
$$R = 2 \cdot (8\ ft + 19 \cdot \cos(15°)) = 52.71\ ft$$

$$V = \frac{\pi \cdot h}{3} \cdot (R^2 + R * r + r^2)$$

$$= \frac{\pi \cdot (8.5)}{3} \cdot \left(\left(\frac{42.87}{2}\right)^2 + \left(\frac{42.87}{2}\right) \cdot \left(\frac{52.71}{2}\right) + \left(\frac{52.71}{2}\right)^2 \right)$$

$$= 15300.8\ ft^3$$

- Section D



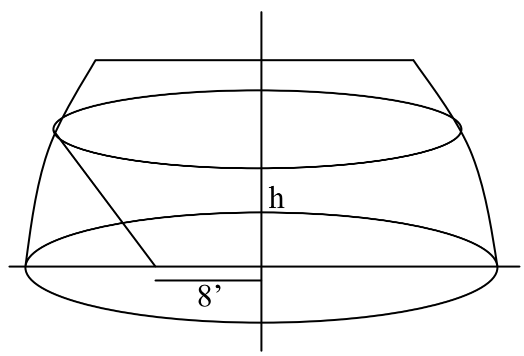
$$h = 19 \cdot \sin(15°) = 4.92\ ft$$

$$V = \frac{\pi \cdot h}{3} \cdot (R^2 + R * r + r^2)$$

$$= \frac{4.92 \cdot \pi}{3} \cdot \left(\left(\frac{52.71}{2}\right)^2 + \frac{52.71}{2} \cdot \frac{54}{2} + \left(\frac{54}{2}\right)^2 \right)$$

$$= 11000.9\ ft^{3 \wedge 2}$$

- Section E



$$(x - 8)^2 + y^2 = 19^2$$

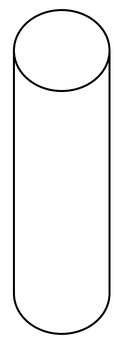
$$x - 8 = \sqrt{19^2 - y^2}$$

$$x = \sqrt{19^2 - y^2} + 8$$

$$V = \pi \cdot \int_0^{h-31.91} \left(8 + \sqrt{19^2 - y^2}\right)^2 dy$$

$$= \pi \cdot \left[\frac{8664 \cdot \sin^{-1}\frac{h-31.91}{19} + (h-31.91)(24 \cdot \sqrt{361 \cdot (h-31.91)^2} - h - 31.91^2 + 1275}{3} \right]$$

- Access tube



$$V = \frac{\pi \cdot D_{Tube}^2}{4} \cdot h$$
$$V = \frac{\pi \cdot 3^2}{4} \cdot h$$

- Total volume

$$V = V_A + V_B + V_C + V_D + V_E - V_{Tube}$$

$$= 363.3 + 10003.57 + 15300.8 + 11000.9 + \pi \cdot \left[\frac{8664 \cdot \sin^{-1}\frac{h-31.91}{19} + (h-31.91)(24 \cdot \sqrt{361 \cdot (h-31.91)^2} - h - 31.91^2 + 1275}{3} \right] - \frac{\pi \cdot 3^2}{4} \cdot h$$

$$V = 36669 + \pi \cdot \left[\frac{8664 \cdot \sin^{-1}\frac{h-31.91}{19} + (h-31.91)(24 \cdot \sqrt{361 \cdot (h-31.91)^2} - h - 31.91^2 + 1275}{3} \right] - \frac{\pi \cdot 3^2}{4} \cdot h$$

Representative diameter for short term tank 5

The tank was considered similar to two trapezoids stacked on each other, as shown below.

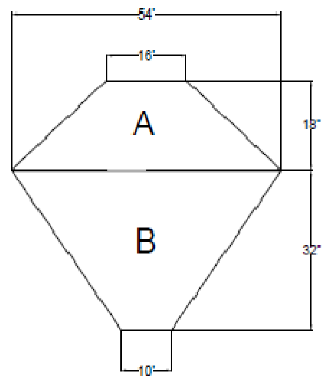
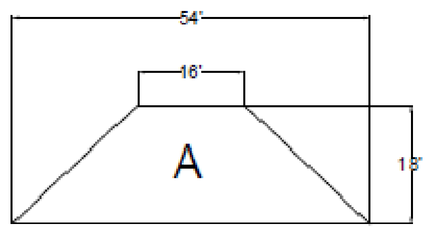


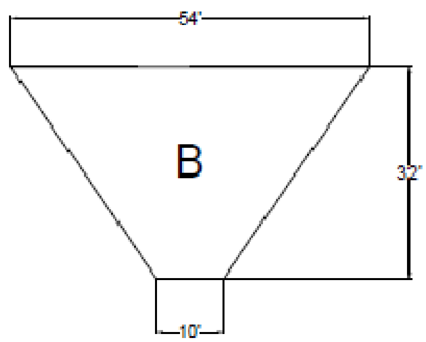
Figure B.2. Simplified shape for short term tank 5 diameter calculation.

The diameter which passes through the point halfway between the top and bottom of each trapezoid was calculated, and the two were weighted based on their volume, resulting in an overall diameter.



$$length\ of\ midspan\ of\ A = \frac{54+16}{2} = 35'$$

$$Area\ of\ A = \frac{1}{2}(18'(16'+54')) = 315\ ft^2$$



$$length\ of\ midspan\ of\ B = \frac{54+10}{2} = 32'$$

$$Area\ of\ A = \frac{1}{2}(32'(10'+54')) = 1024\ ft^2$$

$$Representative\ diameter = \frac{35'(315\ ft^2) + 32'(1024\ ft^2)}{(315\ ft^2 + 1024\ ft^2)} = 32.7\ ft$$

Densimetric Froude number

$$F_d = \frac{v}{\sqrt{g'd}}$$
$$g' = g\frac{\rho_f - \rho_a}{\rho_a}$$
$$\rho = \frac{1}{515.379}(1000 - 0.0178(T-4)^{1.7})$$
$$\rho_f = \frac{1}{515.379}(1000 - 0.0178(18.21-4)^{1.7}) = 1.9372\ \frac{slug}{CF}$$
$$\rho_a = \frac{1}{515.379}(1000 - 0.0178(28.39-4)^{1.7}) = 1.9324\ \frac{slug}{CF}$$
$$g' = 32.2\frac{ft}{s^2}\left(\frac{1.9372 - 1.9324}{1.9324}\right) = 0.08\frac{ft}{s^2}$$

The densimetric Froude number becomes:

$$F_d = \frac{0.24\frac{ft}{s}}{\sqrt{\left(0.08\frac{ft}{s^2}\right)(0.5\ ft)}} = 1.20$$

The required densimetric Froude number is:

$$F_d > C\frac{H}{D}$$

Because the inlet is vertical and under negatively buoyant conditions, C = 0.8

$$F_d > C\frac{H}{D}$$
$$F_d > 0.8\left(\frac{14.6\ ft}{0.5\ ft}\right)$$
$$F_d > 23.36$$

Hydraulic parameter from Roberts et al (2006)
The criterion for a tank to be mixed under vertically oriented, negatively buoyant jets is:

$$\frac{\sqrt{Msin\theta}}{(B)^{1/3}H^{2/3}} > 0.85 - 0.05n$$
$$M = 0.0113\frac{ft^4}{s^2}$$
$$\theta = 90^0$$
$$B = g'Q = \left(0.079\frac{ft}{s^2}\right)(0.047\ cfs) = 0.0037\frac{ft^4}{s^3}$$
$$H = 14.6\ ft$$
$$\frac{\sqrt{\left(0.0113\frac{ft^4}{s^2}\right)\sin(90^0)}}{\left(0.0037\frac{ft^4}{s^3}\right)^{1/3}(14.6\ ft)^{2/3}} = 0.115$$

To mix the tank:

$$\frac{\sqrt{Msin\theta}}{(B)^{1/3}H^{2/3}} > 0.8$$

For positively buoyant jets with horizontal inlets:

$$\frac{\sqrt{M}}{(B)^{1/3}H^{2/3}} > 1.3$$

Critical temperature difference between inflow and tank volume to cause stratification

$$|\Delta T| < \frac{9{,}371}{gC^2}\frac{Q^2}{H^2d^2}$$
$$|\Delta T| < \frac{9{,}371}{32.2\frac{ft}{s^2}0.8^2}\frac{(0.047\ cfs)^2}{(14.6\ ft)^2(0.5\ ft)^2}$$
$$|\Delta T| < 0.019^O\ C$$

Total chlorine decay coefficient calculation

Table B.2. Data to calculate total chlorine decay coefficients (Drews, 2009).

	Total Chlorine (mg/L)			
Cl:NH3 Ratio	4 C		20 C	
Day	3.5:1	5:1	3.5:1	5:1
0		2.98		2.98
2	2.96	2.48	2.9	1.65
4	2.96	2.58	2.92	1.43
6	2.76	1.89	2.09	1.24
8	2.58	1.75	1.95	1.07
10	2.38	1.58	1.76	1
13	2.24	1.5	1.63	0.86
15	2.15		1.57	
Rate (1/d)	0.027	0.056	0.051	0.081
Average Rate (1/d)	0.0395		0.0635	

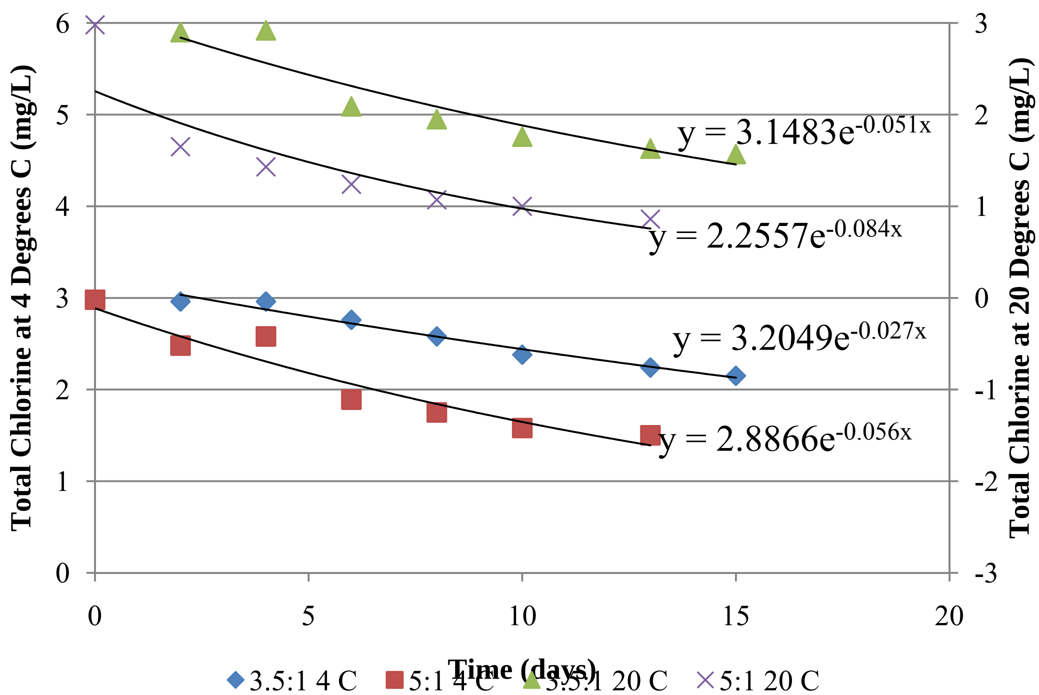


Figure B.3. Total chlorine decay at various temperatures and chlorine:ammonia ratios.

Simple first order model for long term tanks D and E

$$C = C_0 e^{-kt}$$

Calculation of C_0

Tank was drained to an estimated 27.7 ft, which had 0.07 mg/L total chlorine, and refilled to 73 ft with water containing 1.83 mg/L.

$$C_0 = \frac{(27.7\ ft)\left(0.07\frac{mg}{L}\right) + (73\ ft - 27.7\ ft)(1.83\frac{mg}{L})}{73\ ft} = 1.14\ mg/L$$

$$C_0 = 1.14\ mg/L$$

$$k = -0.064\ 1/d$$

$$t = 8\ days$$

$$C = \left(1.14\frac{mg}{L}\right) e^{-\left(0.064\frac{1}{d}\right)(8\ d)} = 0.68\ mg/L$$

Similarly for long term tank E, the initial concentration was 1.5 mg/L with a time of 21 days.

$$C = \left(1.5\frac{mg}{L}\right) e^{-\left(0.064\frac{1}{d}\right)(21\ d)} = 0.39\ mg/L$$

APPENDIX C

RESULTS OF THE SOUTH DAKOTA RURAL WATER TANK SURVEY

Table C.1. Information collected from the South Dakota rural water tank survey.

	Above-Ground Reservoir	**Standpipe**	**Elevated**	**Under-Ground Reservoir**	**Clear well**	**Unknown**
Number of Tanks	83	107	108	47	22	2
Minimum Capacity (gal)	20,000	16,000	25,000	8,000	40,000	-
Average Capacity (gal)	838,000	152,000	310,000	144,000	262,000	-
Maximum Capacity (gal)	7.5 Mgal	475,000	3 Mgal	681,000	621,027	-
Minimum Height (ft)	11	20	20	9	10	-
Average Height (ft)	26	56	114	14	13	-
Maximum Height (ft)	58	130	200	30	18	-
Minimum Diameter	19	10	15	20	38	-
Average Diameter (ft)	55	22	40	32	38	-
Maximum Diameter	140	56	104	42	38	-
Minimum H:D Ratio	0.14	1.00	-	0.25	-	-
Average H:D Ratio	0.59	3.01	-	0.52	-	-
Maximum H:D Ratio	0.98	10.83	-	1.50	-	-
Common Inlet/Outlet	51%	76%	89%	38%	0%	-
Multiple Inlet/Outlet	40%	24%	3%	53%	82%	-
SCADA for Water Level	75%	75%	79%	64%	82%	-
Artificial Mixer Installed	2%	7%	8%	0%	0%	-

APPENDIX D

WATER QUALITY MEASUREMENTS

Table D.1. Water quality data collected for long term tank A (concentrations in mg/L).

Date	Point	Ft from bottom of tank	Temp (C)	Total Chlorine (as Cl)	Monochloramine (as Cl)	Free Ammonia (as N)	Nitrite (as N)	Nitrate (as N)	Notes
8/11/10	PS Off	0		0.17					
8/11/10	1	2	17.65						
8/11/10	2	5	18.38	0.15					
8/11/10	3	8	18.65	0.14					
8/25/10	PS Run	0		2.44	0.55	0.17	0.0015	0.21	Booster chlorinating at pump station
8/25/10	1	2	18.48						
8/25/10	2	5	18.71	0.35				0.3	
8/25/10	3	8	18.83	0.47	0.41	0.39	0.006	0.29	
9/19/10	1	2	16.67						
9/19/10	2	5	16.81	0.6	0.7	>.5	0.011		
9/19/10	3	8	16.35	0.6					
10/21/10	1	2	15.35						
10/21/10	2	5	15.49	0.49	0.4	0.19	0.005	0.34	
10/21/10	3	8	15.31	0.45					
10/21/10	4	11	15.4	0.45					
10/21/10	5	14	15.15	0.46	0.36	0.3	0	0.33	

Table D.2. Water quality data collected for long term tank B (concentrations in mg/L).

Date	Point	Ft from bottom of tank	Temp (C)	Total Chlorine (as Cl)	Mono chloramine (as Cl)	Free Ammonia (as N)	Nitrite (as N)	Nitrate (as N)
9/19/10	1	2	15.29	1.02	1.14	0.27	0.003	0.21
9/19/10	2	9	15.01	1.05				
9/19/10	3	16	15.28	1.01				
9/19/10	4	23	15.31	1.08	0.46	0.18	0.004	0.21
10/21/10	1	2	14.64	1	1.02	0.66	0.007	0.26
10/21/10	2	9	14.72	1.04	1.13	0.58	0.004	0.26
10/21/10	3	16	14.62	1.05	1.21	0.8	0.004	0.27
10/21/10	4	23	14.68	1.04	1.2	0.7	0.0045	0.26

Table D.3. Water quality data collected for long term tank C (concentrations in mg/L).

Date	Ft from bottom of tank	Temperature (C)	Total Chlorine (as Cl)
8/10/10	2.5	18.21	>2
8/10/10	7.5	26.09	>2
8/10/10	12.5	28.15	>2
8/10/10	17.5	28.39	>2
8/22/10	2.5	19.02	2.26
8/22/10	7.5	26.65	1.94
8/22/10	12.5	27.83	1.94
8/22/10	17.5	28.04	1.94
9/16/10	2.5	16.99	2.48
9/16/10	7.5	16.96	2.5
9/16/10	12.5	17.69	2.42
9/16/10	17.5	19.34	2.32
10/20/10	2.5	14.78	2.58
10/20/10	7.5	14.82	2.56
10/20/10	12.5	14.88	2.5
10/20/10	17.5	16.72	2.6

Table D.4. Water quality data collected for long term tank D (concentrations in mg/L).

Date	Height (ft)	Temp (C)	Total Cl	Mono chlora mine	Free NH_3	Nitrite	Nitrate	Notes
8/11/10	6.9	19.34	0.92					
8/11/10	13.9	29.36	*0.065*					Total chlorine average of 0.07 and 0.06
8/11/20	20.9	30.46	0.06					
8/11/10	34.9	30.68	0.06					
8/11/10	48.9	29.96	0.04					
8/11/10	62.9	30.37	0.05					
8/11/10	69.9							
8/25/10	6.9	19.27	1.83	1.98	0.42	0.007	0.22	
8/25/10	13.9	26.22	0.39					
8/25/10	20.9	26.37	0.42					
8/25/10	34.9	27.13	0.4					
8/25/10	48.9	27.47	0.4					
8/25/10	62.9	27.13	0.42				0.34	
8/25/10	69.9	27.35	0.4	0.39	0.45	0.006	0.34	
9/17/10	6.9	17.75	1.25	1.38	0.39	0.003	0.2	
9/17/10	13.9	18.52	1.01					
9/17/10	20.9	20	0.45	0.58	0.5	0.002	0.25	
9/17/10	34.9	20.92	0.44					
9/17/10	48.9	21.11	0.45	0.61	0.37	0.002	0.26	
9/17/10	62.9	21.16	0.44					
9/17/10	69.9	21.32	*0.445*	0.63	0.51	0.001	0.26	Total chlorine average of .47 and .43
10/20/10	6.9	15.75	1.18	1.56	0.17	0.003	0.2	
10/20/10	13.9	16.1	1.02					
10/20/10	20.9	16.27	1.03	1.08	0.25	0.002	0.2	
10/20/10	34.9	16.81	1.07					
10/20/10	48.9	17.32	1.05	1.08	0.22	0.002	0.2	
10/20/10	62.9	17.42	1.07					
10/20/10	69.9	17.49	1.05	1.17	0.24	0.002	0.2	

Table D.5. Water quality data collected for long term tank E (concentrations in mg/L).

Date	Ft from tank base	Temp (C)	Total Cl	Mono chlor amine	Free NH3	Nitrite	Nitrate	Notes
8/10/10	1.5	19.54	1.1					
8/10/10	8.5	20.22	1.12					
8/10/10	22.5	26.96	0.04					
8/10/10	29.5	27.48	0.04					
8/10/10	43.5	27.64	0.06					
8/10/10	57.5	27.64	0.07					
8/10/10	64.5	27.73	0.05					
8/10/10	71.5	28.1	0.06					
8/20/10	1.5	19.54	1.31	1.29	0.33		0.34	
8/20/10	8.5	20.22	1.26			0.007	0.34	
8/20/10	22.5	26.96	0.11				0.81	
8/20/10	29.5	27.48	0.13			0.012	0.81	
8/20/10	43.5	27.64	0.16				0.82	
8/20/10	57.5	27.64	0.09			0.009	0.81	
8/20/10	64.5	27.73	0.1				0.81	
8/20/10	71.5	28.1	0.07	0.39	0.04	0.029	0.82	
8/22/10	1.5	19.82	1.27	1.08	0.39	0.004	0.33	
8/22/10	8.5	22.84	1.05				0.34	
8/22/10	22.5	28.82	0.04				0.82	
8/22/10	29.5	29.25	0.03				0.80	
8/22/10	43.5	29.35	0.02				0.80	
8/22/10	57.5	29.23	0.05				0.81	
8/22/10	64.5	29.24	0.03				0.81	
8/22/10	71.5	29.18	0.05	0.1	0.09	0.004	0.96	
9/16/10	1.5	17.98	1.49	1.97	0.26	0.006	0.27	
9/16/10	8.5	18.6	1.51					
9/16/10	22.5	20.83	1					
9/16/10	29.5	21.19	1.02					
9/16/10	43.5	21.46	1					
9/16/10	57.5	21.41	1.03					
9/16/10	64.5	21.37	1				0.25	
9/16/10	71.5	21.56	1.01	1.06	0.42	0.004	0.24	

Table D.5. Continued

10/20/10	1.5	15.59	1.39	1.44	0.36	0.007	0.21	Monochloramine value is the average of 1.46 and 1.53
10/20/10	8.5	15.85	1.34					
10/20/10	22.5	16.15	1.33	1.495	0.39	0.006	0.22	Monochloramine value is the average of 1.64 and 1.52, and free ammonia value is the average of .43 and .24
10/20/10	29.5	16.26	1.26					
10/20/10	43.5	16.57	1.23	1.58	0.355	0.005	0.22	Monochloramine value is the average of 1.61 and 1.51, while free ammonia is the average of .43 and 0.24
10/20/10	57.5	16.36	1.2					
10/20/10	64.5	16.35	1.22	1.56	0.335	0.002	0.23	
10/20/10	71.5	16.47	1.22	1.44	0.4	0.004	0.23	

Table D.6. Water quality data collected for short term tanks (concentrations in mg/L)

	Total Chlorine Bottom of Tank	Total Chlorine Top of Tank	Free Chlorine Bottom of Tank	Free Chlorine Top of Tank
ST1 Prior to Power Outage	0.94	0.05		
ST3 Prior to Recirculation Pump	1.29	0.04	0.87	0.03
ST3 After Recirculation Pump	0.95	0.12	0.68	0.01
ST4 When Equipment Installed	0.54	0.2	0.48	0.15
ST5 Prior to Power Outage	0.31	0.08	0.12	0.01
ST5 After Power Outage	0.88	0.45	0.69	0.23
ST6 When Equipment Installed	0.28	0.31	0.04	0.05
ST6 When Equipment Removed	0.28	0.24	0.02	0.05
ST7 When Equipment Installed	3.3	3.24		
ST7 When Equipment Removed	3.58	3.33		
ST8 When Equipment Installed	2.96	2.88		
ST8 When Equipment Removed	1.92	1.92		

APPENDIX E

COMPARISON OF SHORT AND LONG TERM TANKS

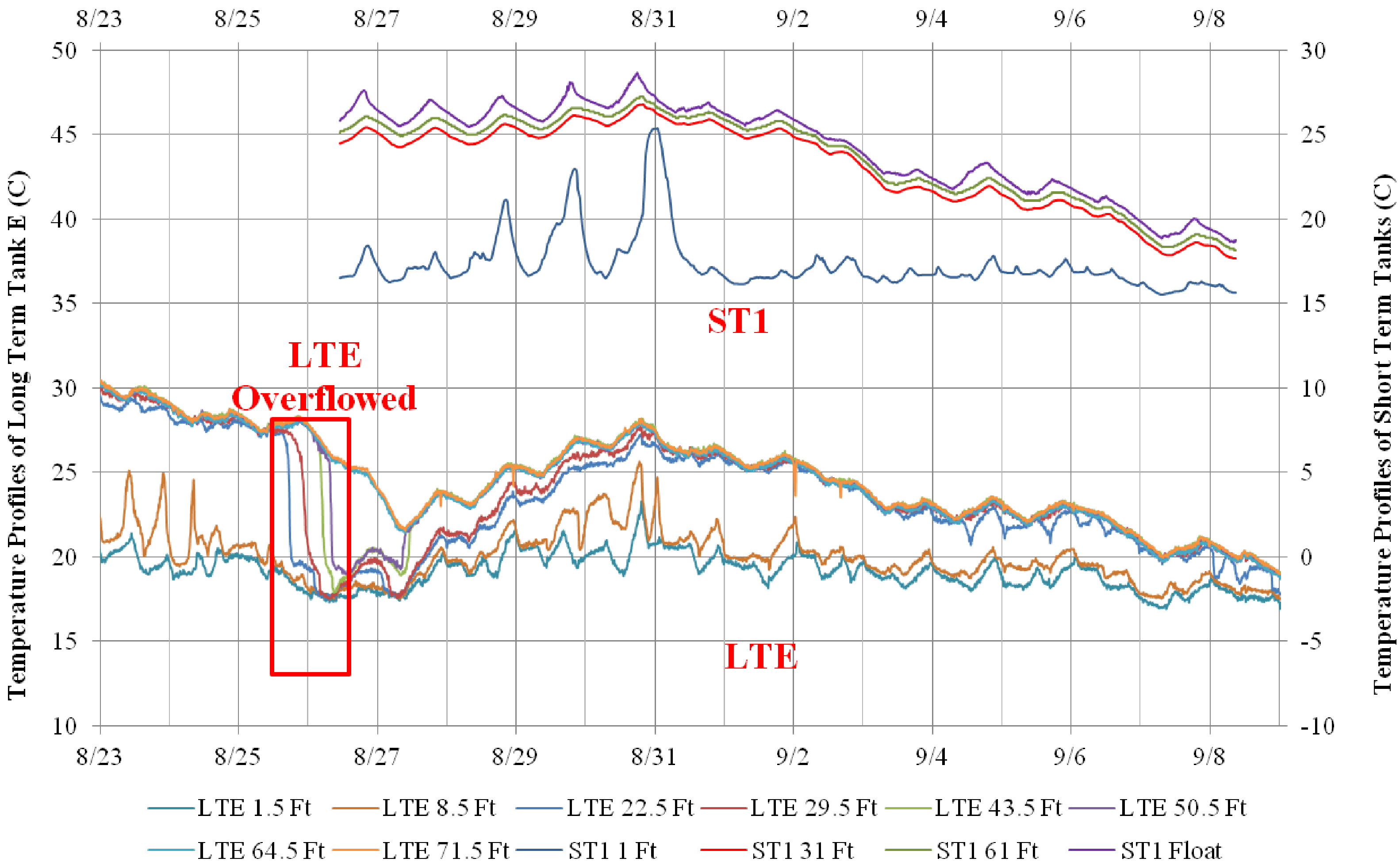


Figure E.1. Comparison of short term tank 1 with long term tank E.

