Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
STUDIES INTO THE HYDRAULICS OF WASTE STABILISATION PONDS

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

Environmental Engineering

at

Massey University,

Turitea Campus, Palmerston North, New Zealand.

Andy Shilton

2001
ABSTRACT

Wastewater stabilisation ponds are used extensively to provide wastewater treatment throughout the world. A review of the literature indicated that, while understanding the hydraulics of waste stabilisation ponds is critical to their optimisation, the research in this area has been relatively limited and that there is a poor mechanistic understanding of the flow behaviour that exists within these systems.

Traditional tracer studies were used in this study but, in addition, new methodologies were developed involving drogue-tracking techniques to directly quantify the internal flow pattern. The investigation included study of physical scale models in the laboratory, operational ponds in the field and the simulation of both using computational fluid dynamics (CFD) mathematical modelling.

Twenty experimental configurations were tested in the laboratory with the variables being: retention time; outlet position; inlet type and position; and the influence of a baffle. Ten of these experimental cases were then mathematically modelled and, in general, the simulations had close similarity to the experimental data.

In the next phase of the work, the tracer and drogue tracking techniques were applied on two full-scale waste stabilisation ponds in the field. For one of the ponds a large scale model was also constructed. Mathematical modelling was again performed and a high degree of similarity was achieved. The study then finished with a broad review of wind effects and an investigation of integrating a biodegradation equation within the CFD model.

While it was concluded that a CFD model cannot always be expected to precisely predict the performance of a field pond, this work has validated its use to the extent that it can be pragmatically applied for the systematic evaluation of alternative baffle, inlet and outlet configurations, thereby, addressing a major knowledge gap in waste stabilisation pond design.
ACKNOWLEDGEMENTS

Over the six years that I have worked on this thesis I have received help, assistance and guidance from a large number of people. Of these, I will only be able to mention a few.

My supervisors Professor Rao Bhamidimarri (Massey University, New Zealand), Professor Bruce Melville (University of Auckland, New Zealand) and Professor Duncan Mara (University of Leeds, England) must be first in these acknowledgments. My research work crosses a number of areas. Bruce has been invaluable with regard to the hydraulics – particularly the work with scale models. Duncan is a recognised authority on waste stabilisation pond technology and has hosted me on several visits to England. Rao, being my primary supervisor, has spent many hours giving advice to me on this project. In particular, it is through his experience and mentoring that I have come to understand the philosophy of research.

At the commencement of this work I was awarded a Hume Fellowship to assist me to travel abroad in support of my studies. The benefits of being able to travel to meet and work with leading researchers around the world have been tremendous.

In addition to the knowledge imparted by my supervisors, I was fortunate enough to receive specialist advice from many other academics and practitioners. In particular, I would like to acknowledge Professor Torban Larsen (University of Aalborg, Denmark) with regard to the theoretical evaluation of wind and inlet power; Dr David Glynn (Flowsove Consultants, London) and Dr Mike Malin (CHAM, London) with regards to the computational fluid dynamics modelling; and finally Dr Roger Nokes (University of Canterbury, New Zealand) with regard to Reynolds number effects on scaling.

It is also important to give credit to the students who have worked with me on various projects that have tied in with my broader research into waste stabilisation ponds. In particular, I would like to acknowledge the hydraulic research work undertaken by Murray Kerr, Mike Pratt and Stefan Kreegher. With particular regard to the fieldwork, the cooperation and assistance of the Palmerston North City Council, the Manawatu District Council and Horizons MW was greatly appreciated.
Two colleagues at Massey University who had significant input were Dr Don Bailey and Mr Paul Bickers. Without Don the technique for image tracking of drogues in the laboratory would simply not have been possible, whilst Paul provided a willing sounding board for planning and review of the experimental work.

Undertaking a doctorate part-time requires the sacrifice of considerable quantities of time outside working hours. The indirect role that my family, Bettina, Lilla and Jordan have played in supporting my work has been fundamental to its success.