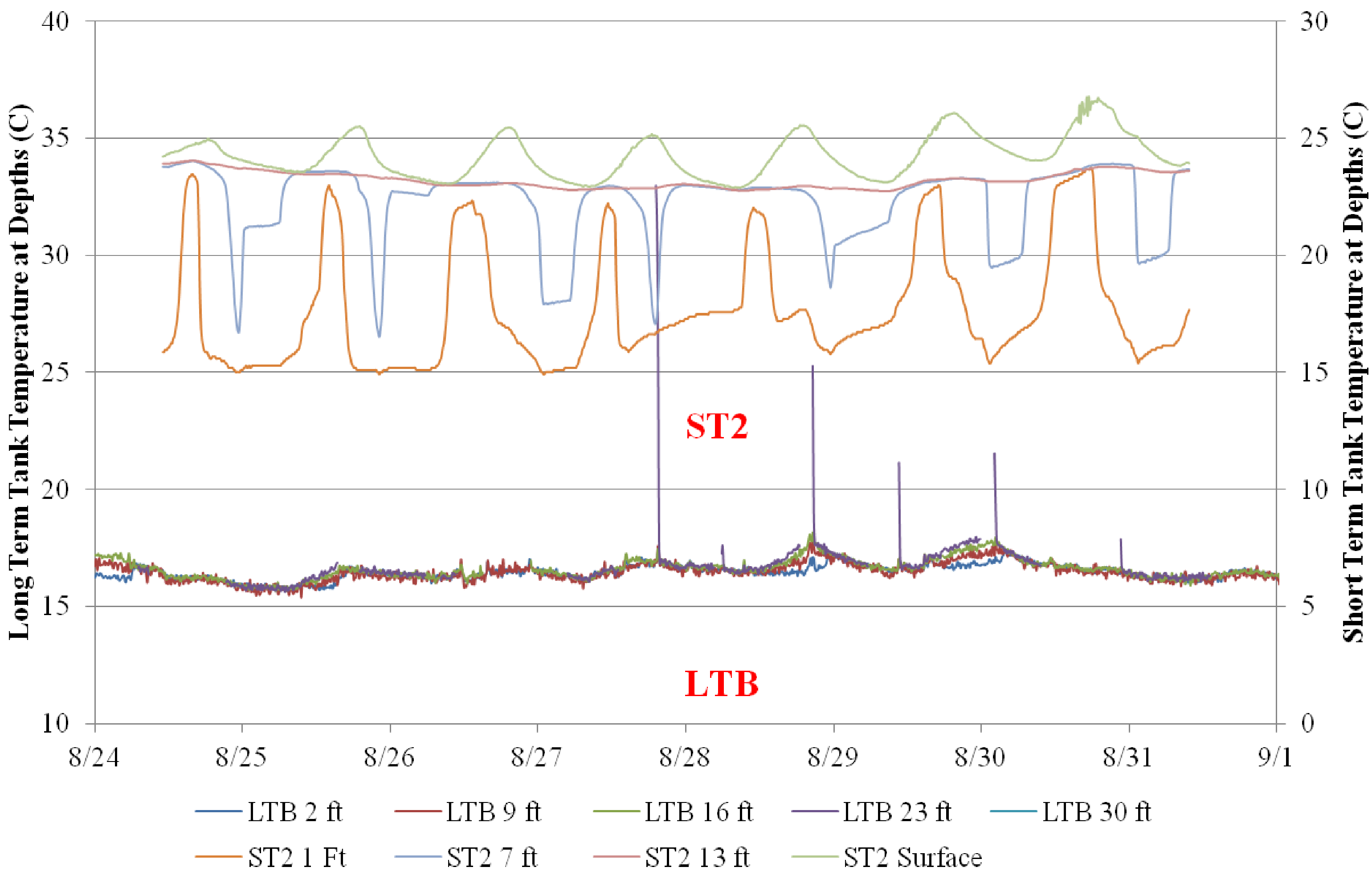


Figure E.2. Comparison of short term tank 2 with long term tank B.

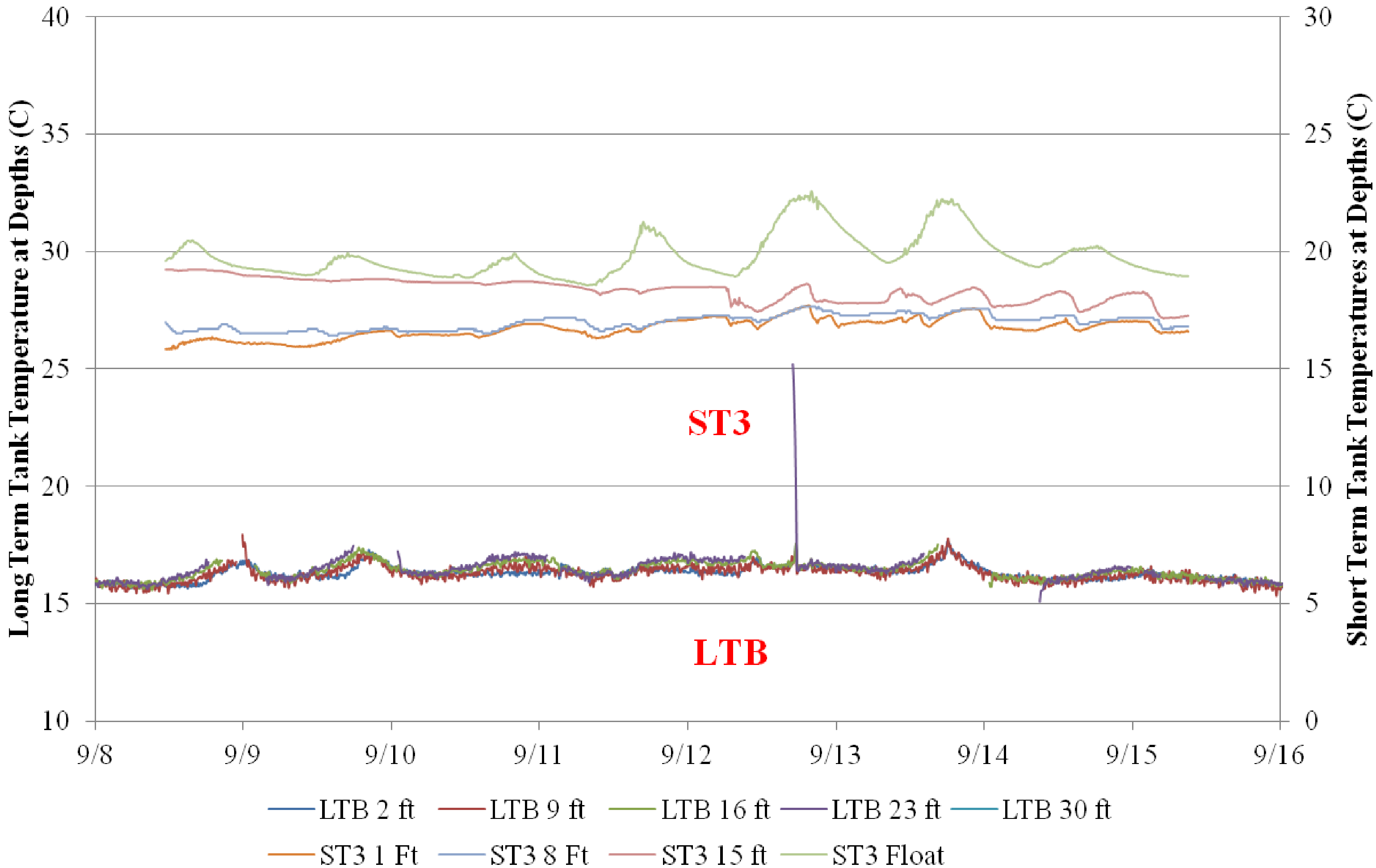


Figure E.3. Comparison of short term tank 3 with long term tank B.

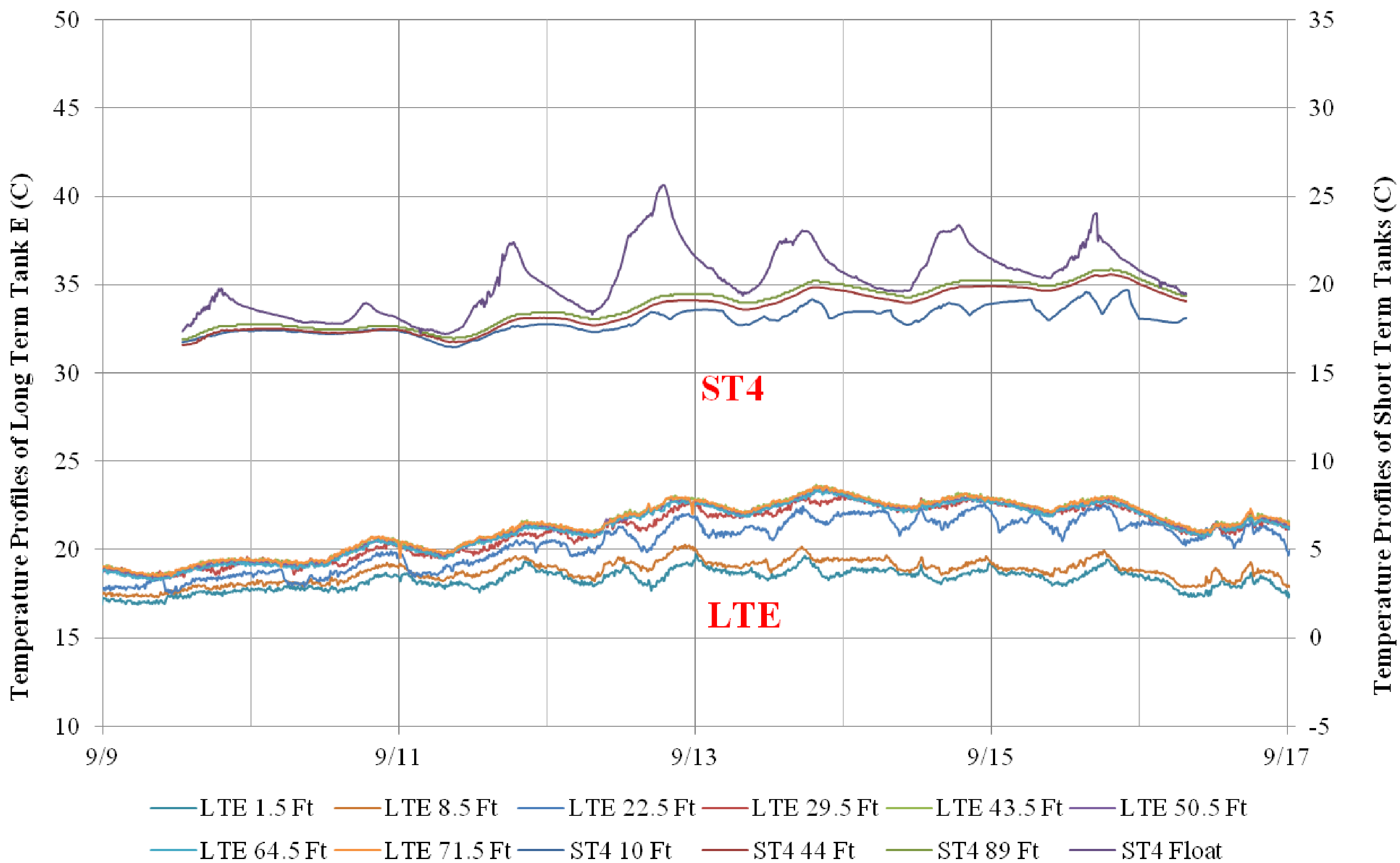


Figure E.4. Comparison of short term tank 4 with long term tank E.

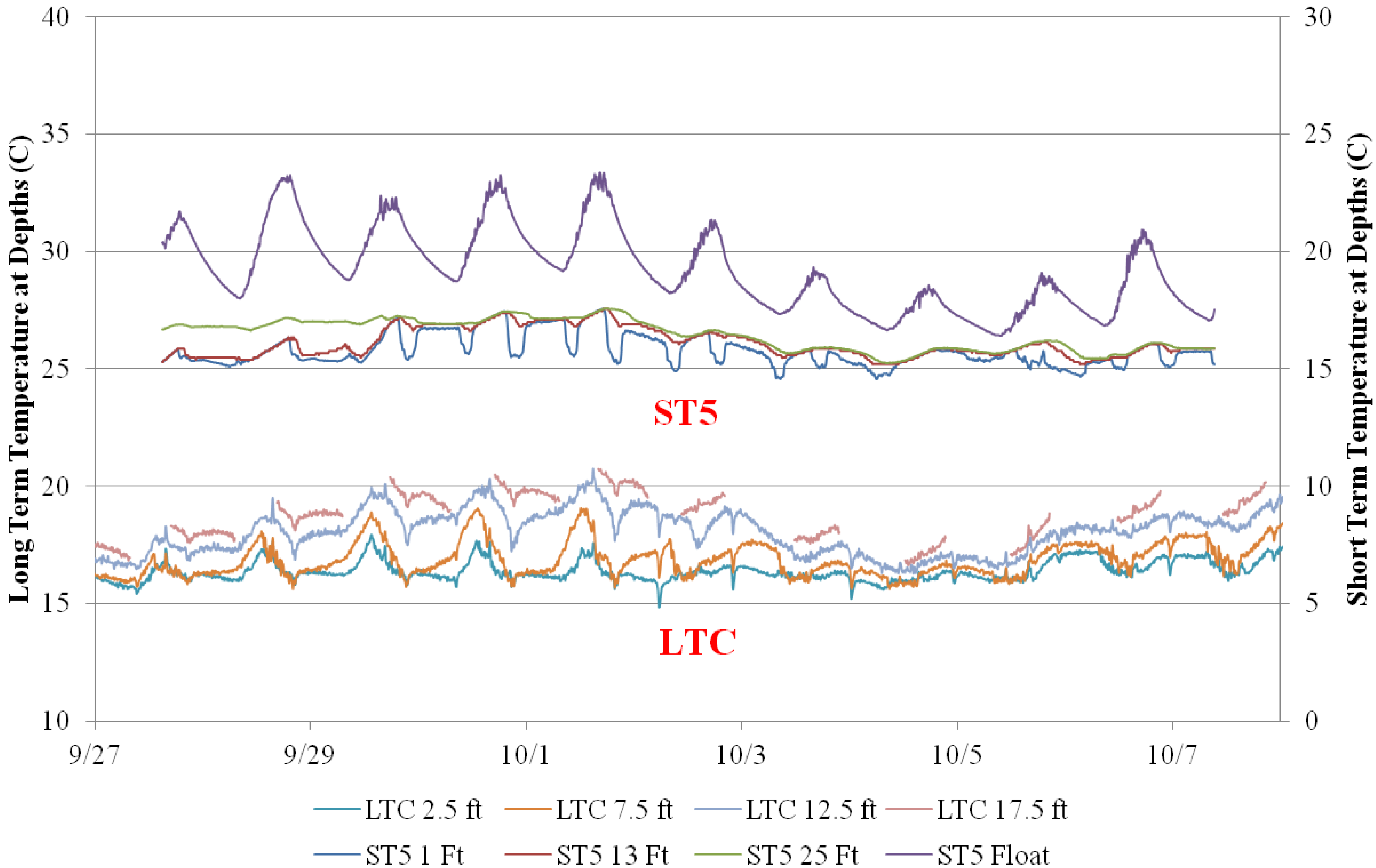


Figure E.5. Comparison of short term tank 5 with long term tank C.

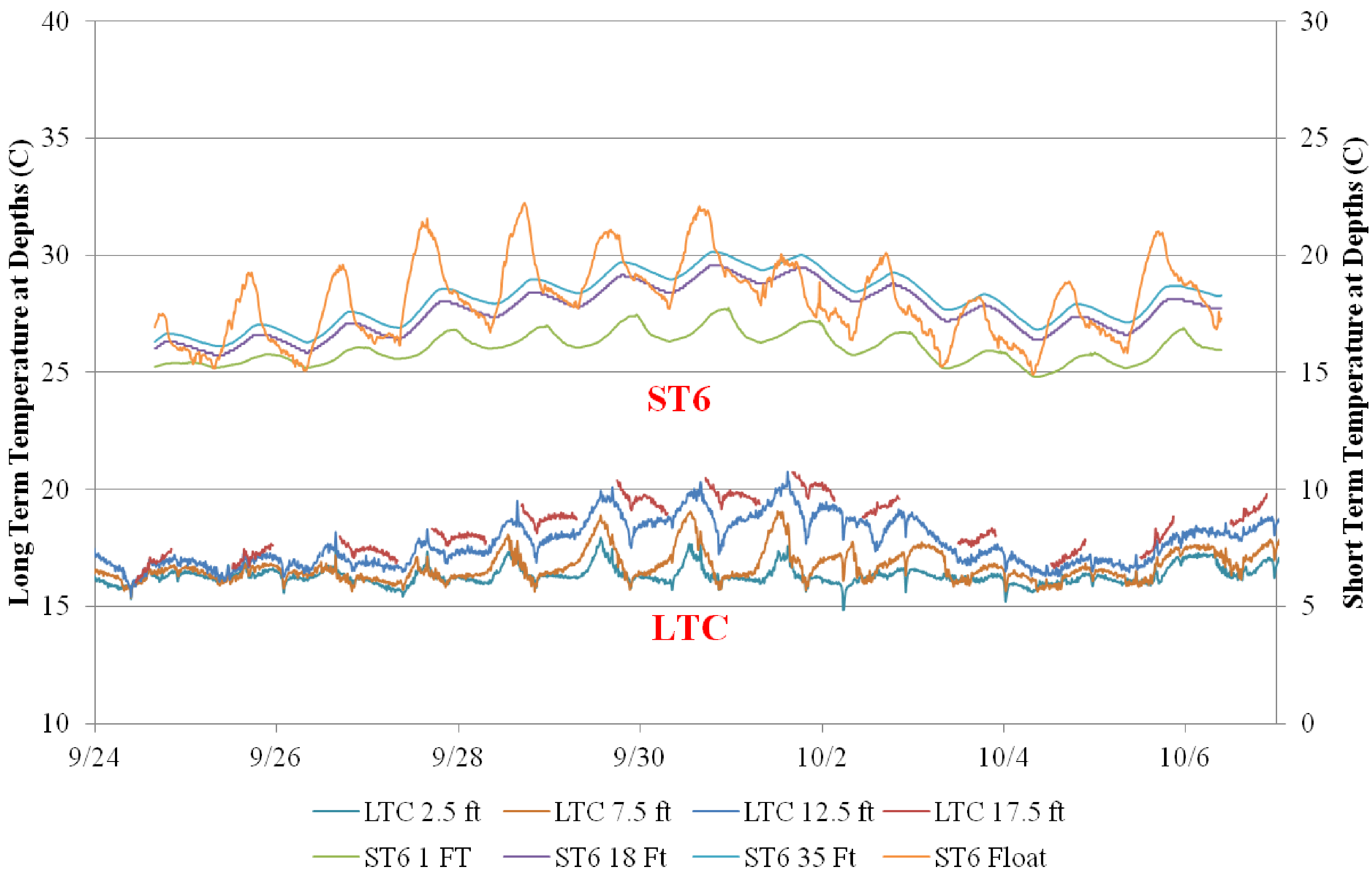


Figure E.6. Comparison of short term tank 6 with long term tank C.

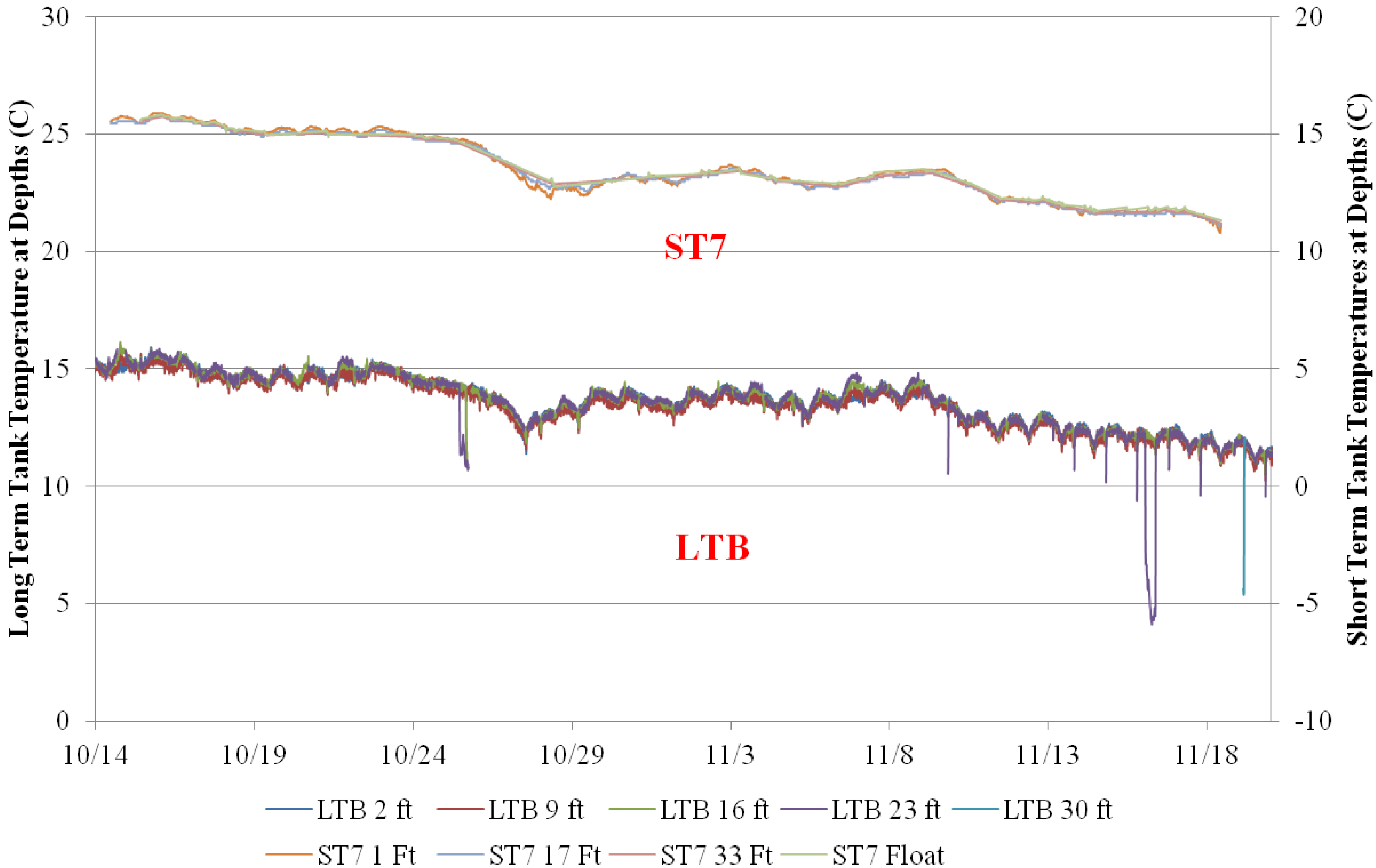


Figure E.7. Comparison of short term tank 7 with long term tank B.

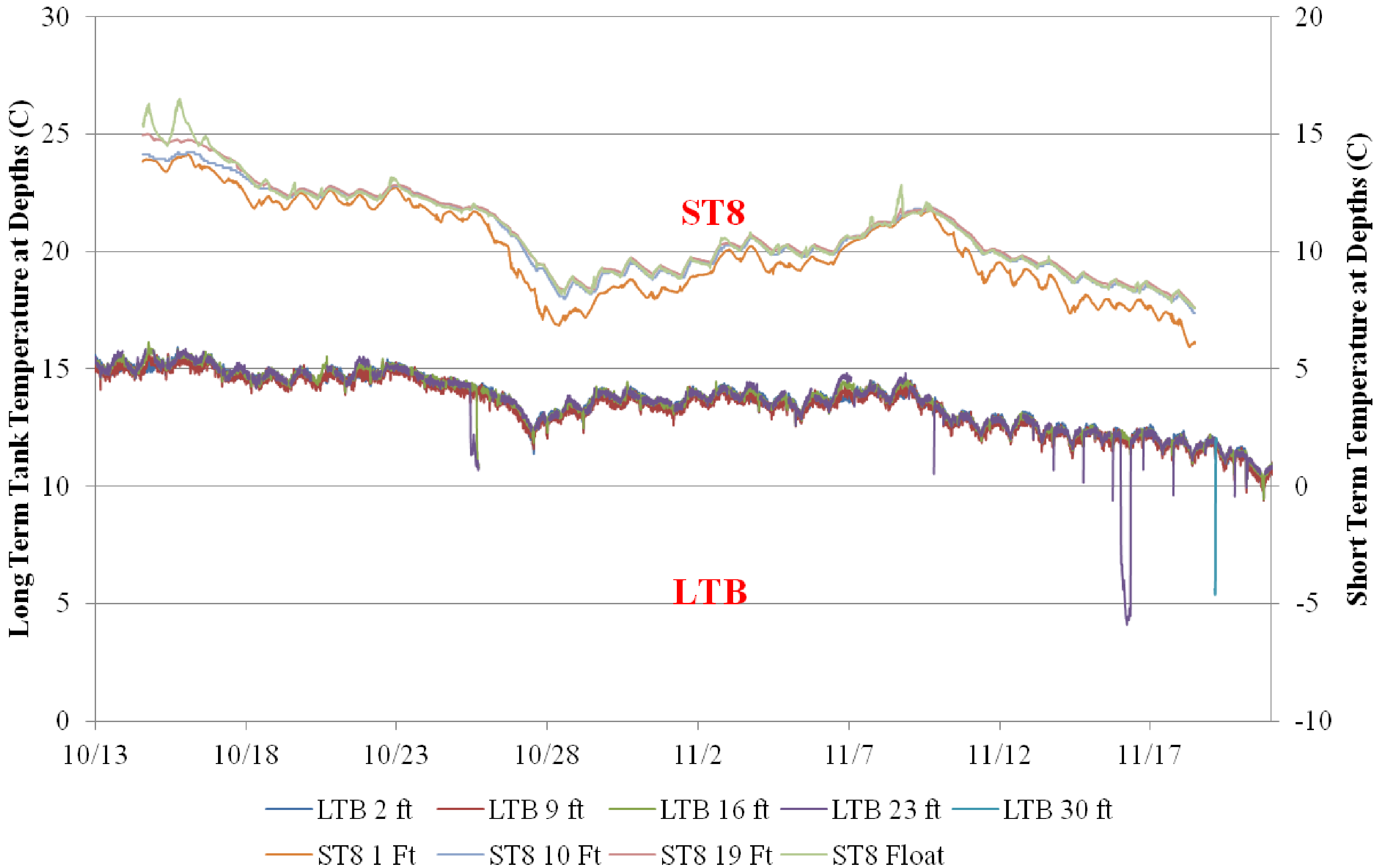


Figure E.8. Comparison of short term tank 8 with long term tank B.

APPENDIX F

VOLUMETRIC EXCHANGE REQUIREMENTS TO ENSURE MIXING

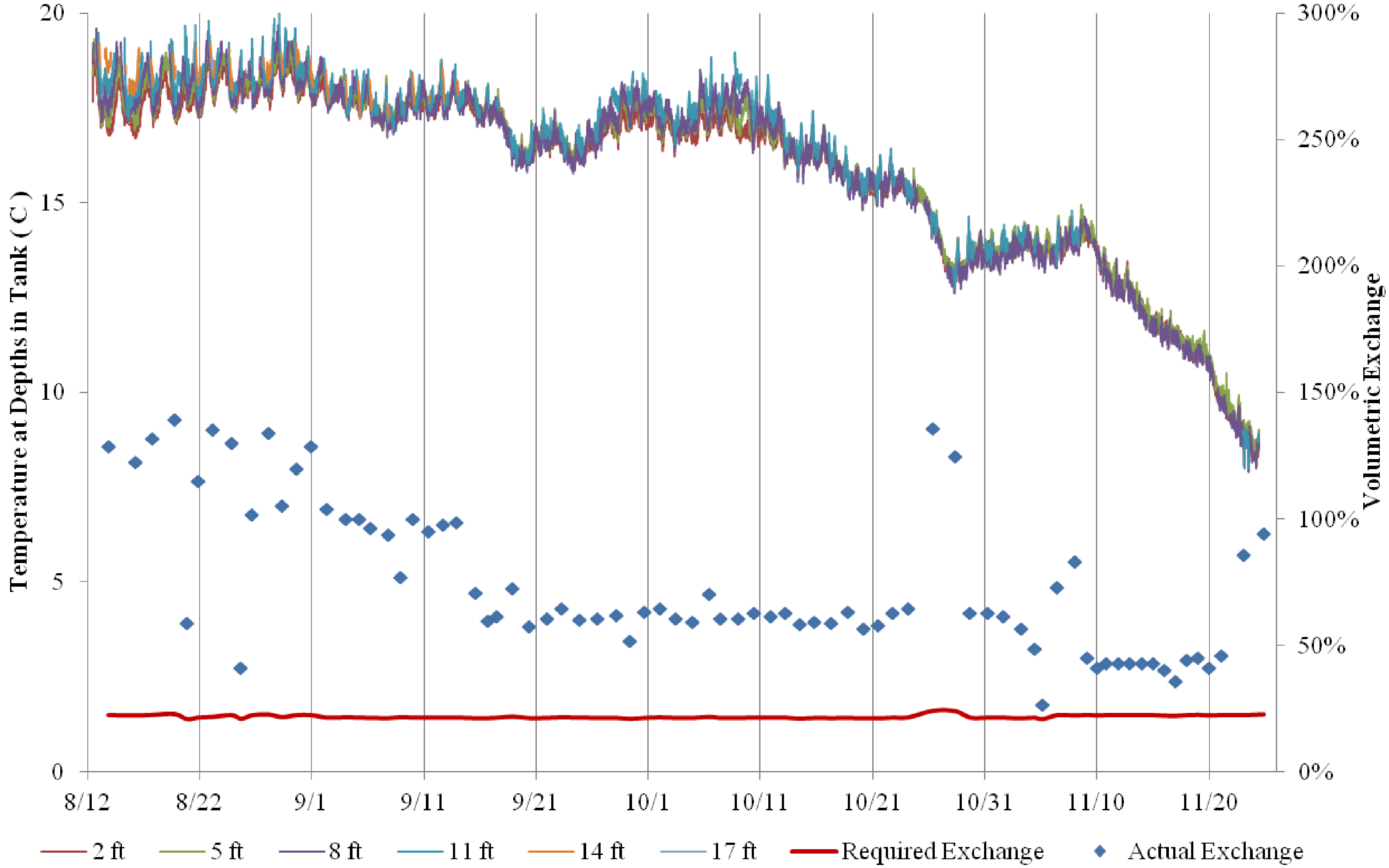


Figure F.1. Temperature profile with actual and required volumetric exchange ratios for long term tank A.

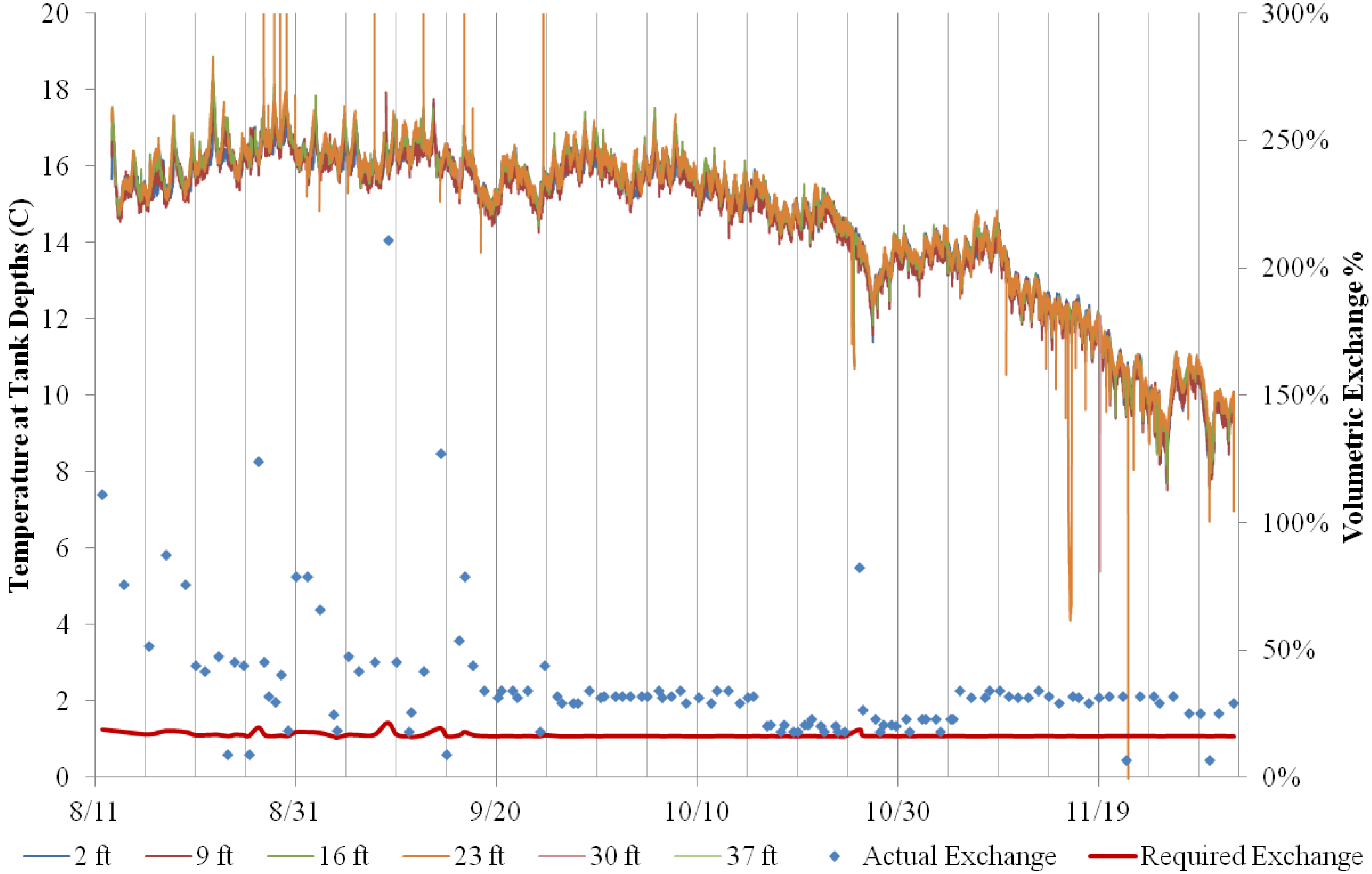


Figure F.2. Temperature profile with actual and required volumetric exchange ratios for long term tank B.

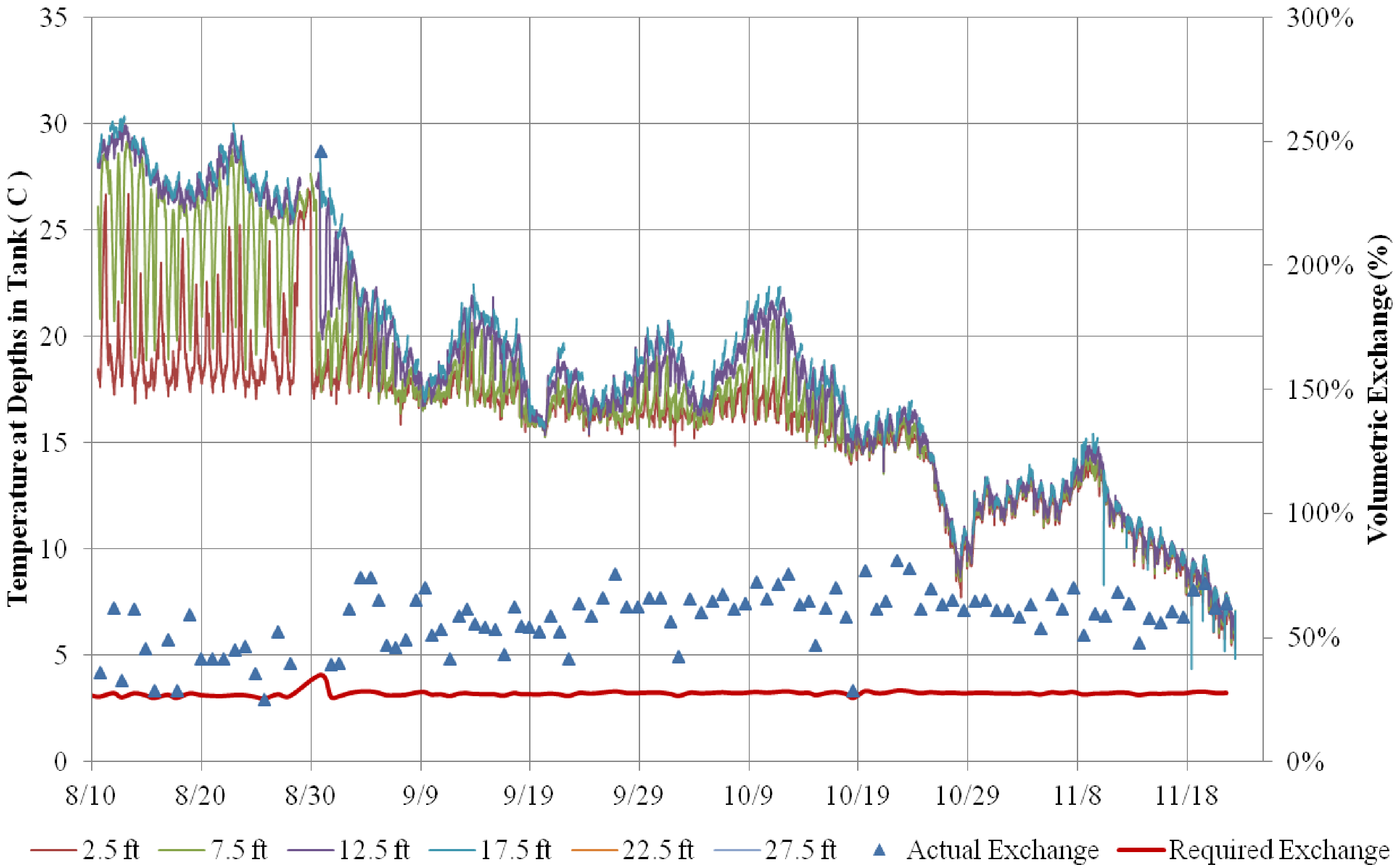


Figure F.3. Temperature profile with actual and required volumetric exchange ratios for long term tank C.

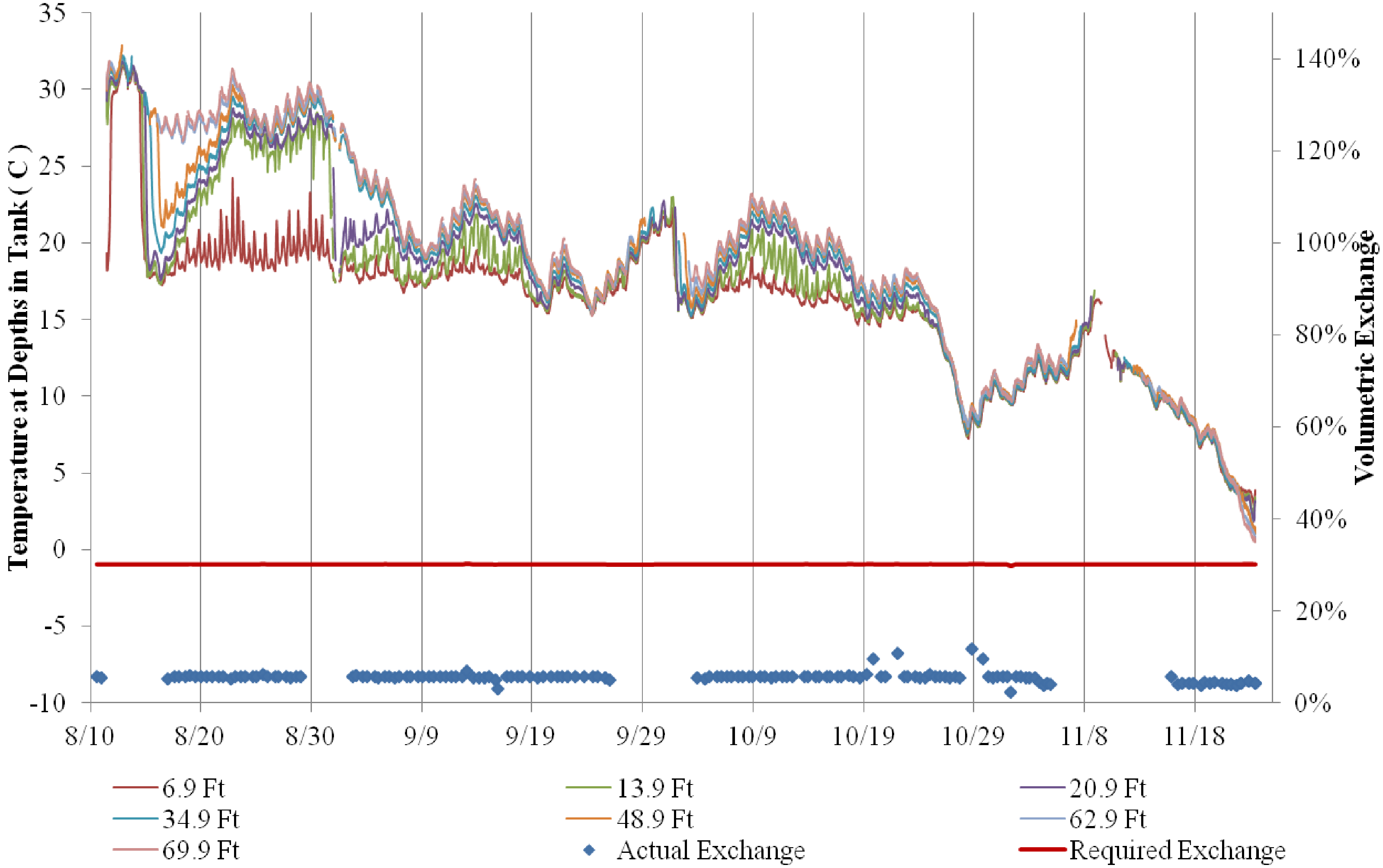


Figure F.4. Temperature profile with actual and required volumetric exchange ratios for long term tank D.

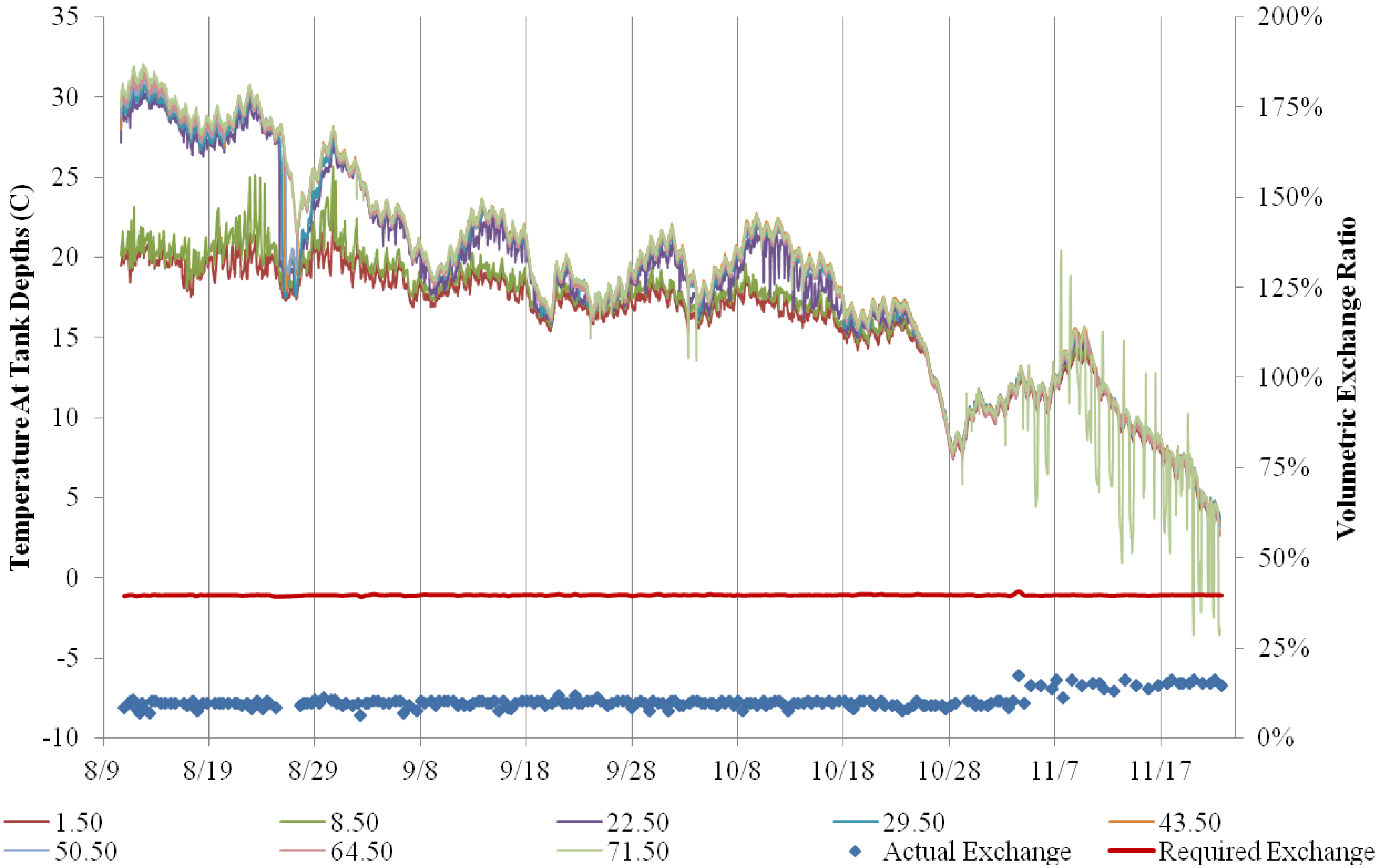


Figure F.5. Temperature profile with actual and required volumetric exchange ratios for long term tank E.

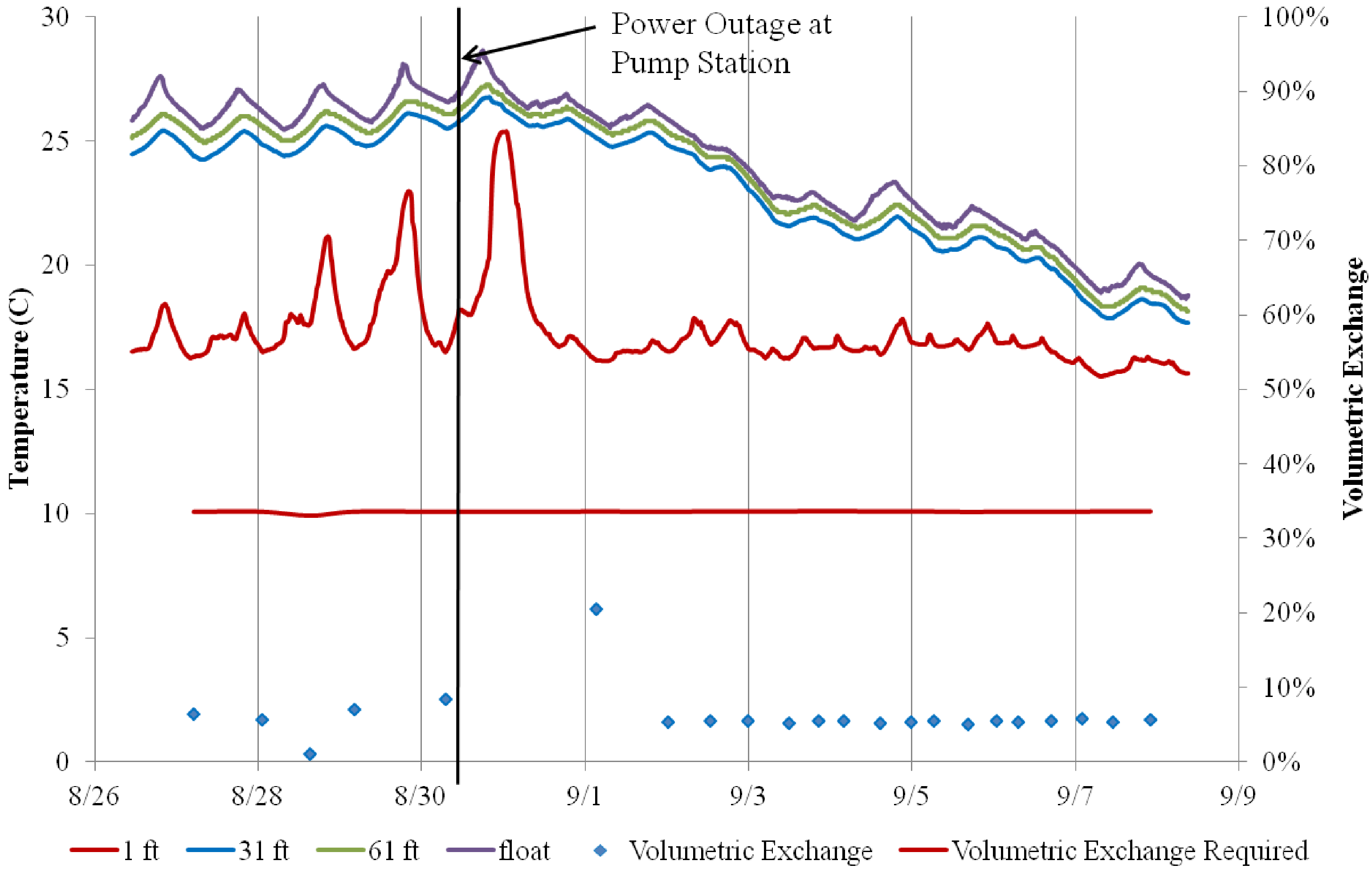


Figure F.6. Temperature profile with actual and required volumetric exchange ratios for short term tank 1.

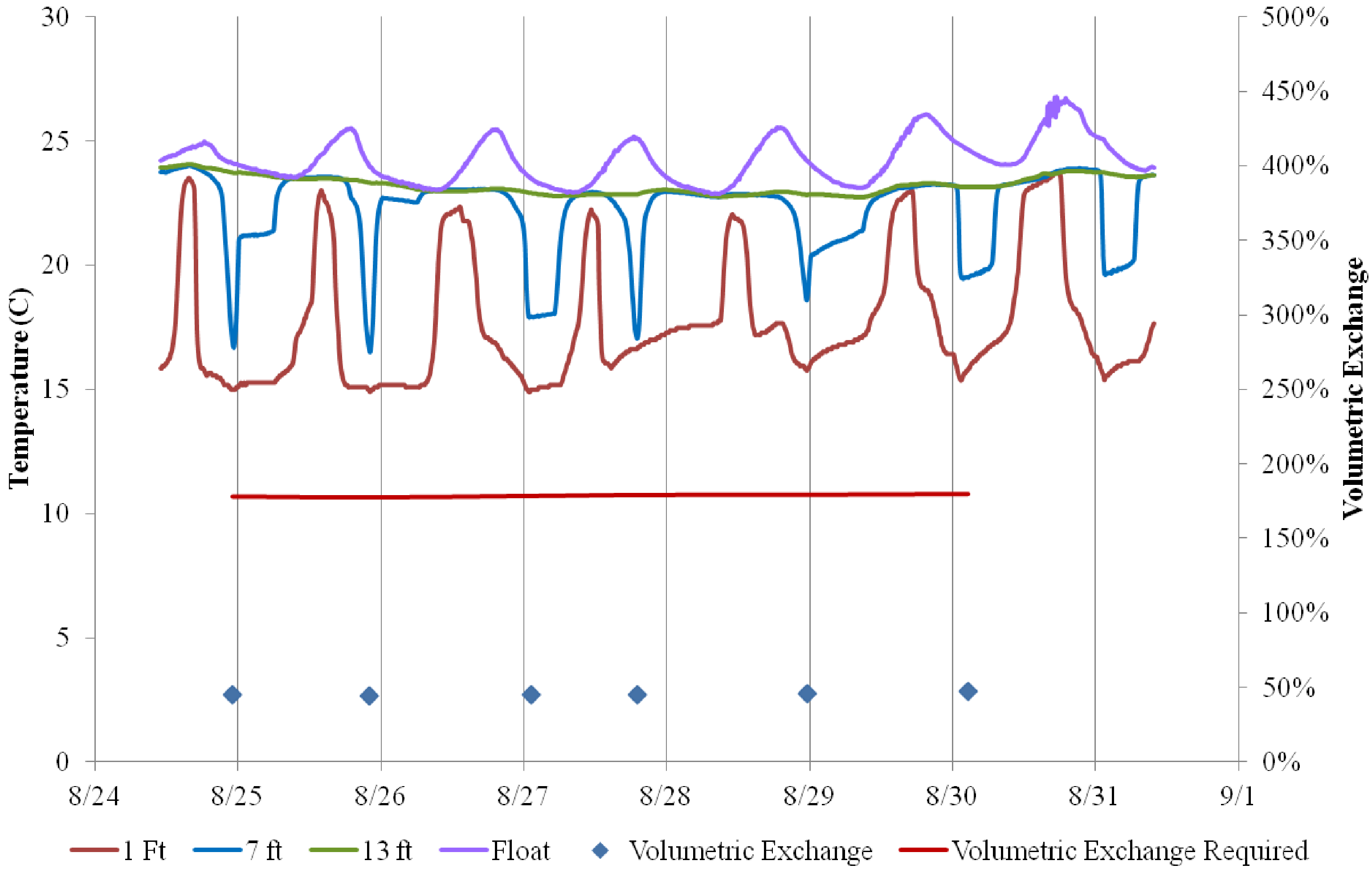


Figure F.7. Temperature profile with actual and required volumetric exchange ratios for short term tank 2.