This thesis is dedicated to my mother Heather Shilton, one of New Zealand’s early woman scientists and my late father Dr Ted Shilton, a man who gave so much to the community he served.
TABLE OF CONTENTS

ABSTRACT .................................................................................................................. 2

ACKNOWLEDGEMENTS .............................................................................................. 3

TABLE OF CONTENTS ............................................................................................... 5

LIST OF FIGURES ....................................................................................................... 14

LIST OF TABLES ......................................................................................................... 19

1 INTRODUCTION ..................................................................................................... 20

1.1 Background .......................................................................................................... 20

1.2 Research Needs and Aim of Thesis ....................................................................... 20

1.3 Specific Objectives and Approach ........................................................................ 21

2 REVIEW OF THE LITERATURE ............................................................................. 22

2.1 Overview of Chapter .............................................................................................. 22

2.2 Pond Types ........................................................................................................... 22
  2.2.1 Anaerobic Ponds ............................................................................................. 22
  2.2.2 Anoxic Ponds .................................................................................................. 23
  2.2.3 Facultative Ponds ........................................................................................... 23
  2.2.4 Aerated Ponds/Lagoons ................................................................................ 24
  2.2.5 Maturation Ponds .......................................................................................... 25
  2.2.6 High-Rate Algal Ponds .................................................................................. 25

2.3 Pond Design ......................................................................................................... 26
  2.3.1 Loading Rates .................................................................................................. 26
  2.3.2 Empirical Design Equations ........................................................................... 28
  2.3.3 Pond Design using Reactor Theory ................................................................. 29
2.4 Fluid Flow and Mixing In Ponds ......................................................... 45
  2.4.1 Hydrology .......................................................... 45
  2.4.2 Stratification ....................................................... 46
  2.4.3 Wind ............................................................... 48
  2.4.4 General Studies of Pond Hydraulics ....................................... 49

2.5 Tracer Studies ........................................................................... 50
  2.5.1 The Stimulus Response Technique ........................................... 50
  2.5.2 Research using Tracer Studies ............................................... 53

2.6 Drogue Tracking Studies .............................................................. 56

2.7 Physical Modelling Studies ............................................................ 57
  2.7.1 The Froude Number ...................................................... 58
  2.7.2 The Reynolds Number .................................................... 59
  2.7.3 The Froude Number and Reynolds Number Conflict ..................... 60
  2.7.4 The Inlet Jet .................................................................. 61
  2.7.5 Previous Research using Physical Models ................................... 63

2.8 Mathematical Modelling Studies .................................................... 66
  2.8.1 Computational Fluid Dynamics .............................................. 66
  2.8.2 Mathematical Modelling Studies of Waste Stabilisation Hydraulics .... 67
  2.8.3 Thesis by Wood, 1997, University of Queensland ......................... 69
  2.8.4 Thesis by Salter, 1999, The University of Surrey/Thames Water ........... 72

2.9 Final Summary ............................................................................. 74

3 METHODOLOGY ............................................................................. 76
3.1 Preliminary Research on Physical Models ................................................. 76
  3.1.1 Evaluation of Preliminary Research ................................................. 76

3.2 Design of Laboratory Model ..................................................................... 77
  3.2.1 Adoption of Froude Number Similarity ............................................. 77
  3.2.2 Froude Number Based Design of Model ........................................... 78
  3.2.3 Model Pond Roughness ...................................................................... 80
  3.2.4 Model/Prototype Pond Specifications ............................................. 81
  3.2.5 Data Collection ................................................................................. 83

3.3 Drogue Tracking by Image Analysis in the Model Pond ......................... 84
  3.3.1 Zero Flow Drogue Test ...................................................................... 86

3.4 Tracer Studies in Physical Model .............................................................. 87

3.5 Experimental Configurations in Model Pond ......................................... 89
  3.5.1 Experimental Variables ..................................................................... 90
  3.5.2 Experimental Runs Undertaken ......................................................... 93

3.6 Hydraulic Studies on Field Pond ............................................................... 94
  3.6.1 Field Tracer Studies .......................................................................... 95
  3.6.2 Drogue Survey Technique ................................................................. 95
  3.6.3 Ponds Studied .................................................................................... 96

3.7 The Phoenics CFD Model ......................................................................... 97
  3.7.1 The Simulations Undertaken ............................................................... 98
  3.7.2 Differencing Schemes ...................................................................... 98
  3.7.3 Turbulence Modelling ..................................................................... 99
  3.7.4 Grid Development ........................................................................... 100
  3.7.5 Mass Balance and Residuals Error Checking ................................... 102
  3.7.6 Boundary Conditions ...................................................................... 103

4 EXPERIMENTATION ON A LABORATORY POND ...................................... 105

4.1 Review of Experimental Runs Undertaken ............................................ 105

4.2 Run 1 ....................................................................................................... 106
5.1 Introduction ........................................................................................................ 129