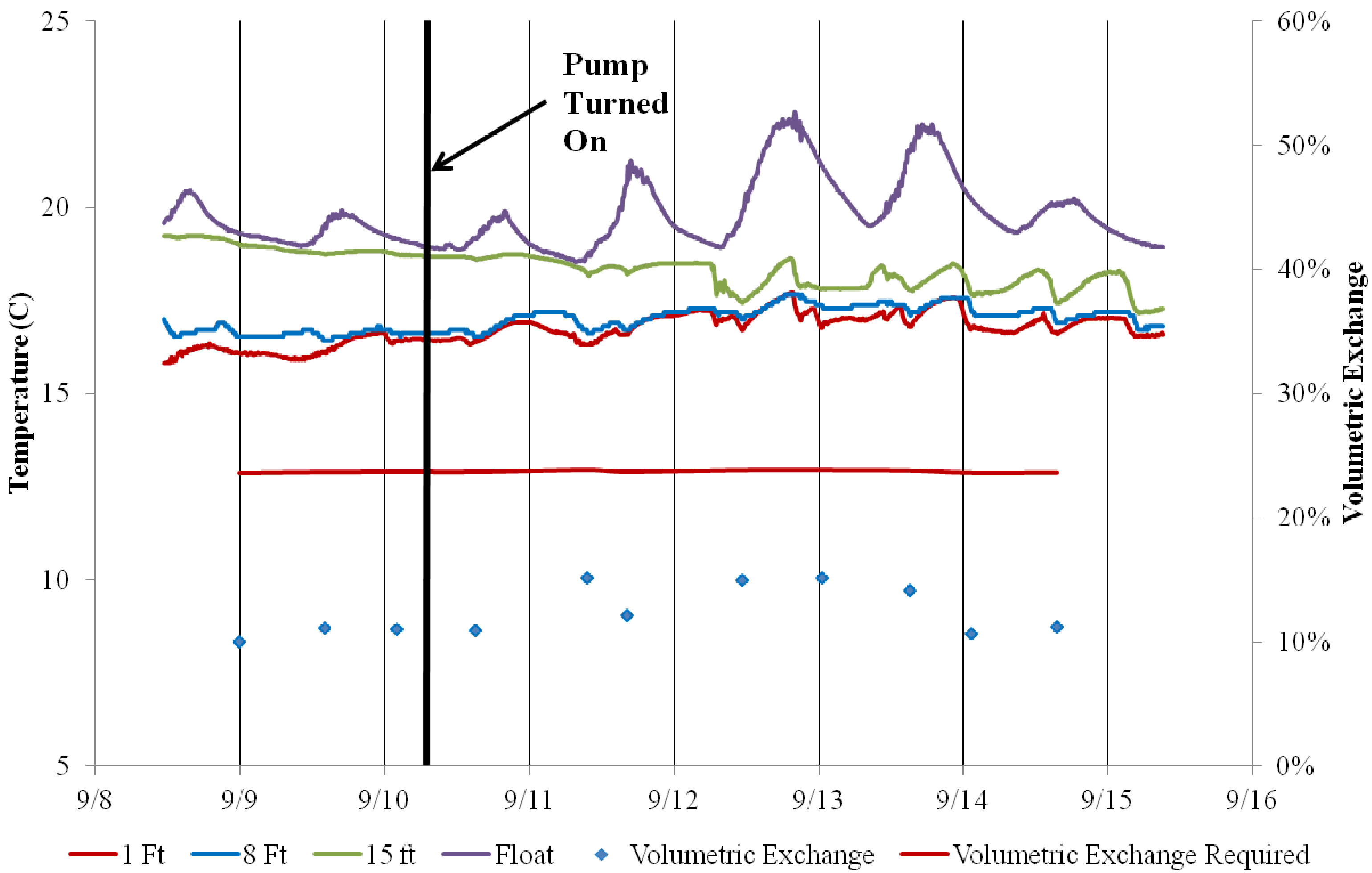


Figure F.8. Temperature profile with actual and required volumetric exchange ratios for short term tank 3.

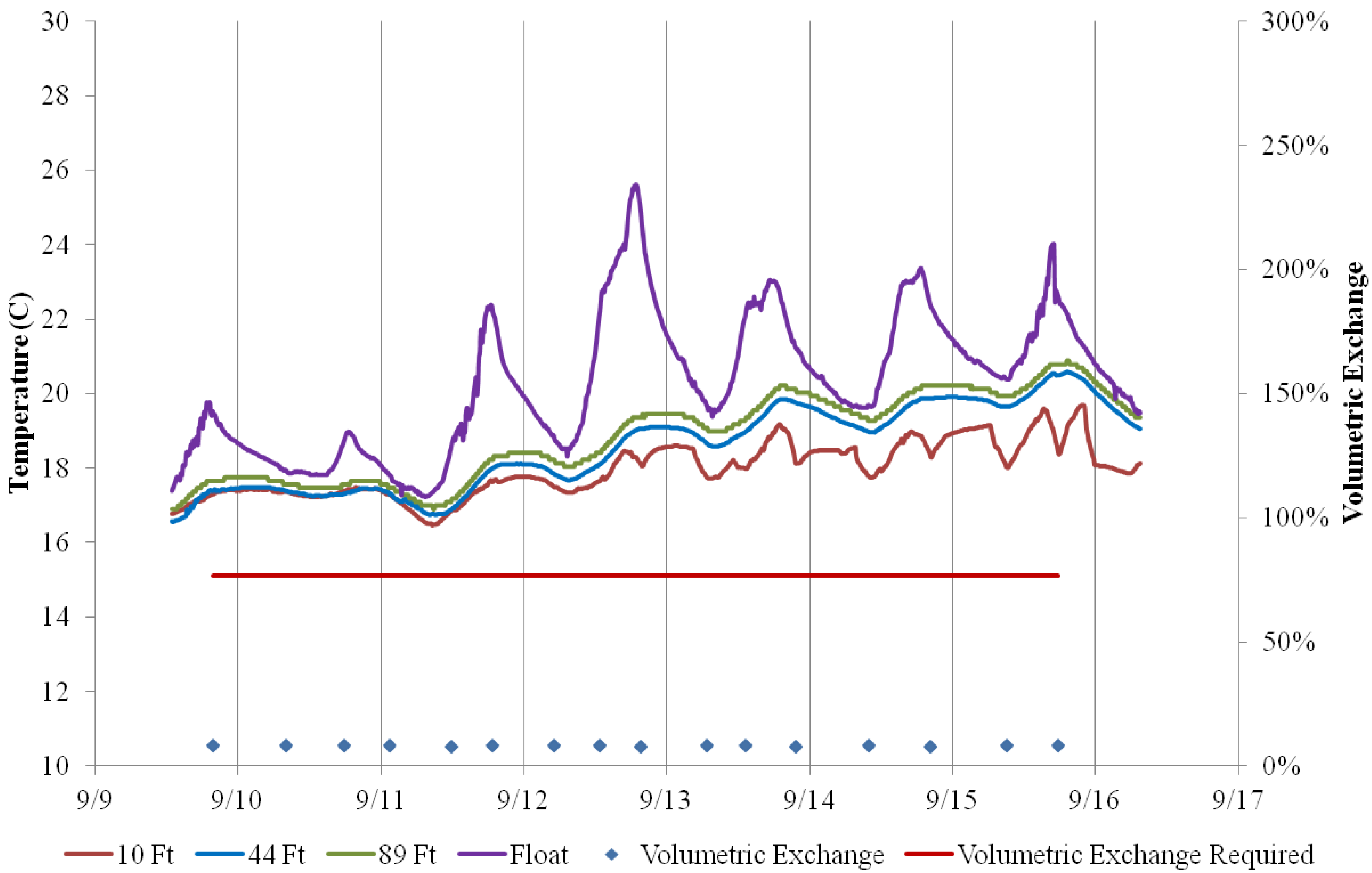


Figure F.9. Temperature profile with actual and required volumetric exchange ratios for short term tank 4.

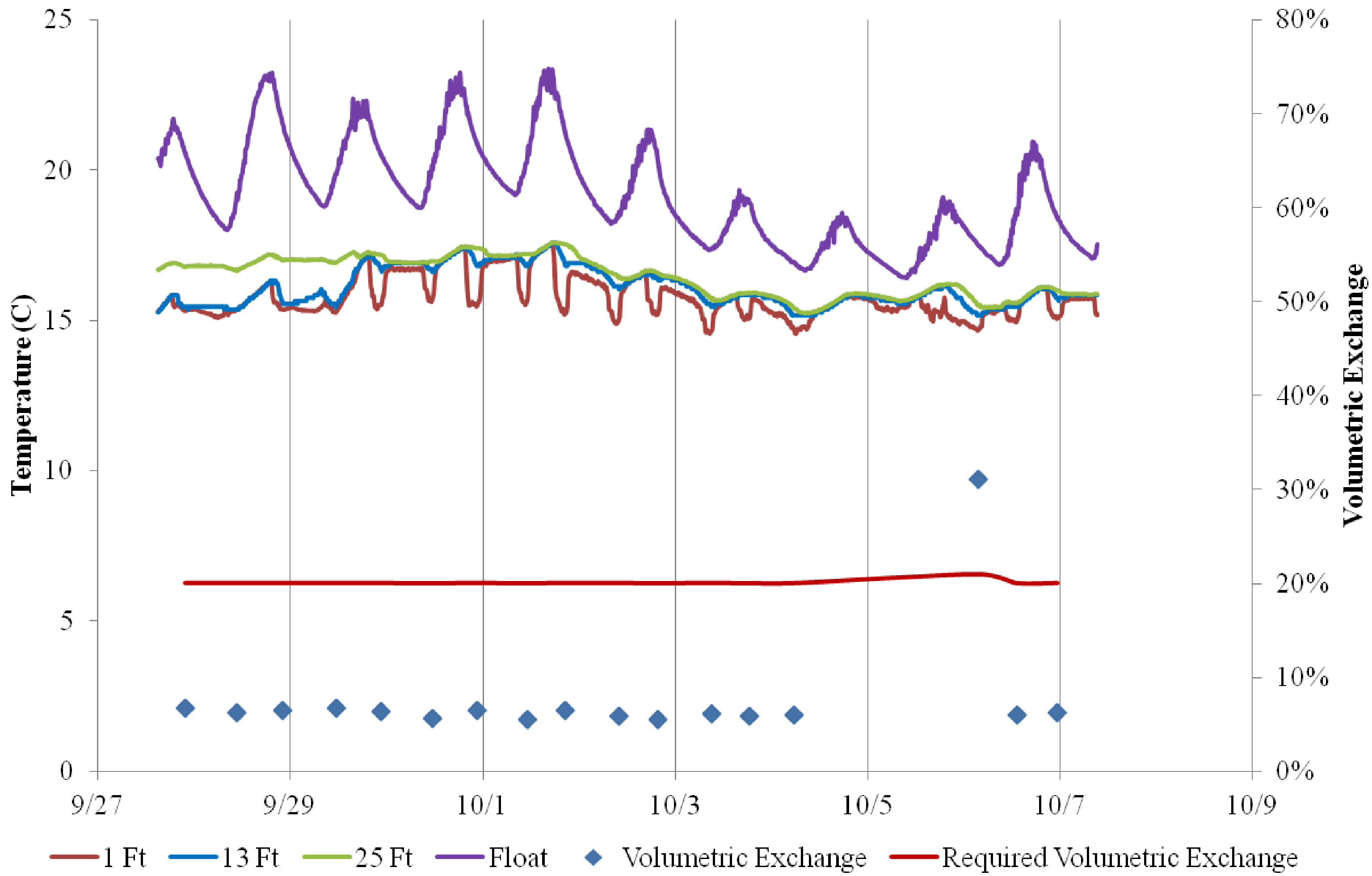


Figure F.10. Temperature profile with actual and required volumetric exchange ratios for short term tank 5.

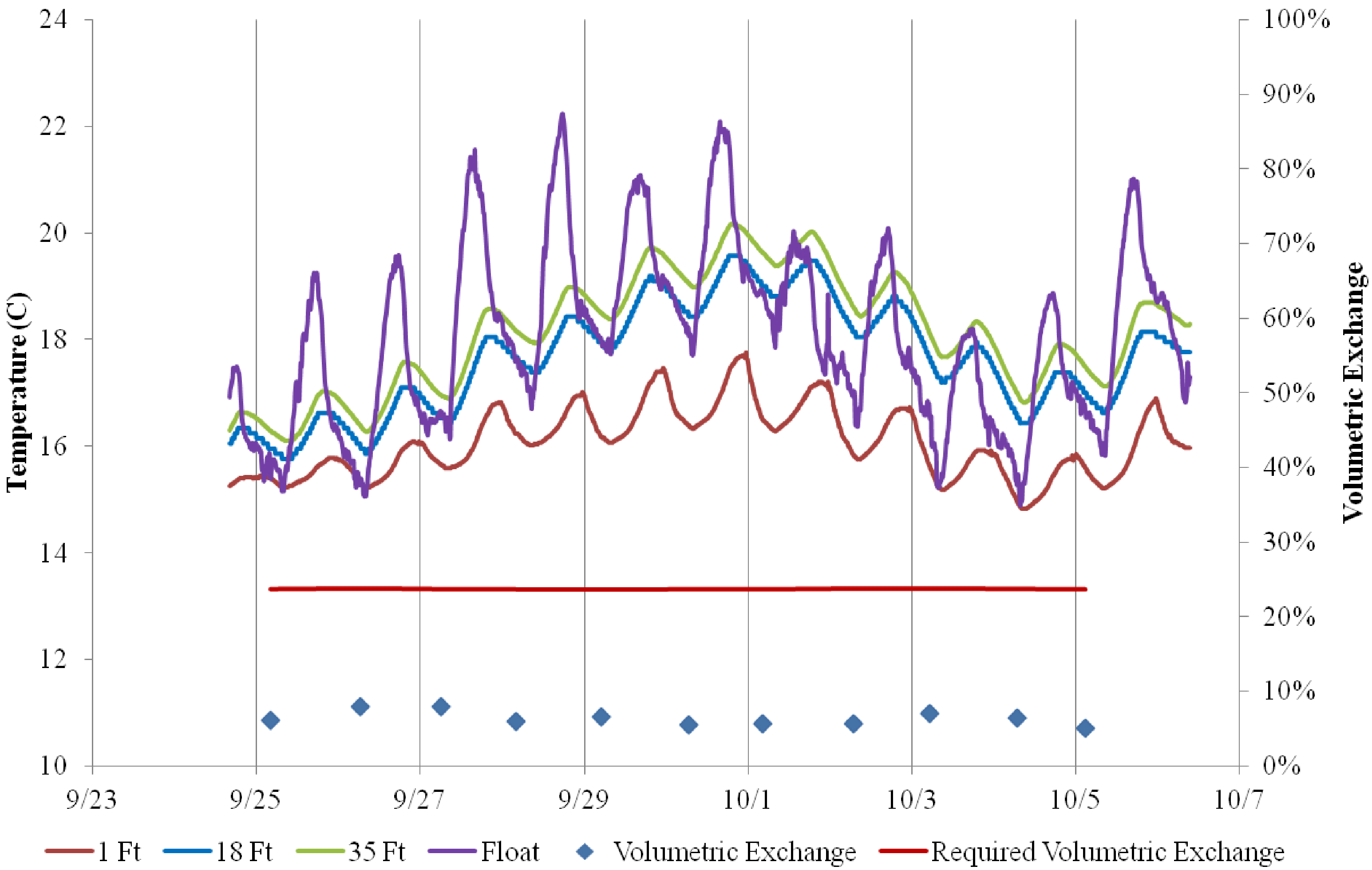


Figure F.11. Temperature profile with actual and required volumetric exchange ratios for short term tank 6.

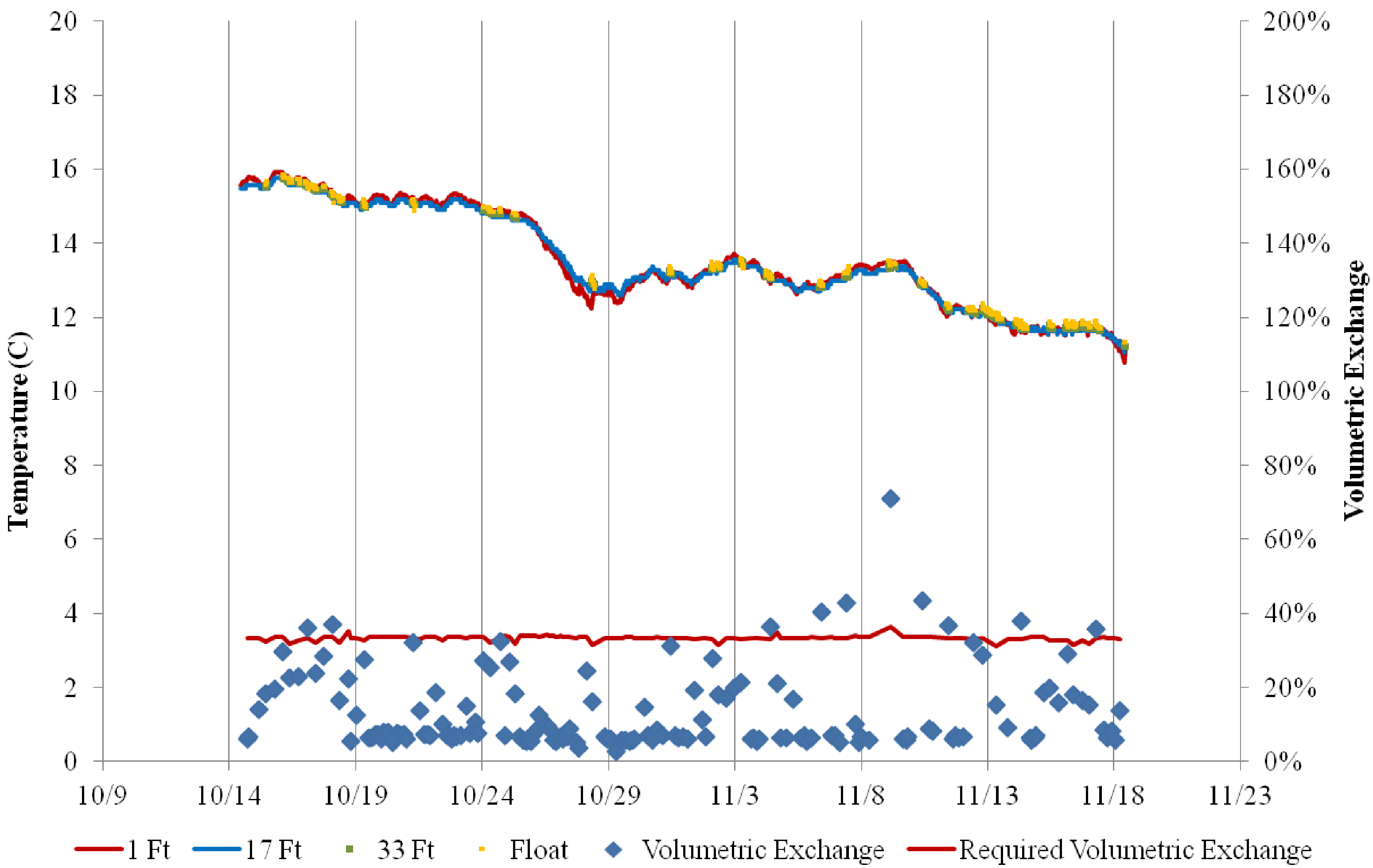


Figure F.12. Temperature profile with actual and required volumetric exchange ratios for short term tank 7.

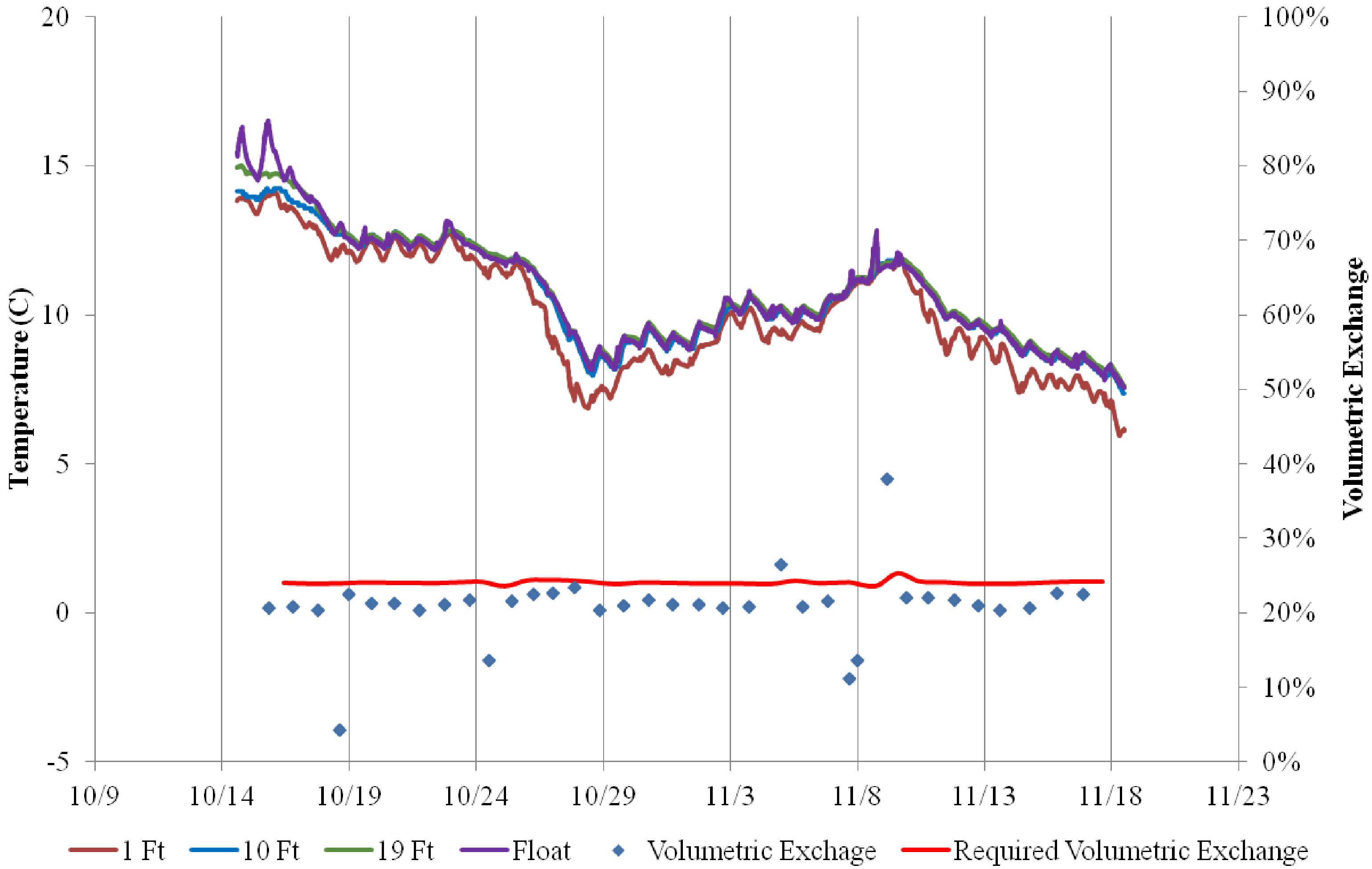


Figure F.13. Temperature profile with actual and required volumetric exchange ratios for short term tank 8.