5.2 Review of Experimental Runs for CFD Modelling ........................................ 131

5.3 Run 9 - High Energy Case ............................................................................... 132
  5.3.1 Preliminary Modelling ............................................................................... 132
  5.3.2 Differencing Schemes ............................................................................... 134
  5.3.3 Grid Refinement ....................................................................................... 134
  5.3.4 Turbulence Models .................................................................................. 137
  5.3.5 Modelling of Tracer Insertion .................................................................. 137
  5.3.6 Final Run 9 Model ................................................................................... 137

5.4 Run 16 High Energy Case - Baffled ............................................................... 139

5.5 Run 10 Low Energy Case ................................................................................ 141

5.6 Run 17 Large Horiz. Inlet/Short HRT .............................................................. 144

5.7 Run 18 Large Horiz. Inlet/Short HRT/Baffled ............................................... 146

5.8 Run 15 Vertical Inlet/Short HRT ..................................................................... 148

5.9 Run 19 Vertical Inlet/Short HRT/Baffled ....................................................... 149

5.10 Runs 13 and 20, Large and Small Horiz. Inlet/Long HRT .......................... 150

5.11 Run 7 Mid Position Inlet ................................................................................ 152

5.12 Examination of Scaling Methodology ............................................................ 155
  5.12.1 Horizontal Inlet Configurations ............................................................... 156
  5.12.2 Vertical Inlet Configuration .................................................................... 159
  5.12.3 Experimental Error ................................................................................ 161
  5.12.4 Determination of In-Pond Reynolds and Froude Numbers .................... 162
  5.12.5 Assessment of Using Froude Number Similarity in this Study ............... 166

5.13 Final Evaluation ............................................................................................. 167

6 EXPERIMENTATION AND MODELLING OF FIELD PONDS ............ 169
6.1 The Rongotea Pond Studies ................................................................. 169
  6.1.1 Tracer Studies on the Field Pond .................................................... 169
  6.1.2 CFD Simulation of Tracer Study on Field Pond ................................ 171
  6.1.3 Tracer Studies on a Scale Model Pond ............................................. 174
  6.1.4 Comparison of Flow Pattern in CFD Simulation to Laboratory Pond .... 177

6.2 The Ashhurst Pond Studies ................................................................. 179
  6.2.1 Experimental Measurement of Flow Pattern and Velocity .................. 179
  6.2.2 CFD Simulation of Flow Pattern and Velocity .................................. 182
  6.2.3 Tracer Study and CFD Simulation of the Field Pond ......................... 183

6.3 Final Evaluation ...................................................................................... 184

7 PRACTICAL APPLICATION TO FIELD PONDS ........................................ 185

7.1 Influence of Wind on Pond Hydraulics ............................................... 185
  7.1.1 Simulating Wind in a CFD Model .................................................... 185
  7.1.2 Theoretical Evaluation of Relative Wind and Inlet Mixing Power .......... 189
  7.1.3 Examples of Wind and Inlet Power Analysis ..................................... 190
  7.1.4 Overview of Wind ........................................................................... 193

7.2 Application of Reaction Modelling in CFD ......................................... 195
  7.2.1 Integration of First Order Coliform Decay into Rongotea CFD Model ... 195

7.3 CFD as an Alternative to Reactor Theory ............................................ 197
  7.3.1 Practical Application for Design .................................................... 198

7.4 Final Evaluation ...................................................................................... 200

8 FINAL DISCUSSION AND CONCLUSIONS ............................................. 201

9 APPENDIX A - PRELIMINARY RESEARCH ON PHYSICAL MODELS ......... 209

9.1 Initial Experimentation .......................................................................... 209

9.2 Evaluation of Initial Experimentation ................................................... 211

9.3 Modelling of Diffusion .......................................................................... 212
9.4 Assessment of Thermal Convection ..................................................... 214
9.5 Assessment of Air Shear ................................................................. 214
9.6 Quantifying Effect of Gravity Spread of Tracer ..................................... 215
9.7 Final Zero Flow Tracer Testing ......................................................... 215
9.8 Coriolis Force .................................................................................. 217
9.9 Vibration ......................................................................................... 217
9.10 Inlet Studies ................................................................................... 218

10 APPENDIX B - 2D PROGRAM FOR APPROXIMATING MASS DIFFUSION OF TRACER FROM A SINGLE POINT .................................... 219

11 APPENDIX C - DIFFUSIVITY OF RHODAMINE WT .............................. 223

12 APPENDIX D – PHYSICAL MODELLING ............................................. 225

12.1 Run 1 .............................................................................................. 225
  12.1.1 Drogue Tracking ................................................................. 225
  12.1.2 Tracer Studies ........................................................................ 227
  12.1.3 Evaluation of Run 1 .............................................................. 228

12.2 Run 2 .............................................................................................. 229
  12.2.1 Drogue Tracking ................................................................. 229
  12.2.2 Evaluation of Run 2 .............................................................. 232

12.3 Run 3 .............................................................................................. 233
  12.3.1 Drogue Tracking ................................................................. 233
  12.3.2 Tracer Studies ........................................................................ 234
  12.3.3 Evaluation of Run 3 .............................................................. 234

12.4 Run 4 .............................................................................................. 235
  12.4.1 Drogue Tracking ................................................................. 235
  12.4.2 Tracer Studies ........................................................................ 235
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.13</td>
<td>Run 13</td>
<td>253</td>
</tr>
<tr>
<td>12.13.1</td>
<td>Drogue Tracking</td>
<td>253</td>
</tr>
<tr>
<td>12.13.2</td>
<td>Evaluation of Run 13</td>
<td>254</td>
</tr>
<tr>
<td>12.14</td>
<td>Run 14</td>
<td>254</td>
</tr>
<tr>
<td>12.14.1</td>
<td>Tracer Studies</td>
<td>254</td>
</tr>
<tr>
<td>12.14.2</td>
<td>Evaluation of Run 14</td>
<td>255</td>
</tr>
<tr>
<td>12.15</td>
<td>Run 15</td>
<td>255</td>
</tr>
<tr>
<td>12.15.1</td>
<td>Tracer Studies</td>
<td>255</td>
</tr>
<tr>
<td>12.15.2</td>
<td>Evaluation of Run 15</td>
<td>257</td>
</tr>
<tr>
<td>12.16</td>
<td>Run 16</td>
<td>257</td>
</tr>
<tr>
<td>12.16.1</td>
<td>Drogue Tracking</td>
<td>257</td>
</tr>
<tr>
<td>12.16.2</td>
<td>Tracer Studies</td>
<td>258</td>
</tr>
<tr>
<td>12.16.3</td>
<td>Evaluation of Run 16</td>
<td>259</td>
</tr>
<tr>
<td>12.17</td>
<td>Run 17</td>
<td>260</td>
</tr>
<tr>
<td>12.17.1</td>
<td>Drogue Tracking</td>
<td>260</td>
</tr>
<tr>
<td>12.17.2</td>
<td>Tracer Studies</td>
<td>260</td>
</tr>
<tr>
<td>12.17.3</td>
<td>Evaluation of Run 17</td>
<td>262</td>
</tr>
<tr>
<td>12.18</td>
<td>Run 18</td>
<td>262</td>
</tr>
<tr>
<td>12.18.1</td>
<td>Drogue Tracking</td>
<td>262</td>
</tr>
<tr>
<td>12.18.2</td>
<td>Tracer Studies</td>
<td>263</td>
</tr>
<tr>
<td>12.18.3</td>
<td>Evaluation of Run 18</td>
<td>264</td>
</tr>
<tr>
<td>12.19</td>
<td>Run 19</td>
<td>264</td>
</tr>
<tr>
<td>12.19.1</td>
<td>Tracer Studies</td>
<td>264</td>
</tr>
<tr>
<td>12.19.2</td>
<td>Evaluation of Run 19</td>
<td>266</td>
</tr>
<tr>
<td>12.20</td>
<td>Run 20</td>
<td>266</td>
</tr>
<tr>
<td>12.20.1</td>
<td>Drogue Tracking</td>
<td>266</td>
</tr>
<tr>
<td>12.20.2</td>
<td>Tracer Studies</td>
<td>267</td>
</tr>
<tr>
<td>12.20.3</td>
<td>Evaluation of Run 20</td>
<td>268</td>
</tr>