APPENDIX G

DENSIMETRIC FROUDE NUMBERS TO OVERCOME STRATIFIED CONDITIONS IN TANKS

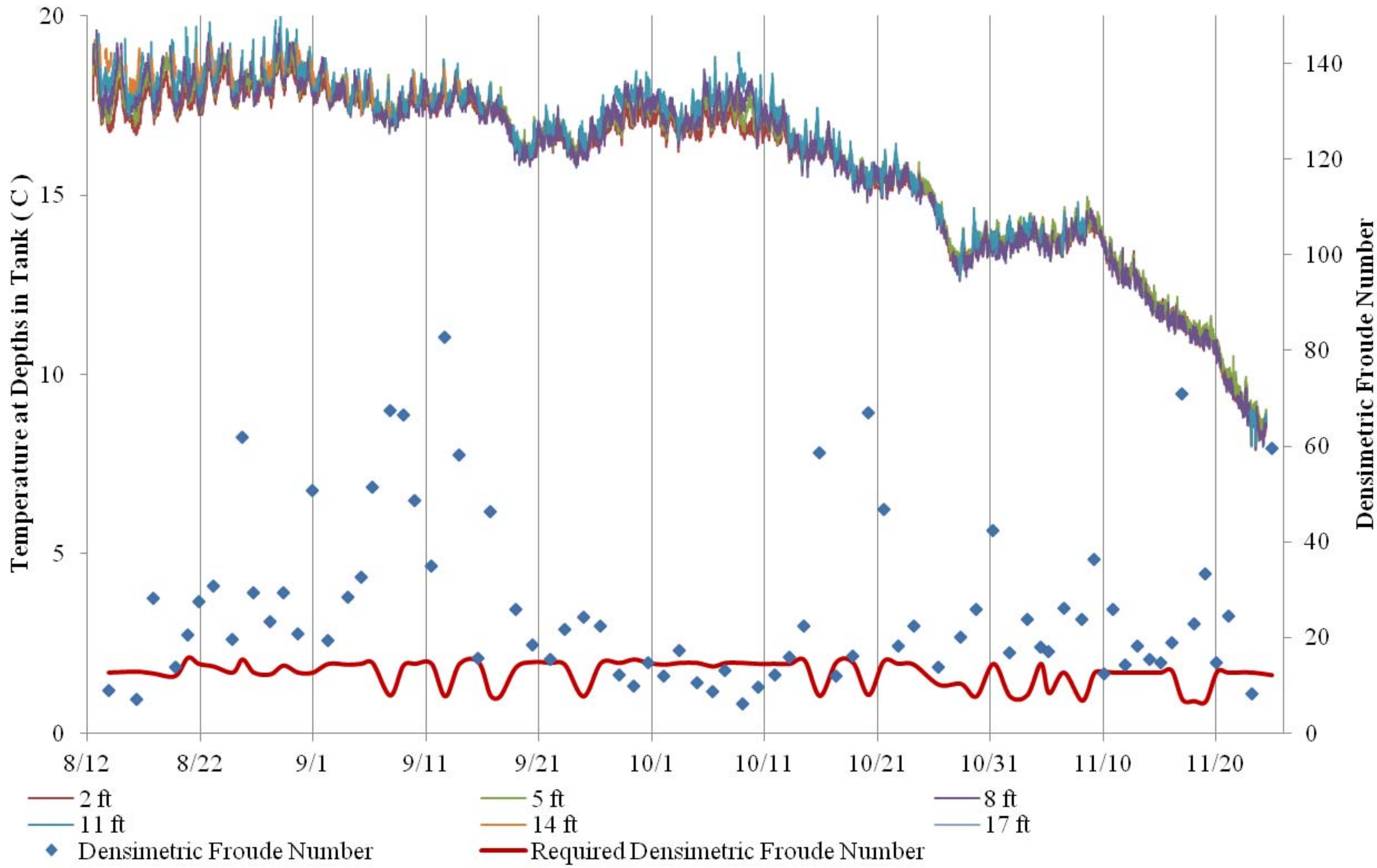


Figure G.1. Temperature profile with actual and required densimetric Froude numbers for long term tank A.

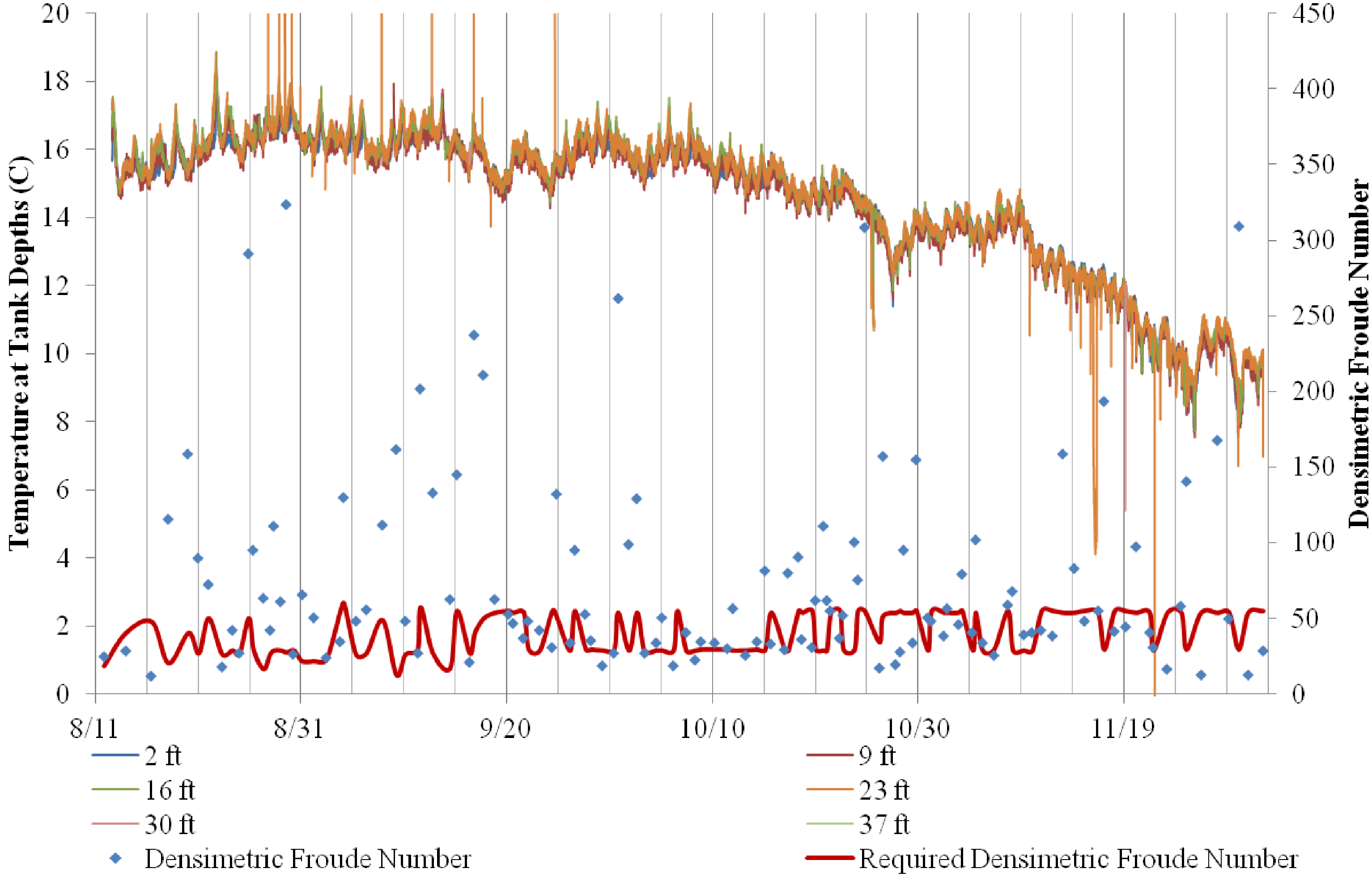


Figure G.2. Temperature profile with actual and required densimetric Froude numbers for long term tank B.

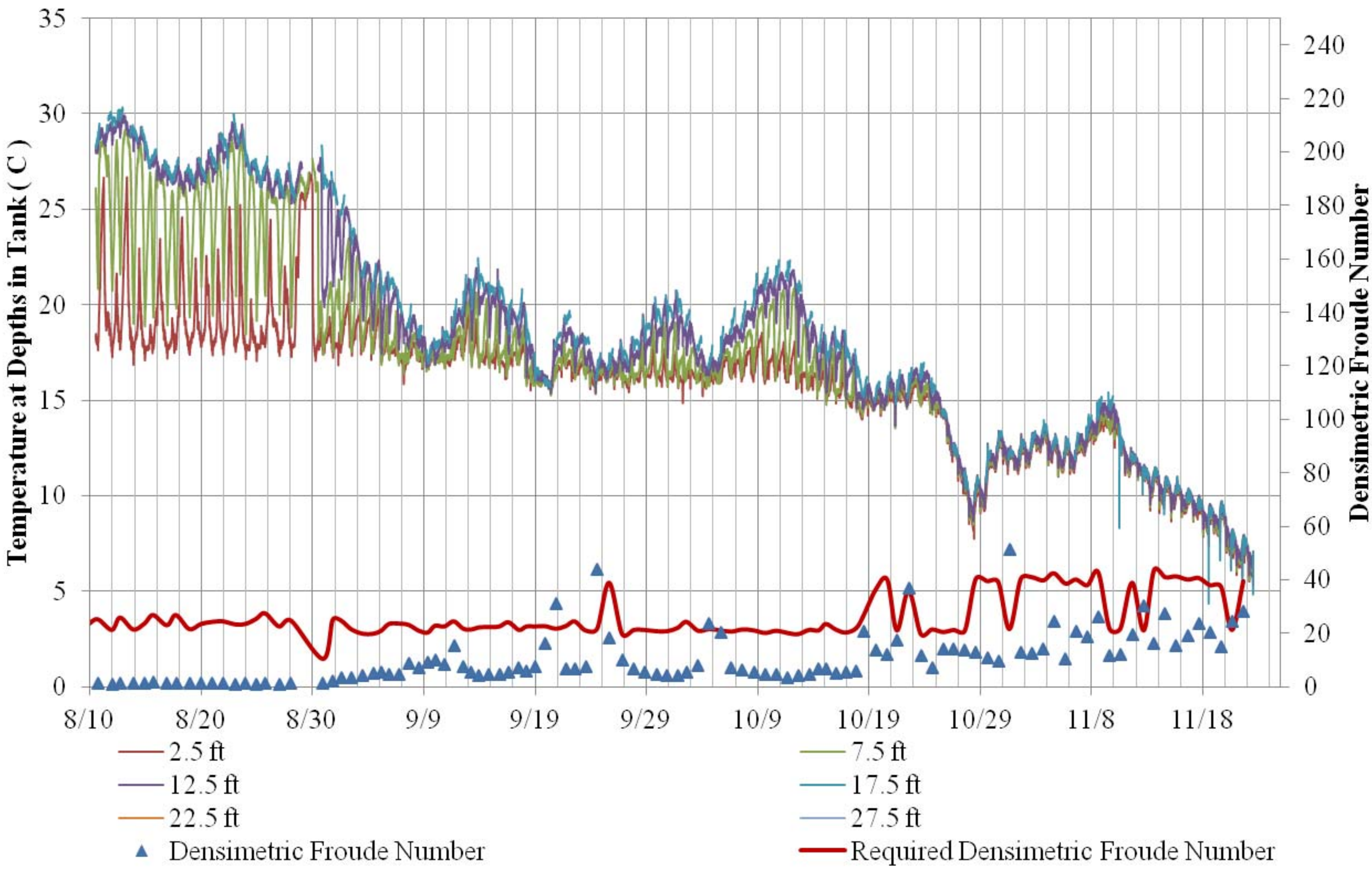


Figure G.3. Temperature profile with actual and required densimetric Froude numbers for long term tank C.

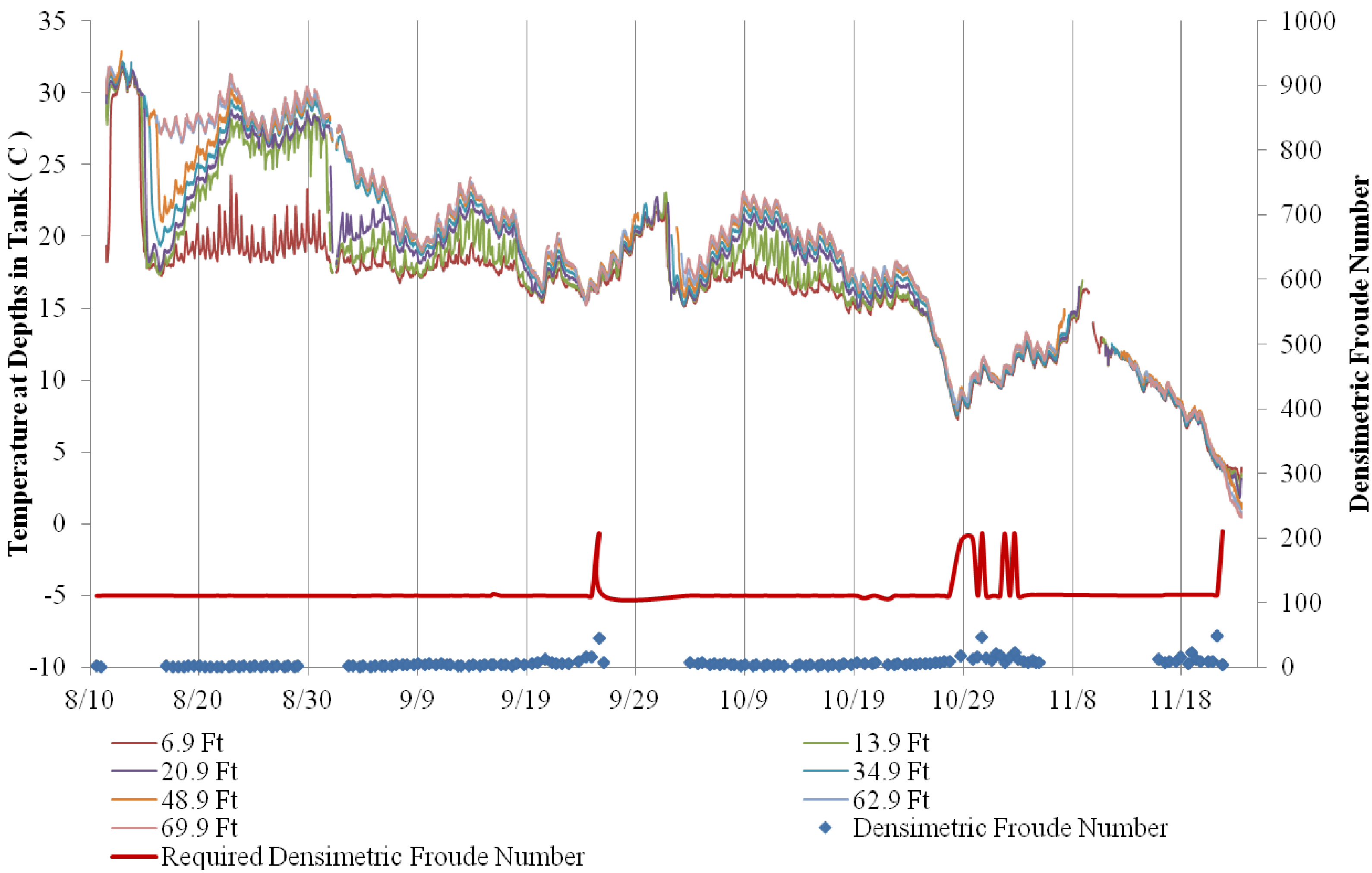


Figure G.4. Temperature profile with actual and required densimetric Froude numbers for long term tank D.

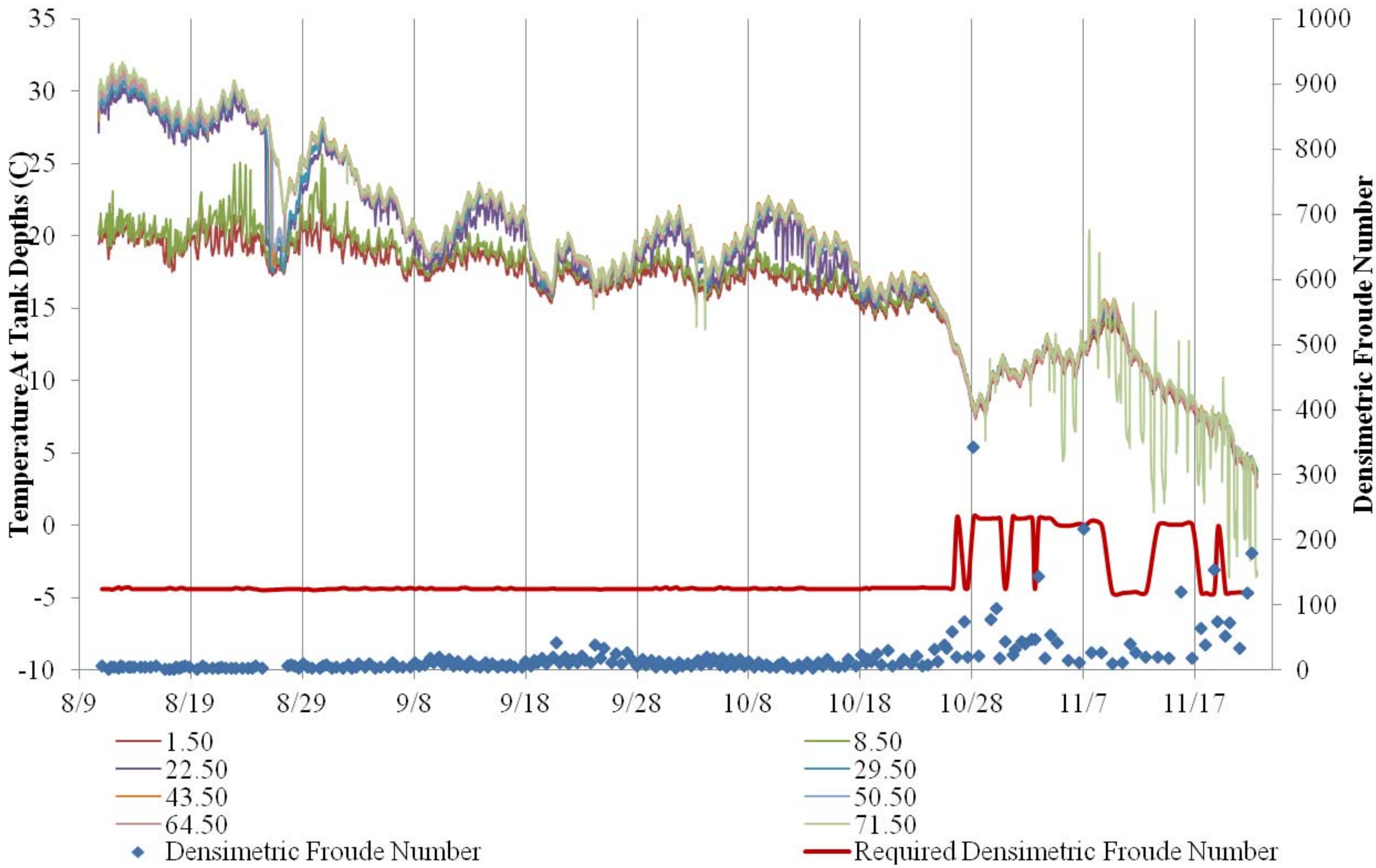


Figure G.5. Temperature profile with actual and required densimetric Froude numbers for long term tank E.

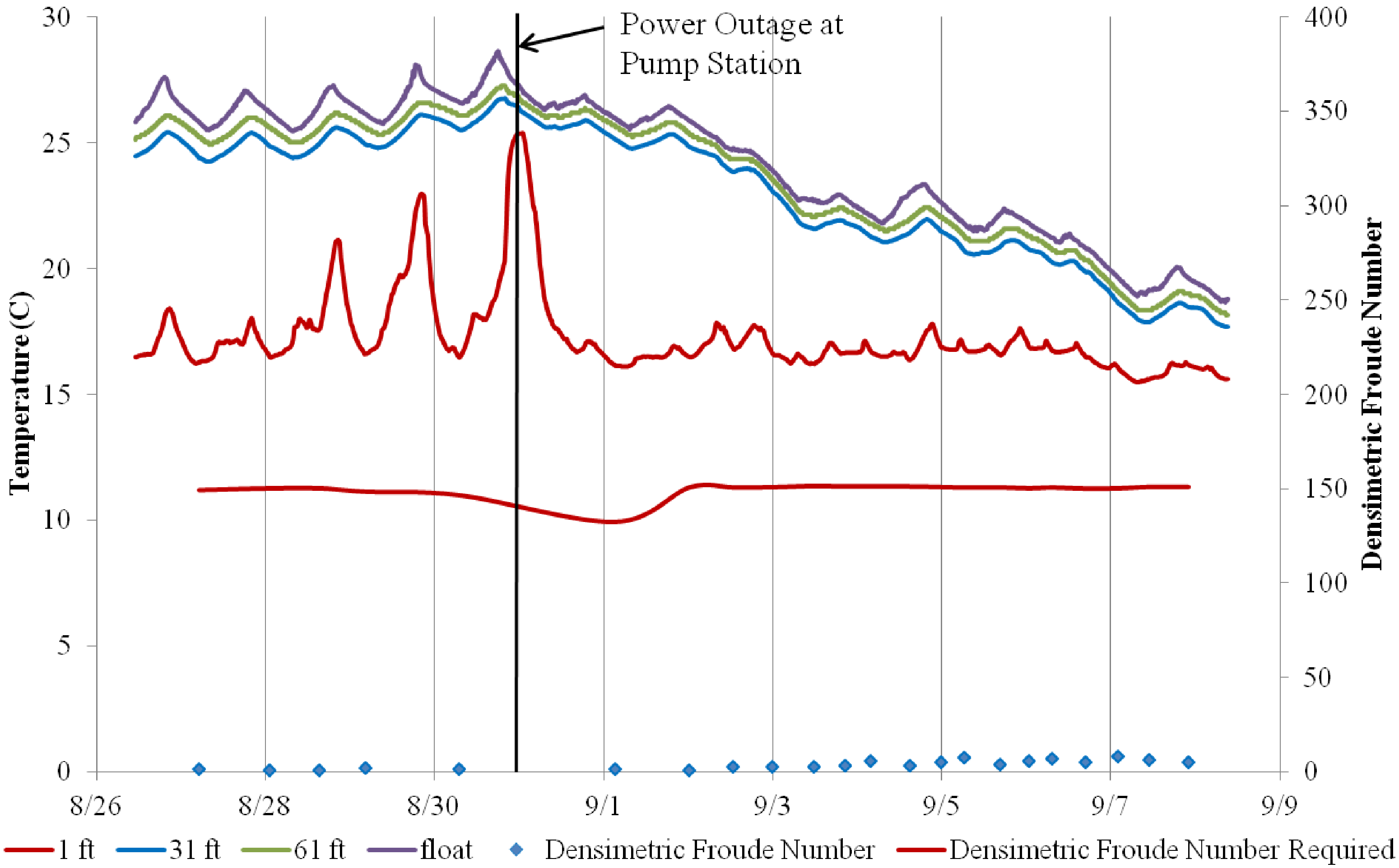


Figure G.6. Temperature profile with actual and required densimetric Froude numbers for short term tank 1.

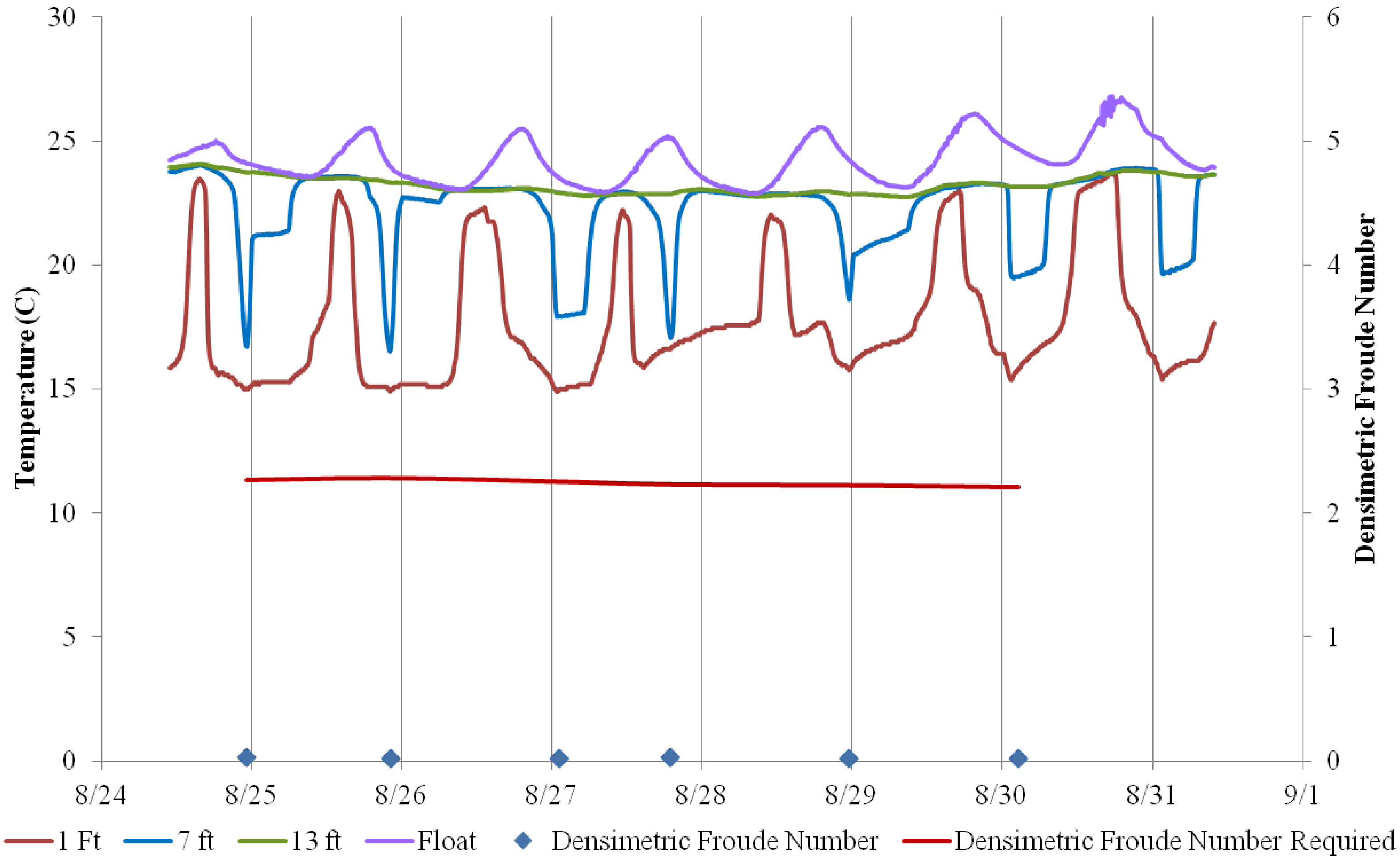


Figure G.7. Temperature profile with actual and required densimetric Froude numbers for short term tank 2.