<tr>
<td>13</td>
<td>REFERENCES</td>
<td>269</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2-1 Facultative pond (Tchobonoglous and Schroeder, 1985, pg. 635) ............... 24
Figure 2-2 The finite stage model (Watters et al., 1973, pg. 16) .................................. 33
Figure 2-3 Conceptual summary of pond model (Fritz et al., 1979, pg. 2725) ............... 42
Figure 2-4 Tracer stimulus response techniques (Levenspiel, 1972, pg. 256) ............... 51
Figure 2-5 Retention time distribution curves for plug, mixed and dispersed flow –
dimensionless concentration and time (Levenspiel, 1972, pg. 277) ......................... 52
Figure 2-6 Chelsham tracer results (Salter, 1999) ......................................................... 55
Figure 2-7 Inlet and outlet configurations tested in the Utah Water Research
Laboratory (Watters et al., 1973, pg. 41) ................................................................. 64
Figure 2-8 Comparison of CFD simulation to experimental data (Wood et al., 1996, pg.
962) .......................................................................................................................... 70
Figure 2-9 3D CFD simulation of tracer data from Mackay ponds (Wood, 1997, pg.
162) .......................................................................................................................... 71
Figure 3-1 Overview of experimental set-up ................................................................. 83
Figure 3-2 Experimental set-up for image analysis on model pond ........................... 85
Figure 3-3 Colour/velocity scale (mm/s) – valid for 10 sec timing ......................... 85
Figure 3-4 Experimental set-up of tracer study on model pond ................................. 88
Figure 3-5 Calibration curve for rhodamine WT ......................................................... 89
Figure 3-6 The experimental drogue ............................................................................ 95
Figure 3-7 Example of typical grid ............................................................................ 101
Figure 4-1 Run 1 drogue tracking pathlines ............................................................. 107
Figure 4-2 Run 1 HRT distribution – first 360 minutes of data ............................... 108
Figure 4-3 Images of tracer dispersion in Run 16a ............................................... 114
Figure 4-4 Comparison of various HRT’s for vertical inlet ................................. 119
Figure 4-5 Comparison of various HRT’s for vertical inlet – dimensionless time ...... 120
Figure 4-6 Comparison of 1.5 and 5 day HRT’s for the small horizontal inlet ....... 121
Figure 4-7 Comparison of 1.5 and 5 day HRT’s for the small horizontal inlet –
dimensionless time ................................................................................................. 121
Figure 4-8 Comparison of Run 9 (small horizontal inlet) and Run 17 (large horizontal
inlet) for a 1.5 day HRT ......................................................................................... 124
Figure 4-9 Comparison of Run 9 (small horizontal inlet) and Run 15 (vertical inlet) for
a 1.5 day HRT ........................................................................................................ 125
Figure 4-10 Comparison of Run 4 (small horizontal inlet) and Run 8 (vertical inlet) for a 5 day HRT