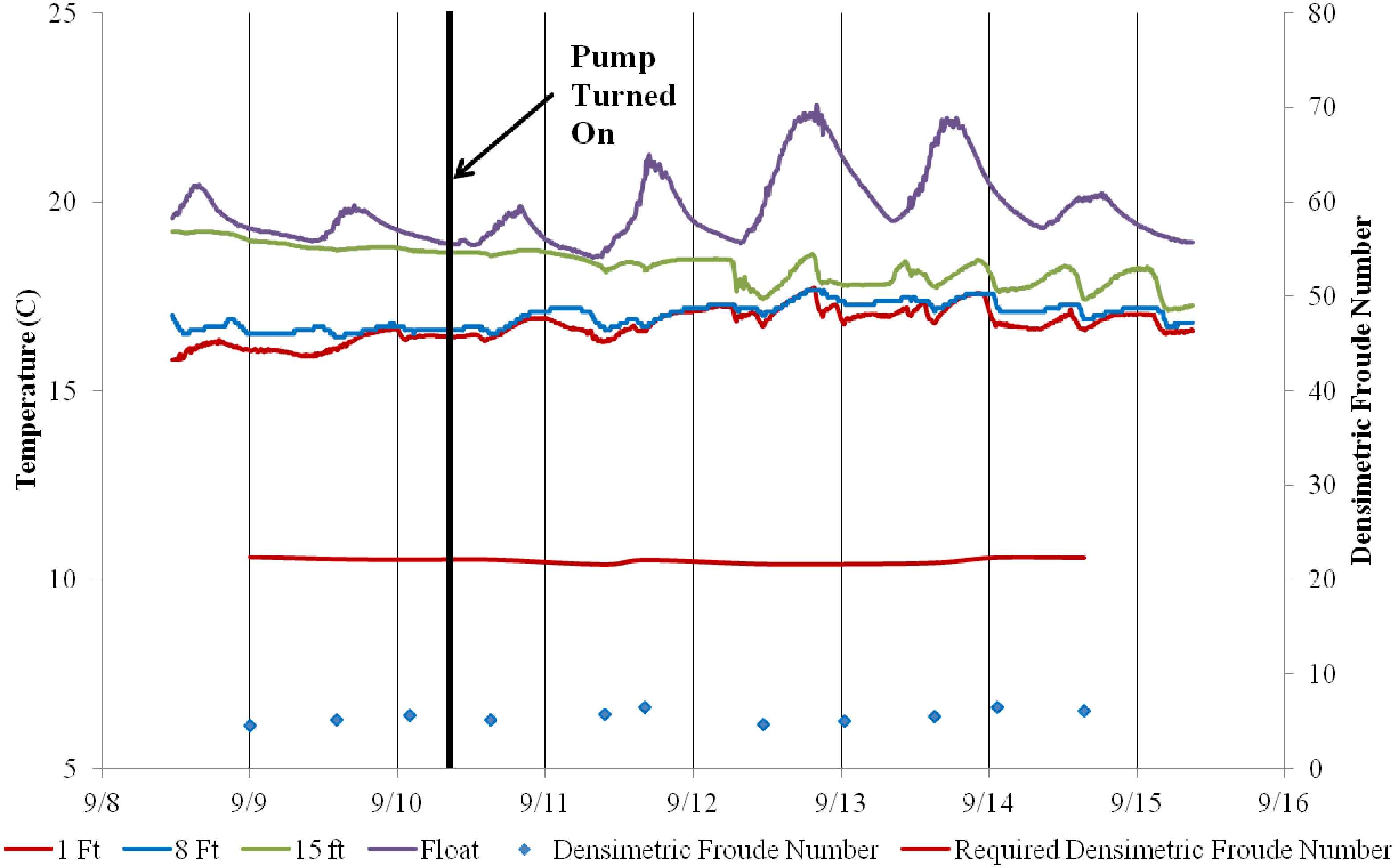


Figure G.8. Temperature profile with actual and required densimetric Froude numbers for short term tank 3.

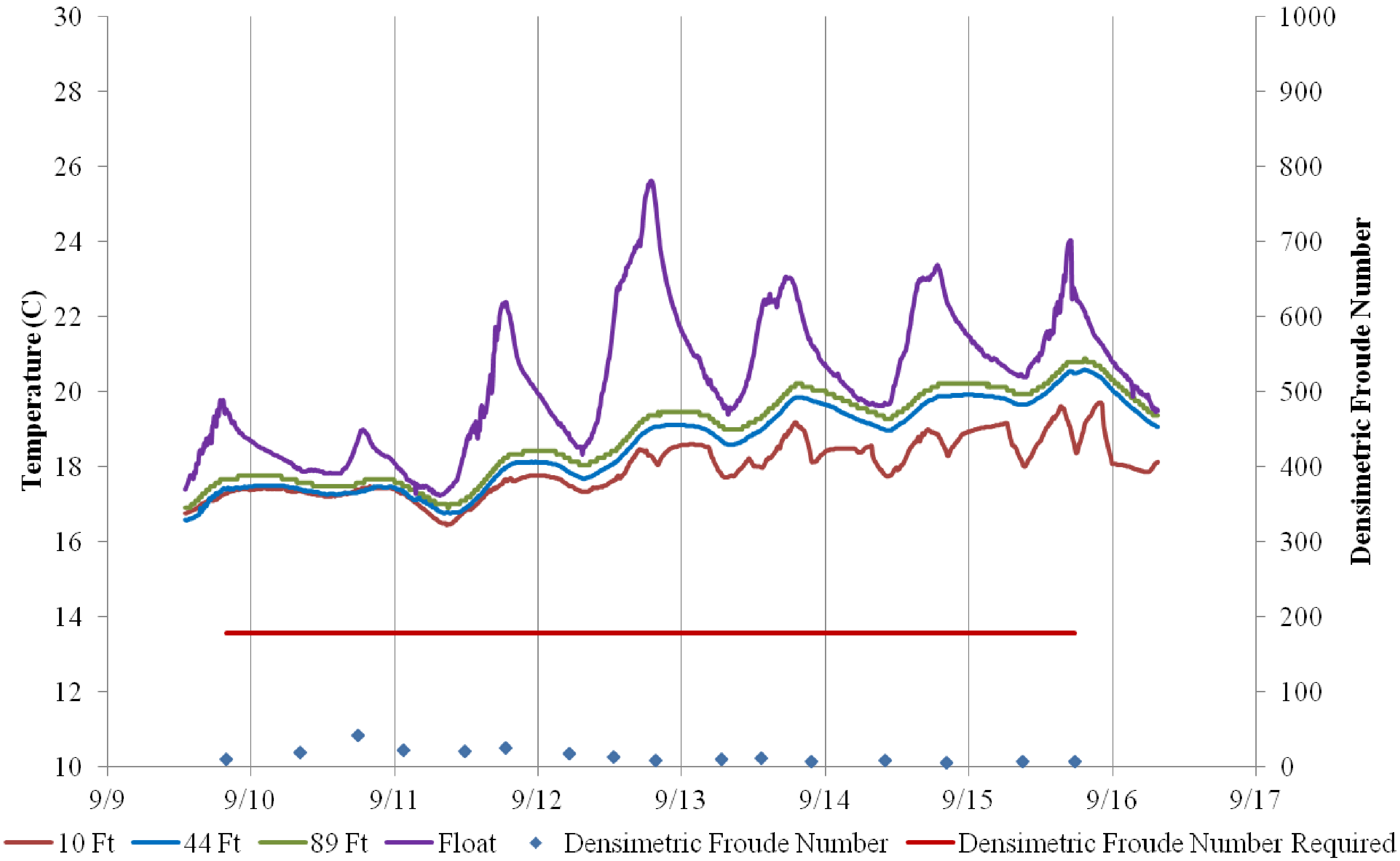


Figure G.9. Temperature profile with actual and required densimetric Froude numbers for short term tank 4.

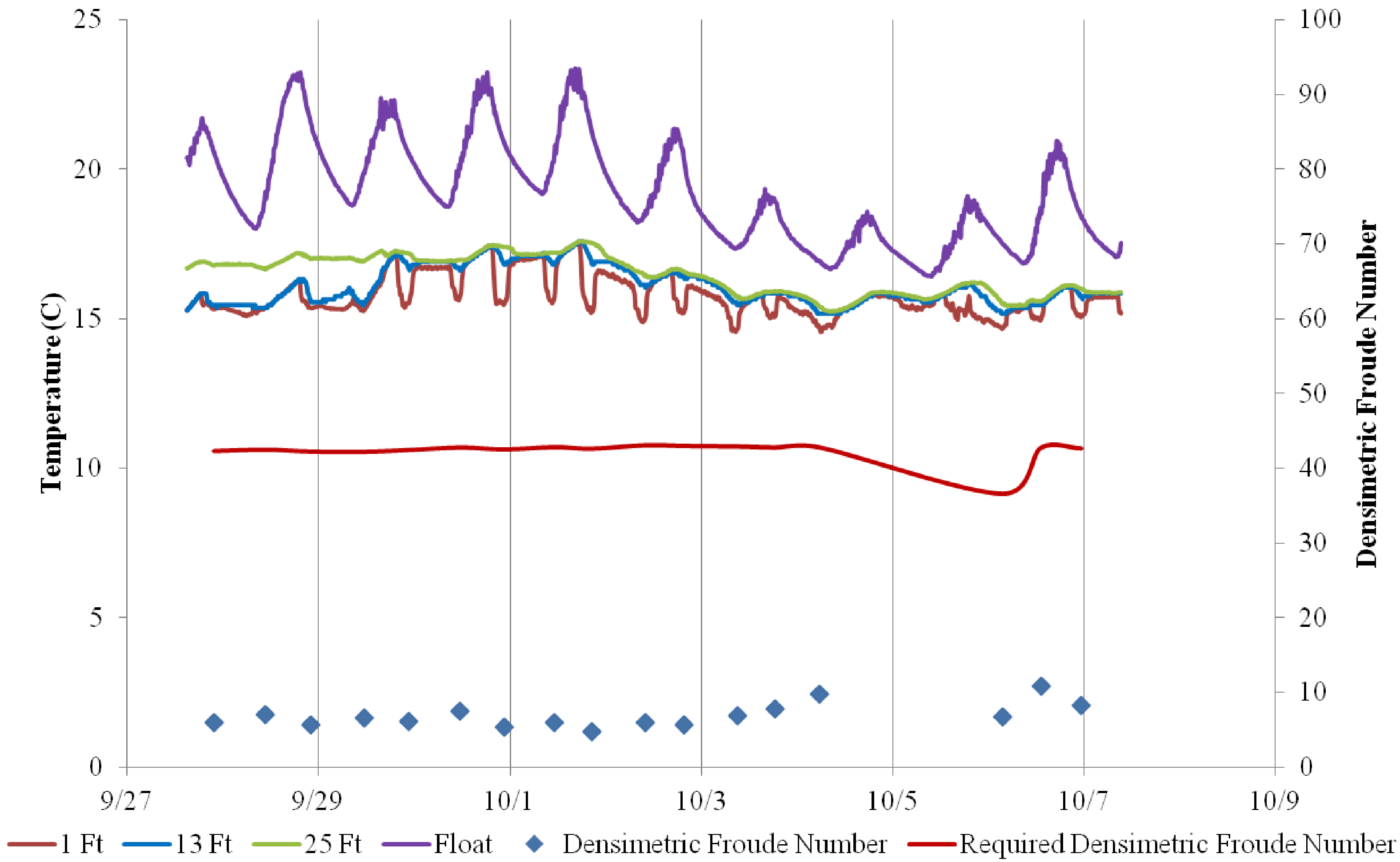


Figure G.10. Temperature profile with actual and required densimetric Froude numbers for short term tank 5.

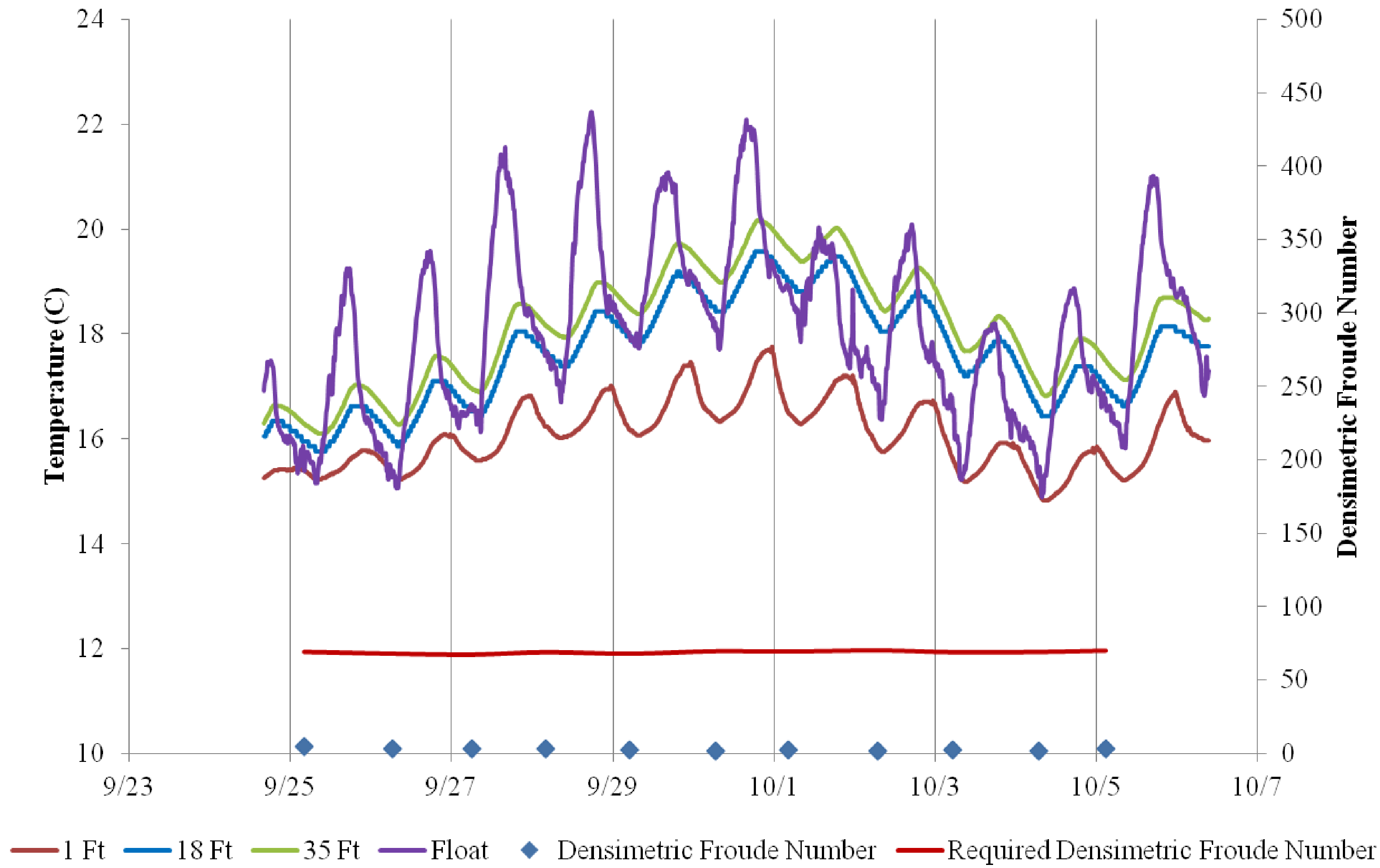


Figure G.11. Temperature profile with actual and required densimetric Froude numbers for short term tank 6.

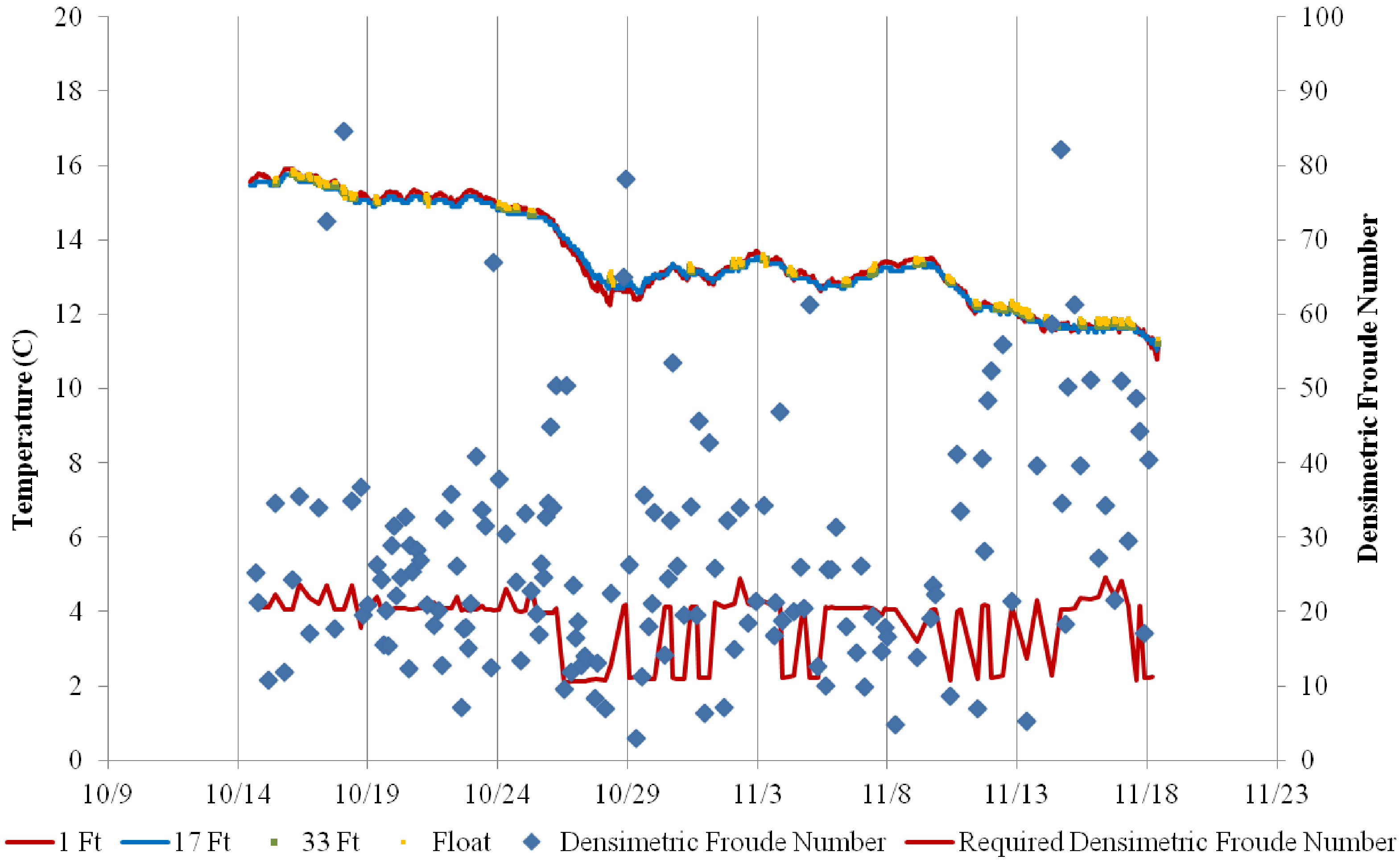


Figure G.12. Temperature profile with actual and required densimetric Froude numbers for short term tank 7.

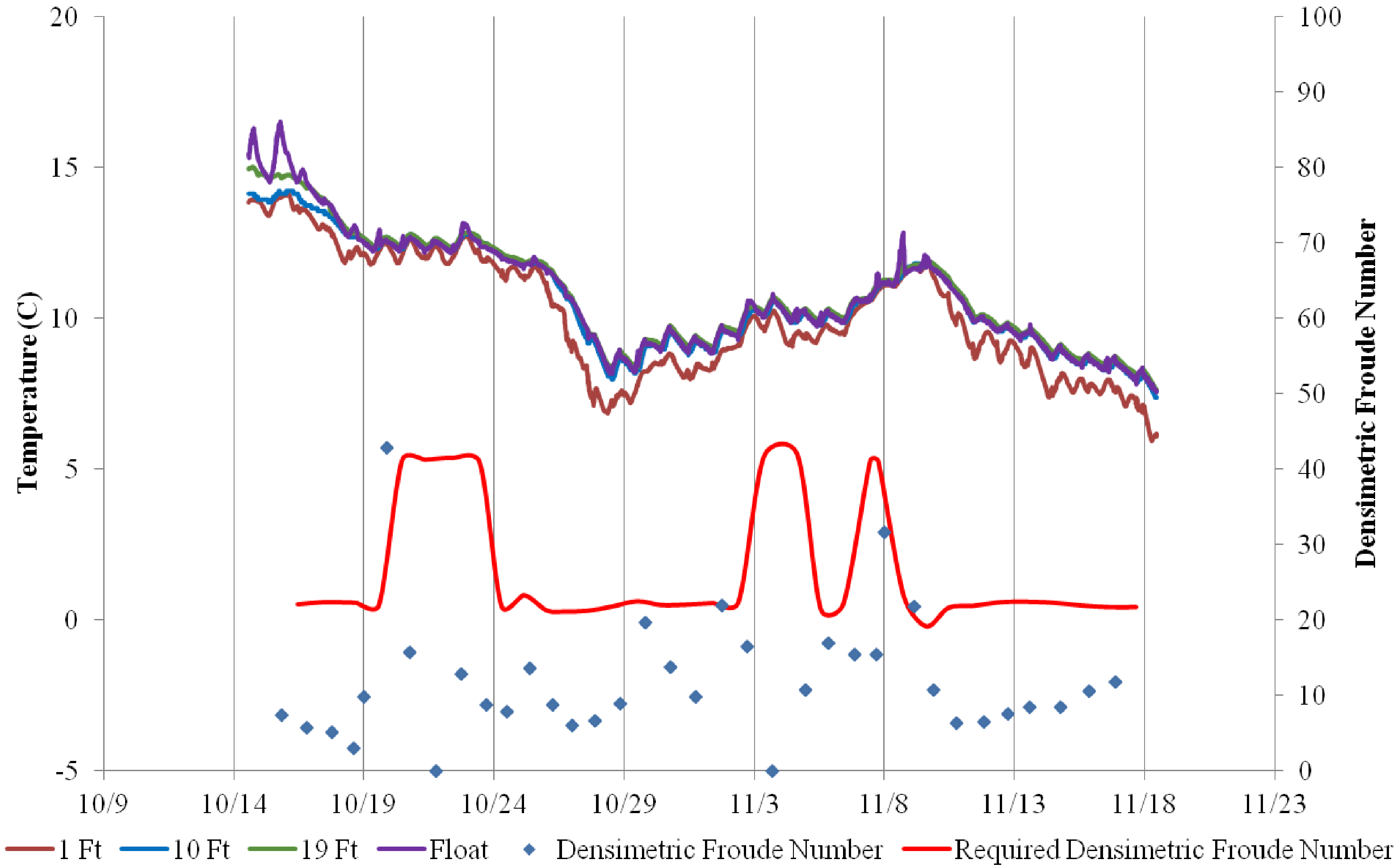


Figure G.13. Temperature profile with actual and required densimetric Froude numbers for short term tank 8.

APPENDIX H

DIMENSIONLESS PARAMETER TO ENSURE MIXING IN TANKS

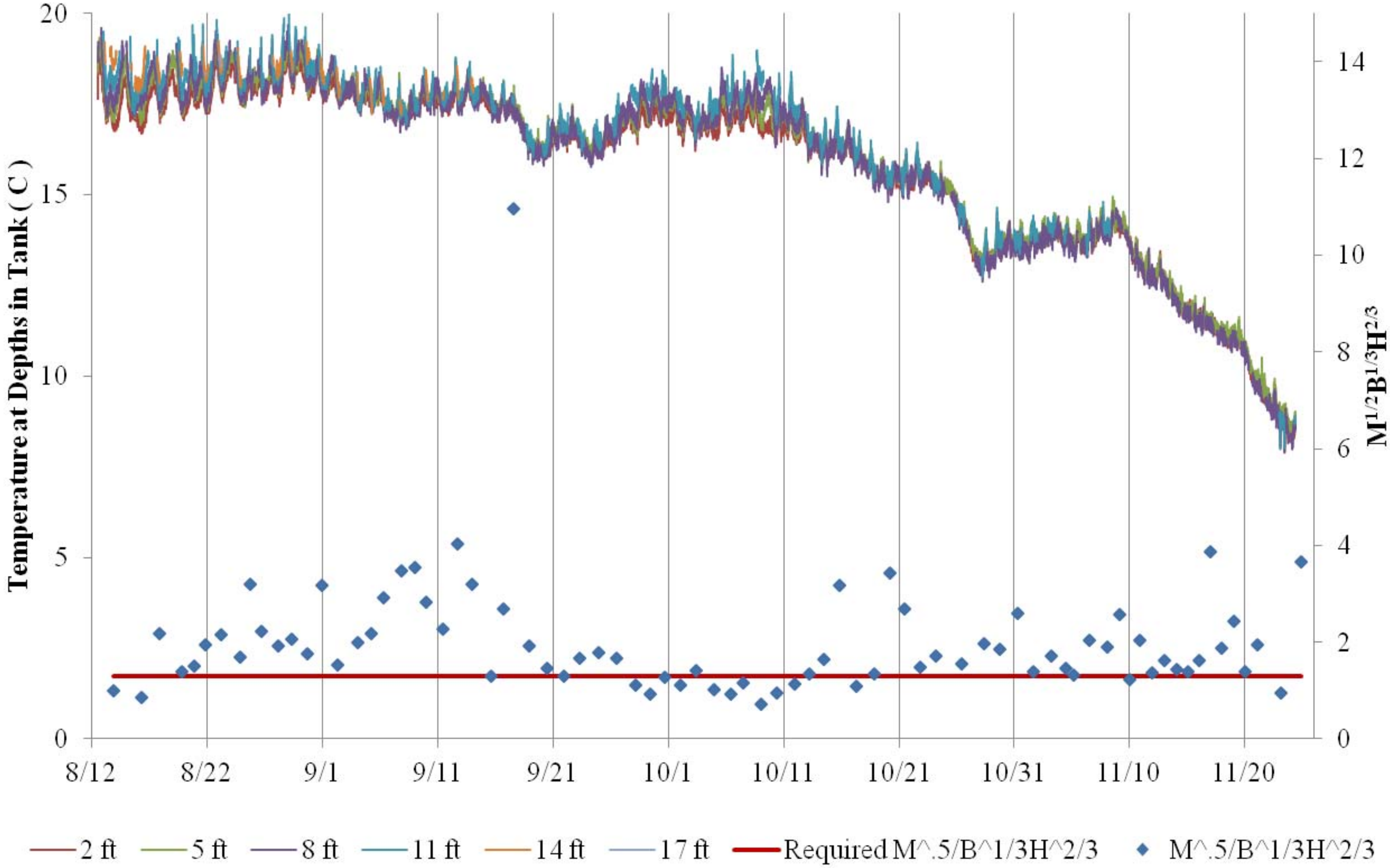


Figure H.1. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank A.

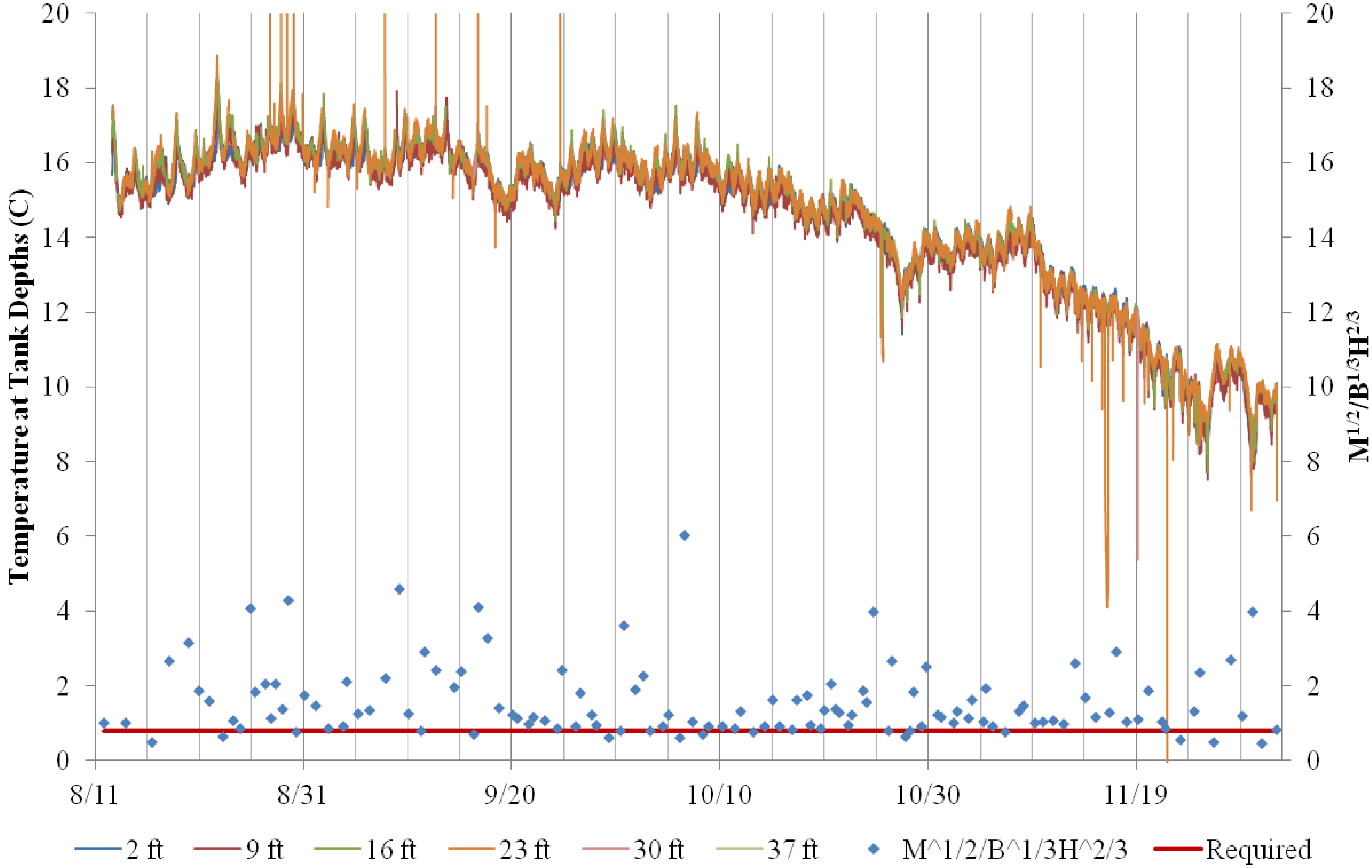


Figure H.2. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank B.

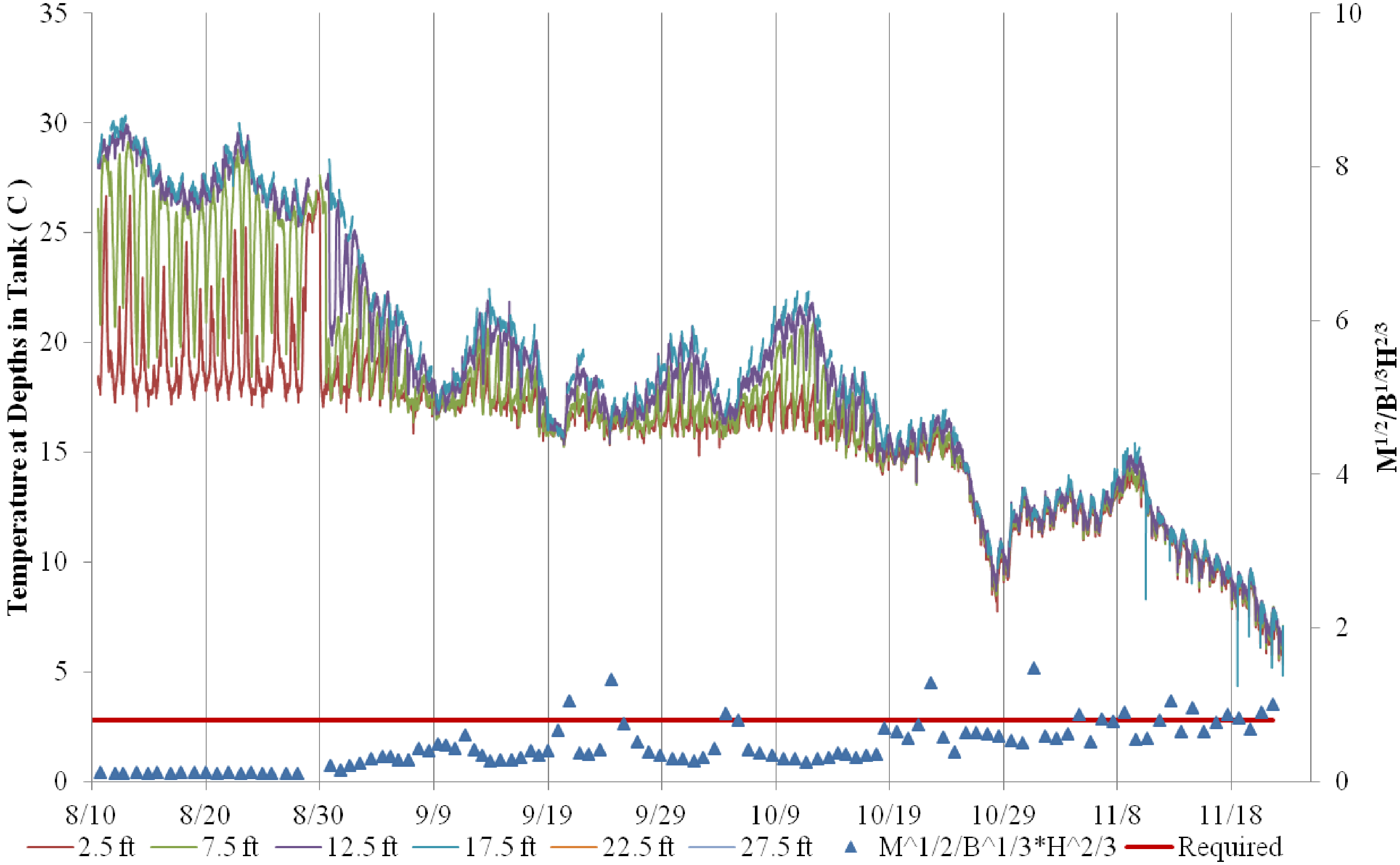


Figure H.3. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank C.

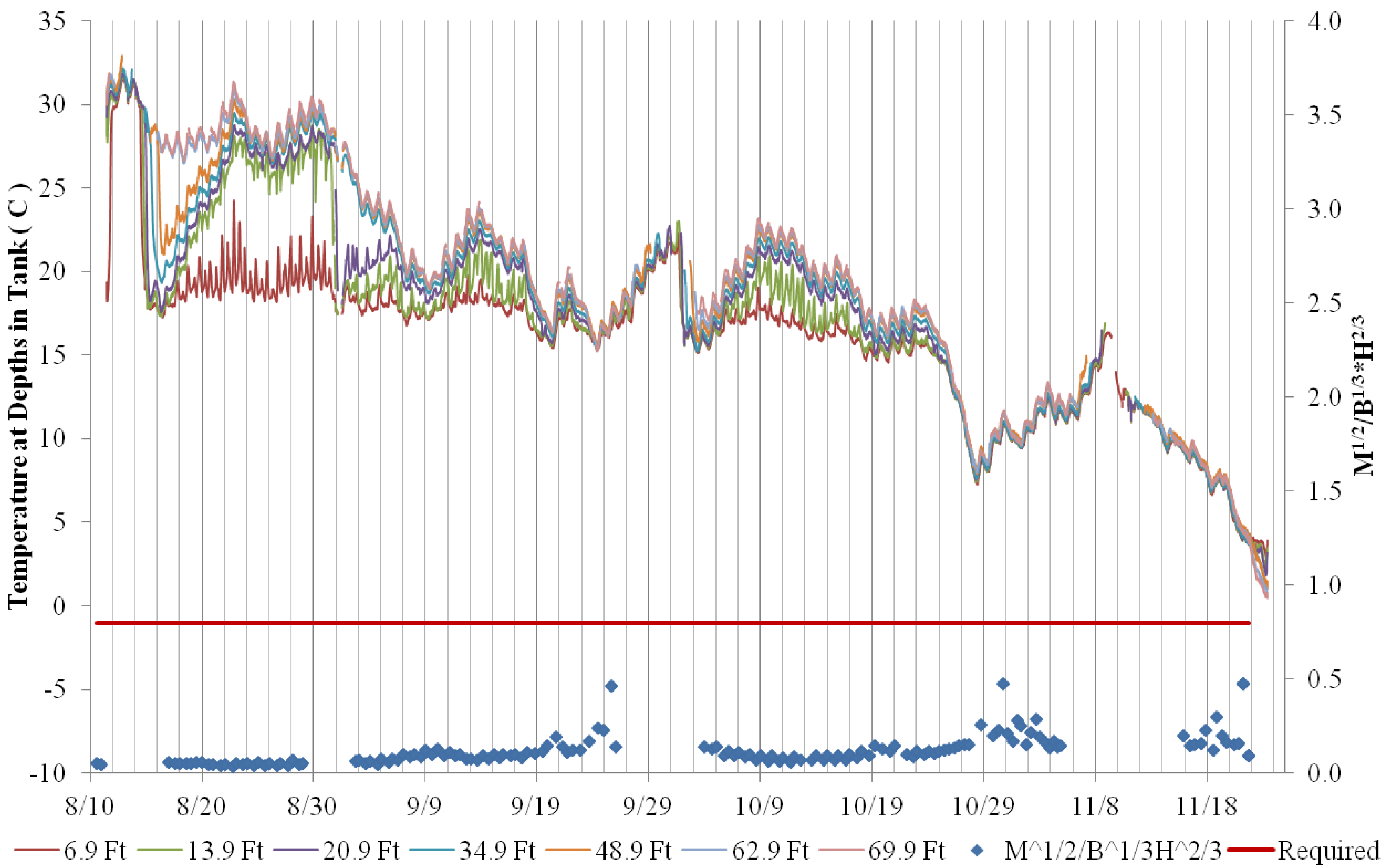


Figure H.4. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank D.

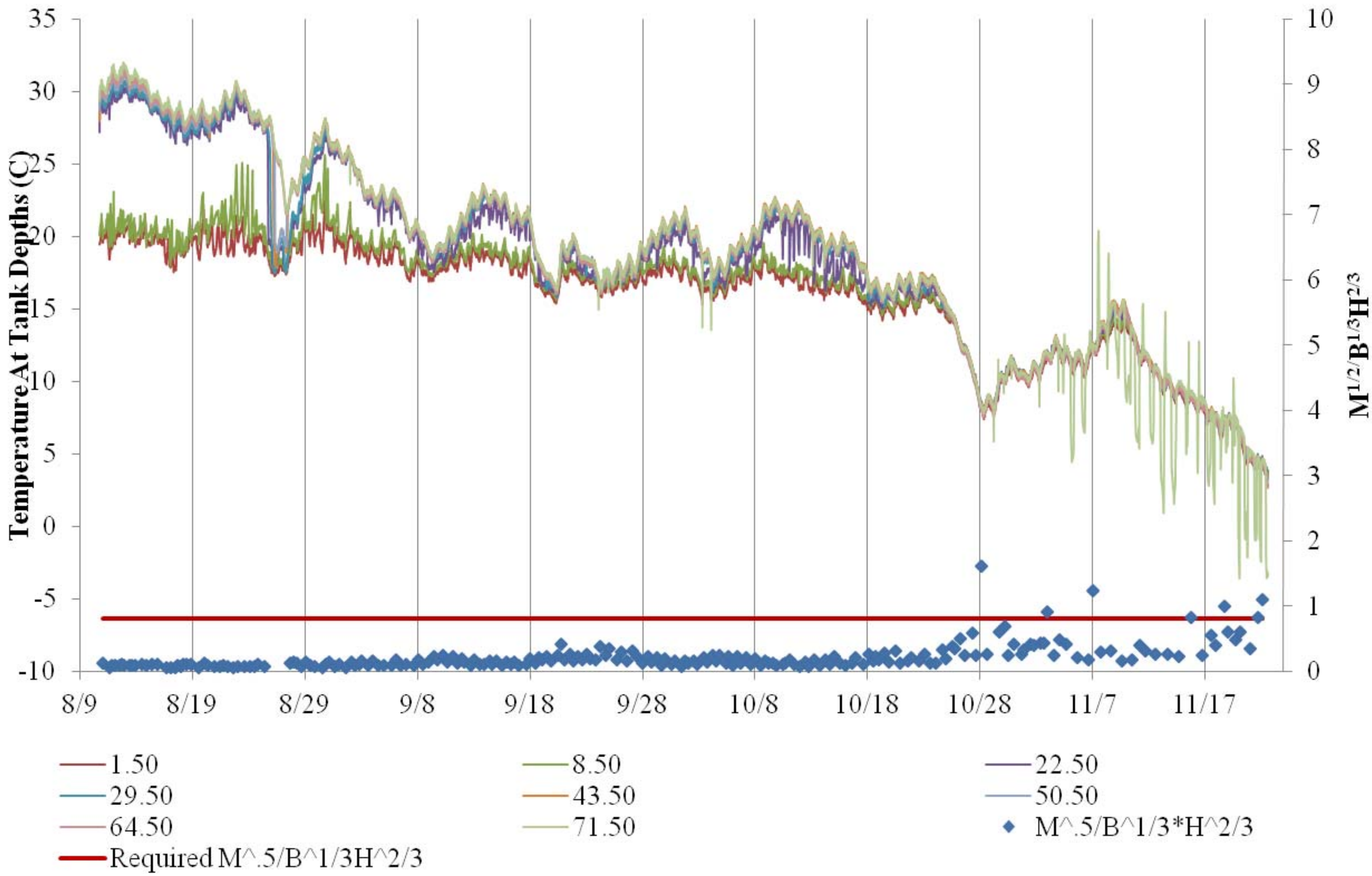


Figure H.5. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for long term tank E.

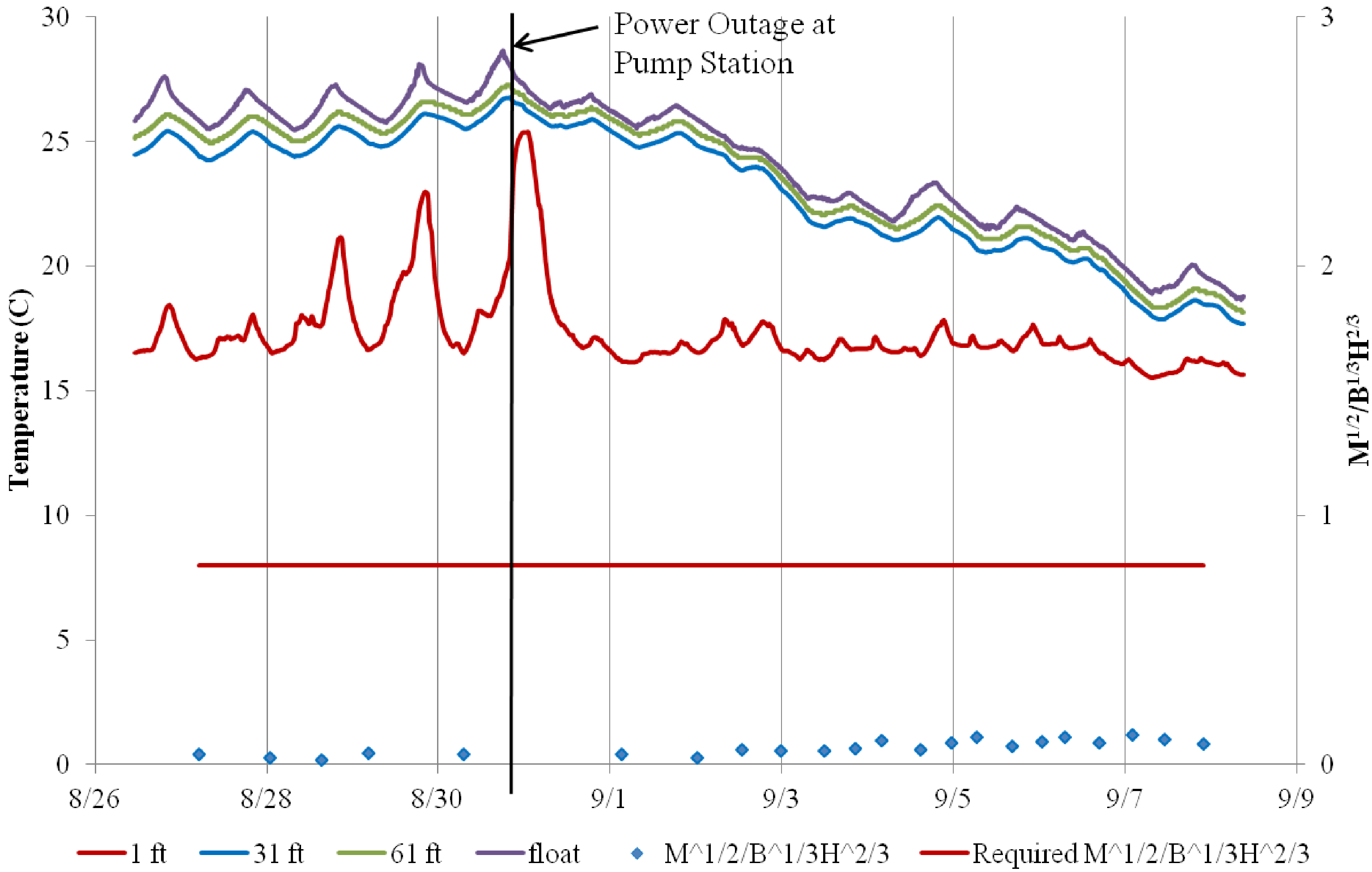


Figure H.6. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 1.

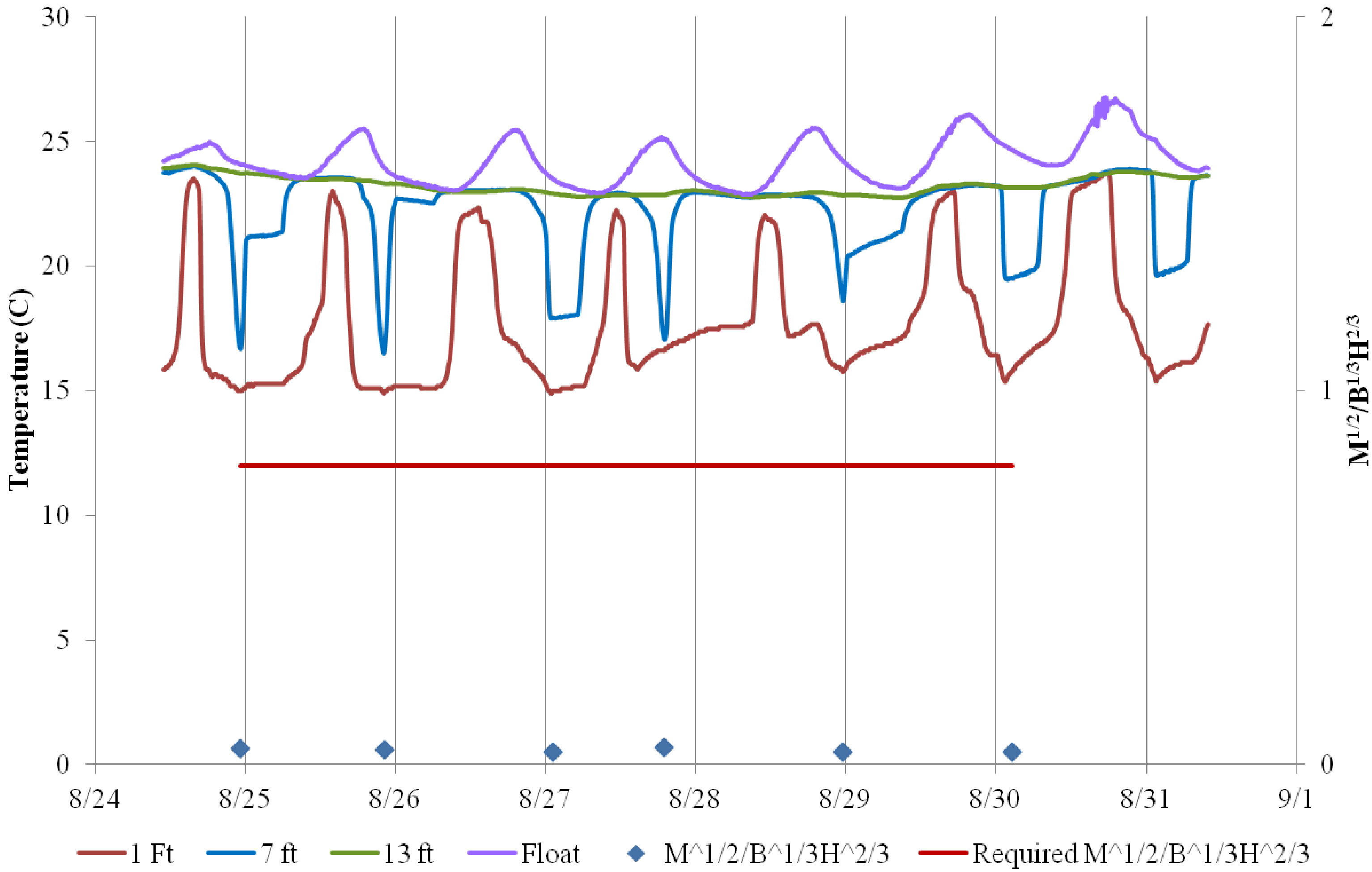


Figure H.7. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 2.

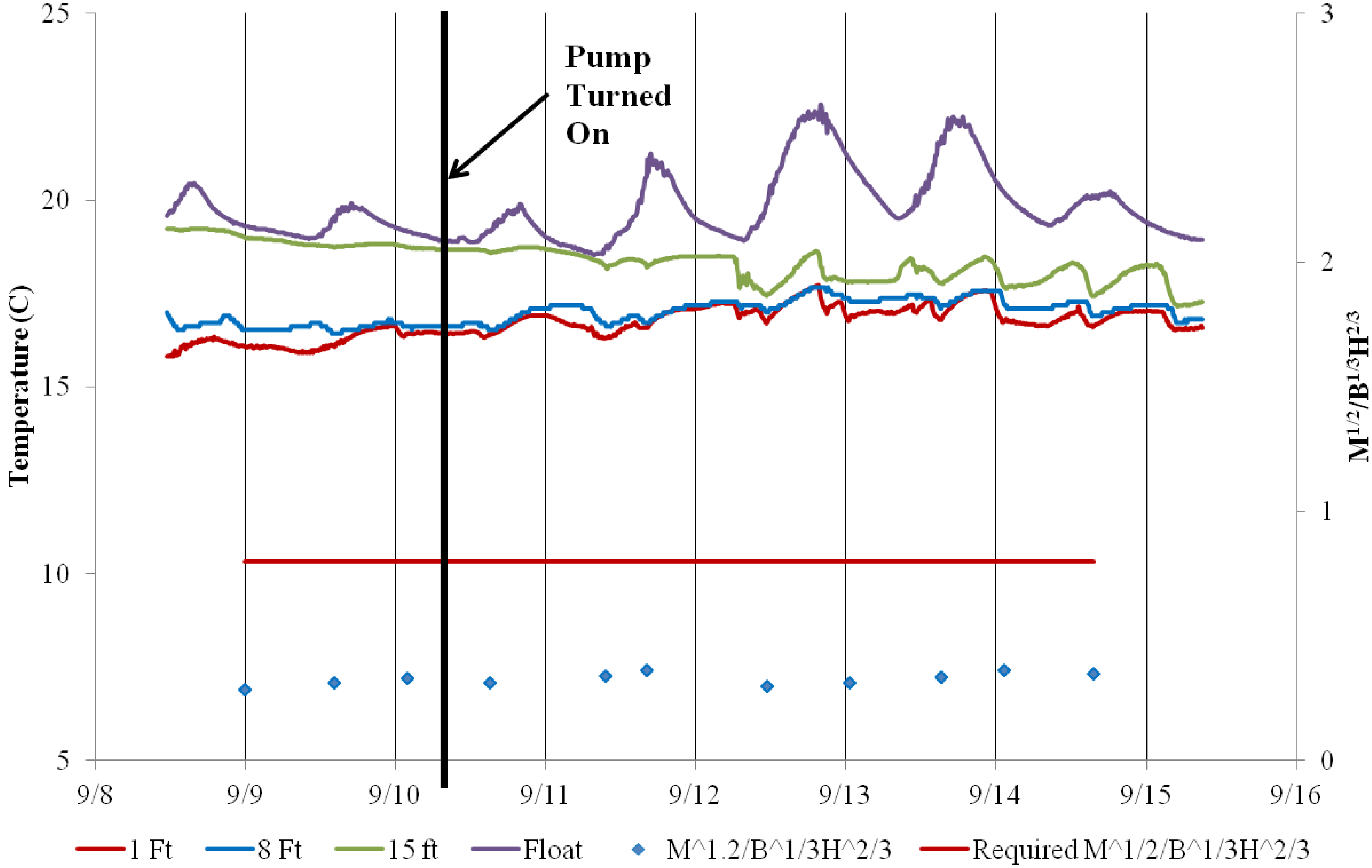


Figure H.8. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 3.