Figure 4-11 Comparison of Run 9 (un-baffled) and Run 16 (baffled) for a 1.5 day HRT
  - small horizontal inlet

Figure 5-1 Initial modelling of Run 9

Figure 5-2 Grid refinement – plot of velocity component along x-axis

Figure 5-3 Grid refinement – plot of velocity component along y-axis

Figure 5-4 Run 9 – effect of time step density

Figure 5-5 Final plot of Run 9 – full data

Figure 5-6 Final plot of Run 9 – first 180 minutes

Figure 5-7 Run 16 – full data

Figure 5-8 Run 16 – first 180 minutes

Figure 5-9 Run 10 – experimental data versus initial CFD model

Figure 5-10 Run 10 – experimental data versus five different CFD model variations

Figure 5-11 Run 17 – full data

Figure 5-12 Run 17 – first 180 minutes

Figure 5-13 Run 18 – full data

Figure 5-14 Run 18 – first 180 minutes

Figure 5-15 Run 15 – full data

Figure 5-16 Run 19 – full data

Figure 5-17 Run 7 drogue tracking pathlines – ‘balanced’ double circulation pattern

Figure 5-18 Run 7 CFD simulation of velocity field

Figure 5-19 Run 7 CFD simulation of velocity field – Chen-Kim k-ε model

Figure 5-20 Combined results horizontal inlet configurations – effect on MHRTC

Figure 5-21 Combined results horizontal inlet configurations – effect on TSC

Figure 5-22 Tracer approaching outlet in a low Reynolds number experiment

Figure 5-23 Varying flow, vertical inlet of fixed diameter – effect on MHRT

Figure 5-24 Varying flow, vertical inlet of fixed diameter – effect on TSC

Figure 5-25 The initial transport of tracer into the model pond – Run 17

Figure 5-26 The initial transport of tracer into the model pond – Run 17

Figure 5-27 Run 17 drogue tracking pathlines

Figure 6-1 Rongotea – commencement of tracer study

Figure 6-2 Rongotea tracer results
Figure 12-6 Thumbnail plots of Run 2 .................................................................................. 231
Figure 12-7 Run 3 drogue tracking pathlines .................................................................. 233
Figure 12-8 Run 3 HRT distribution – first 360 minutes of data ...................................... 234
Figure 12-9 Run 4 drogue tracking pathlines .................................................................. 235
Figure 12-10 Run 4 HRT distribution – first 180 minutes of data ...................................... 236
Figure 12-11 Run 4 HRT distribution – full data ................................................................ 236
Figure 12-12 Run 5 drogue tracking pathlines – plot 28108C ........................................... 238
Figure 12-13 Run 5 drogue tracking pathlines – plot 31108C1 ......................................... 239
Figure 12-14 Run 5 drogue tracking pathlines – plot 31108C2 ......................................... 239
Figure 12-15 Thumbnail plots of Run 6 ............................................................................. 241
Figure 12-16 Run 7 drogue tracking pathlines – each of one hour duration ...................... 243
Figure 12-17 Run 7 drogue tracking pathlines – ‘balanced’ double circulation pattern ......... 243
Figure 12-18 Run 8 drogue tracking pathlines .................................................................. 244
Figure 12-19 Run 8 HRT distribution – full data .............................................................. 245
Figure 12-20 Images of tracer dispersion in Run 8 .......................................................... 245
Figure 12-21 Run 9 drogue tracking pathlines .................................................................. 247
Figure 12-22 Run 9 HRT distribution – first 180 minutes ............................................... 248
Figure 12-23 Run 9 HRT distribution – full data .............................................................. 248
Figure 12-24 Run 10 drogue tracking results ................................................................... 250
Figure 12-25 Run 10 HRT distribution ............................................................................ 250
Figure 12-26 Run 11 drogue tracking pathlines – non-steady ........................................... 251
Figure 12-27 Run 12 drogue tracking pathlines .............................................................. 252
Figure 12-28 Run 13 drogue tracking pathlines .............................................................. 253
Figure 12-29 Run 14 HRT distribution ............................................................................ 254
Figure 12-30 Images of tracer dispersion in Run 15 ........................................................ 256
Figure 12-31 Run 15 HRT distribution ............................................................................ 256
Figure 12-32 Run 16 drogue tracking pathlines .............................................................. 257
Figure 12-33 Images of tracer dispersion in Run 16a ...................................................... 258
Figure 12-34 Run 16 HRT distribution – first 180 minutes of data ................................... 258
Figure 12-35 Run 16 HRT distribution – full data ........................................................... 259
Figure 12-36 Run 17 drogue tracking pathlines .............................................................. 260
Figure 12-37 Run 17 HRT distribution – first 180 minutes of data ................................... 261
Figure 12-38 Run 17 HRT distribution – full data ........................................................... 261
Figure 12-39 Run 18 drogue tracking pathlines ............................................. 262
Figure 12-40 Images of tracer dispersion in Run 18a .................................... 263
Figure 12-41 Run 18 HRT distribution .......................................................... 263
Figure 12-42 Tracer images of Run 19b ......................................................... 265
Figure 12-43 Run 19 HRT distribution .......................................................... 265
Figure 12-44 Run 20 drogue tracking pathlines ......................................... 267
Figure 12-45 Run 20 HRT distribution – first 180 minutes of data ............. 267
Figure 12-46 Run 20 HRT distribution – full data ....................................... 268
LIST OF TABLES

Table 2-1 Experimental data analysed by Nameche and Vasel (1998, pg. 5) ................. 41
Table 3-1 Drogue velocities one day after filling of the pond .......................................... 86
Table 3-2 Thirty minute ‘snapshot’ of drogue X, Y co-ordinates ........................................ 87
Table 3-3 Summary of retention times and flowrates tested in model pond ......................... 90
Table 3-4 Summary of experimental runs ........................................................................ 93
Table 4-1 Summary of experimental runs ........................................................................ 106
Table 5-1 Summary of experimental runs ........................................................................ 131
Table 5-2 Experimentally determined velocity, Reynolds number and Froude number ........ 165
Table 7-1 Wind data at Ashhurst pond – average daily readings ....................................... 194
Table 9-1 Tracer concentrations for zero flow ................................................................... 210
Table 9-2 Simulated tracer concentration due to diffusion after 6 days ............................. 213
Table 11-1 Atomic volume of constituents of rhodamine WT ............................................. 224
Table 12-1 Summary of behaviour in Run 2 ...................................................................... 231