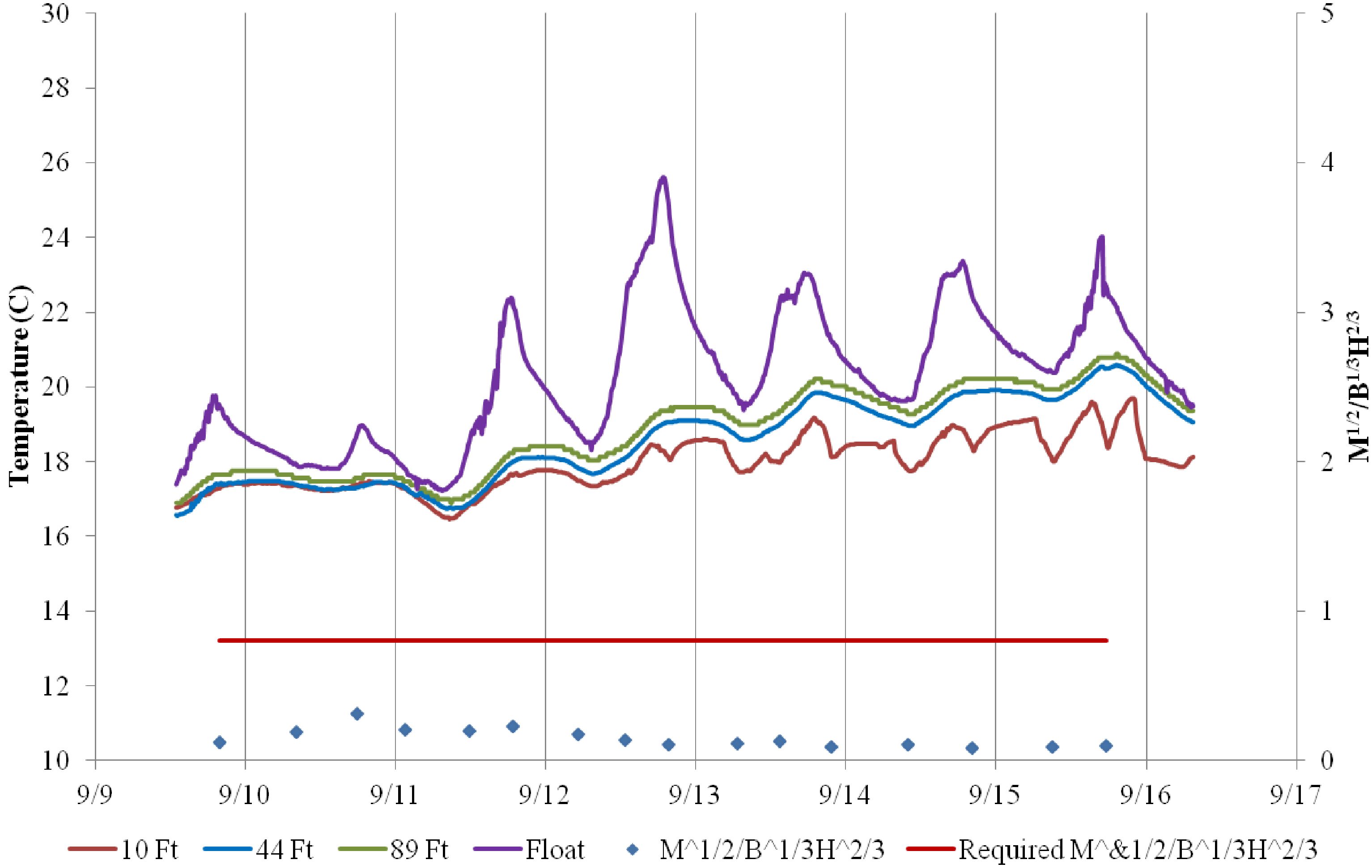


Figure H.9. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 4.

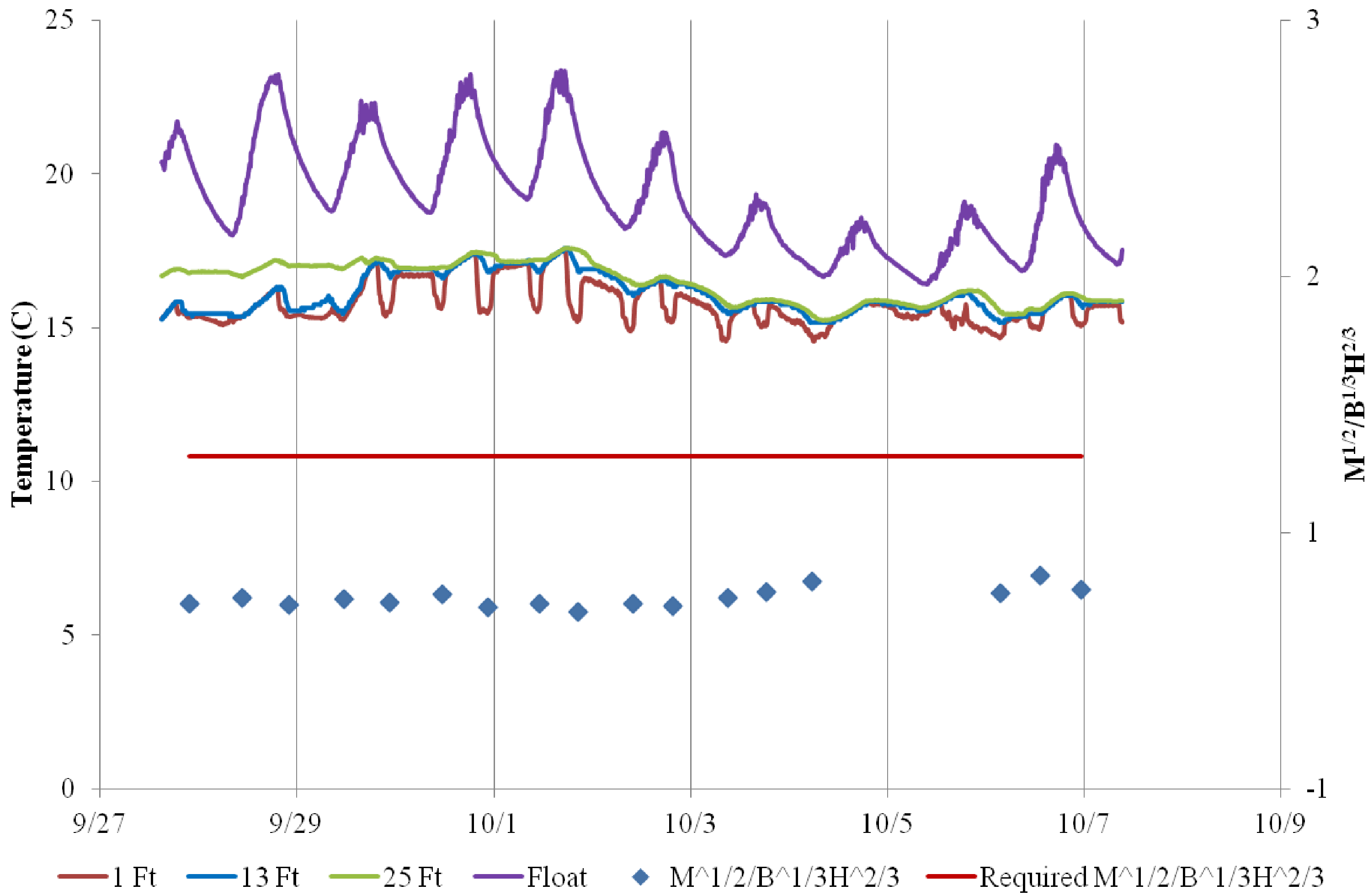


Figure H.10. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 5.

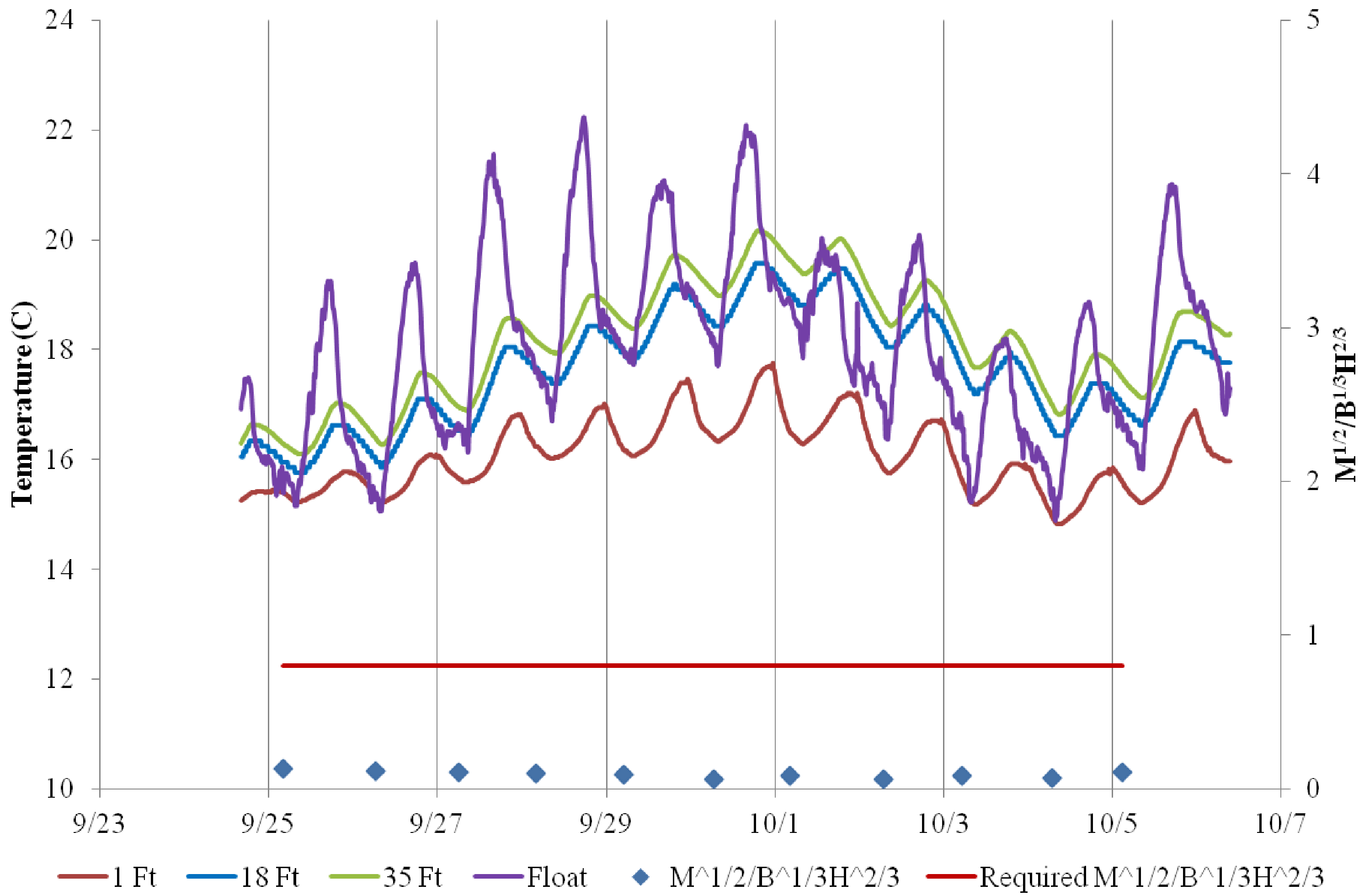


Figure H.11. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 6.

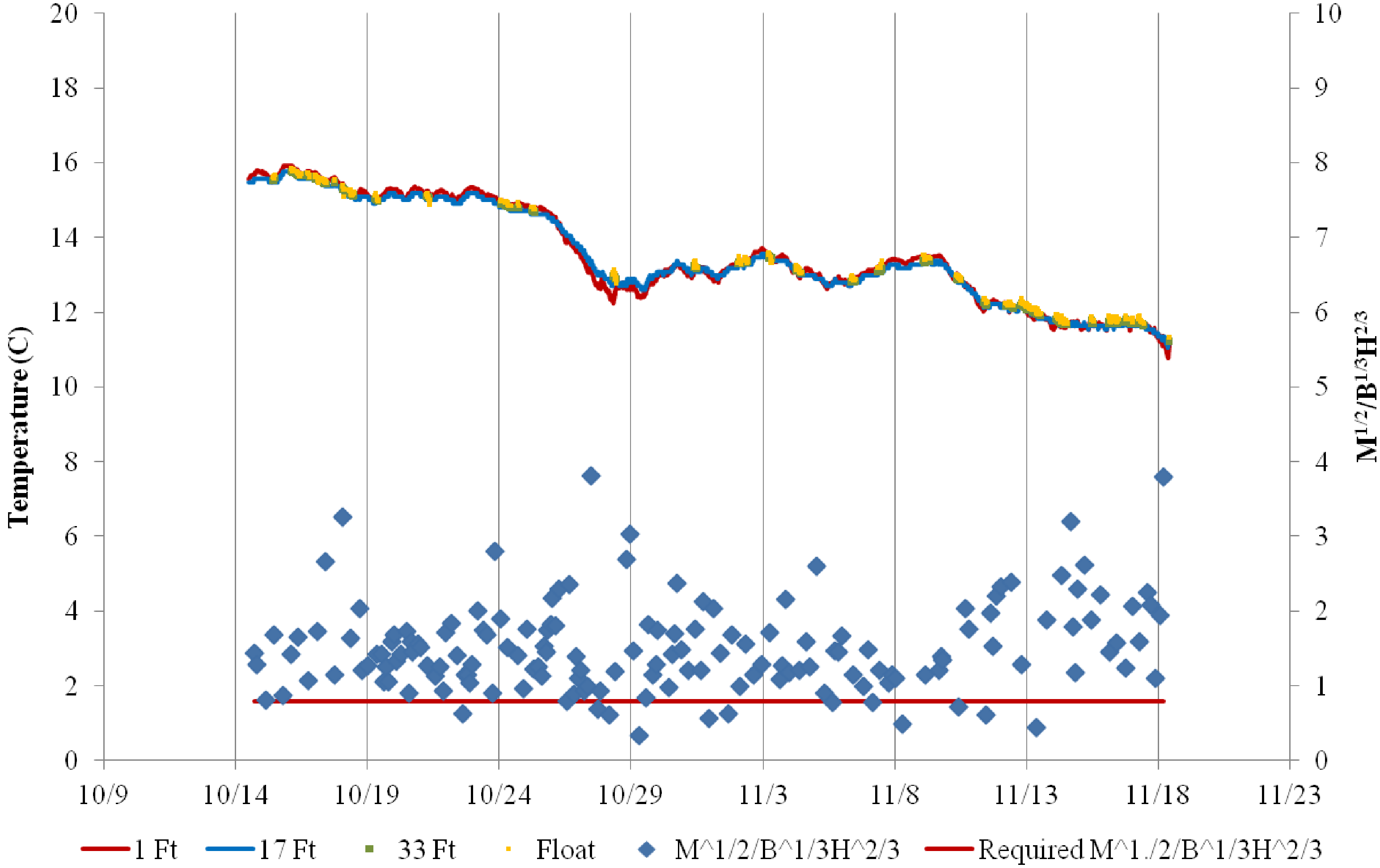


Figure H.12. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 7.

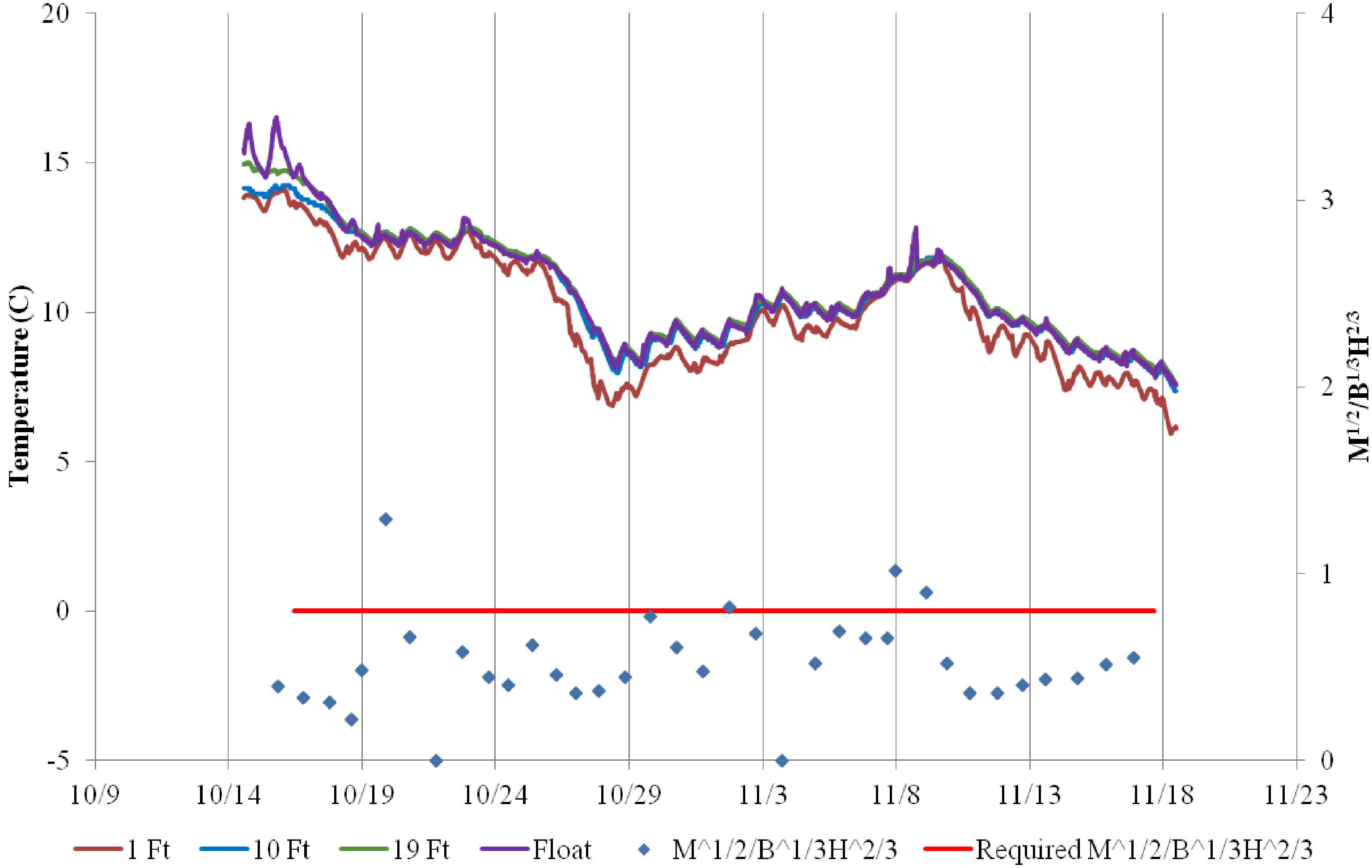


Figure H.13. Temperature profile with actual and required $dM^{1/2}/(B^{1/3}H^{2/3})$ for short term tank 8.

APPENDIX I

RELATIONSHIP OF TEMPERATURES INSIDE AND OUTSIDE OF TANKS

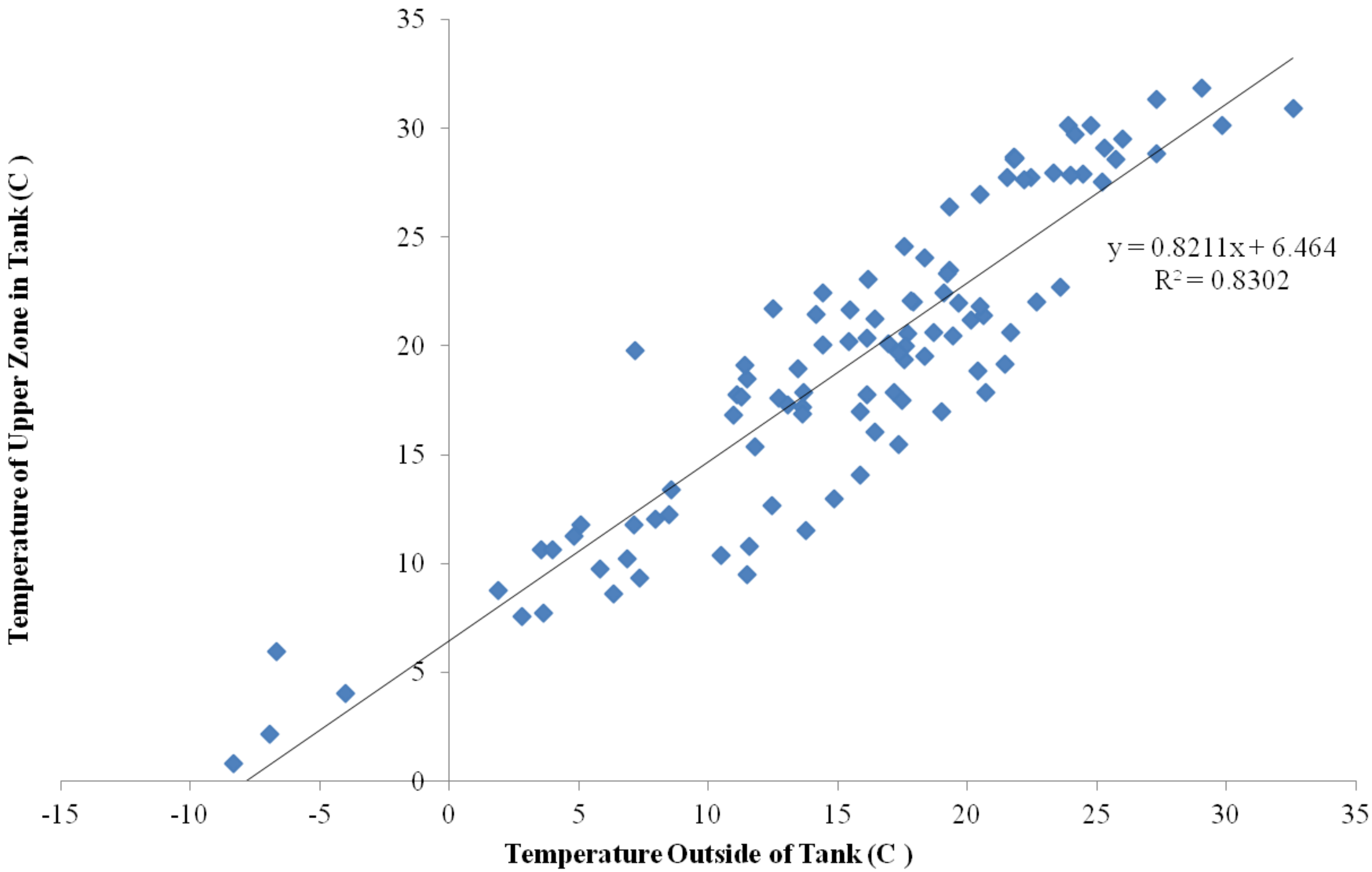


Figure I.1. Relationship of temperature inside and outside of long term tank D.

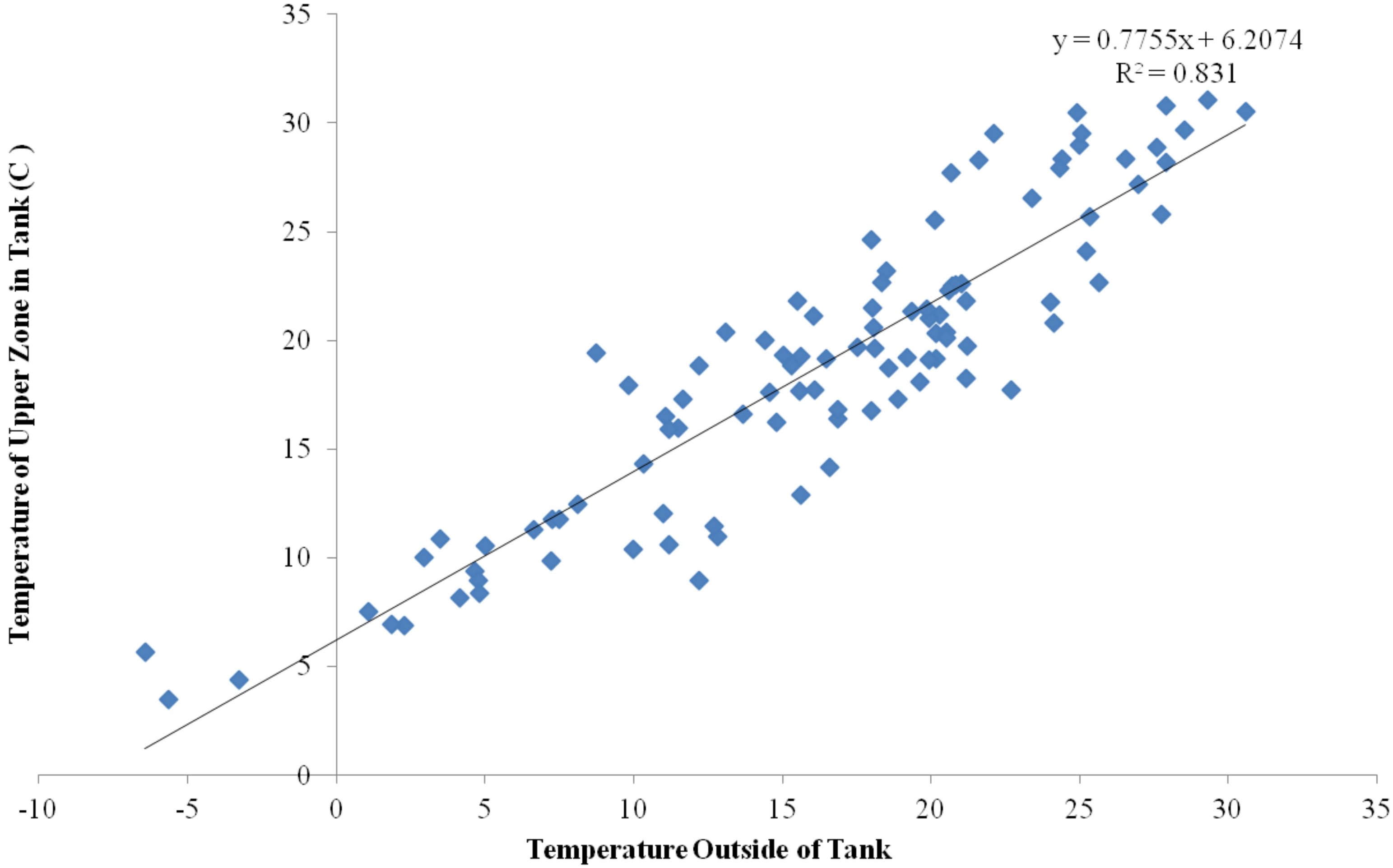


Figure I.2. Relationship of temperature inside and outside of long term tank E.