Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes

Lowell James Lewis

Volume 1

Thesis submitted in fulfilment of the degree of Doctor of Engineering in Sustainability for Engineering and Energy Systems

University of Surrey
Centre for Environmental Strategy
July 2015

Academic Supervisors: Dr John Chew and Dr. Katherine Pond

Industrial Supervisors: Prof. Jeni Colbourne and Iain Woodley

Sponsoring Organisations: Department for Environment, Food and Rural Affairs and Surrey Sports Park Ltd
Acknowledgements

The research presented within this thesis would not have been possible without the support of many people and organisations who I would like to acknowledge.

Firstly my supervisors: Iain Woodley, Jeni Colbourne, John Chew and Katherine Pond. Iain for picking up the baton for Surrey Sports Park and your endless enthusiasm for all things related to sport and the University of Surrey, Jeni for being the driving force behind the project and introducing me to key contacts in the industry, and to John and Katherine for sharing your expertise and academic experience.

The research greatly benefited from the kind generosity of Kali Johal and Steve Pedley of the Robens Centre for Public and Environmental Health and Karen Lavarack and David Reynolds of Thames Water. A special thank you to you all for providing the equipment and laboratory analysis of the water samples throughout the project.

I would also like to thank the NERC NCAS EnFlo Laboratory and in particular Paul Hayden and Alan Wells for their support and guidance throughout the small-scale physical experiments and allowing me to take over part of the lab for many long months.

I would like to thank the Surrey Sports Park for being my home for the duration of the project and the support of Phil Swaden, Luigi Mansi and all the members of the SSP Operational and Estate and Facilities Management teams.

The industrial knowledge gained through the support of the Pool Water Treatment Advisory Group was also greatly appreciated. I hope that my research goes someway to repaying you for your willingness to guide me through the industry and provide experiences I had not thought possible.

Finally I would like to thank Helen and Gareth for putting up with my ceaseless talk about the problems with swimming pools, Sophie for helping me through the toughest times and my extended family of the University of Surrey Hockey Club and Surrey Spartans Hockey Club for providing the distraction I needed to keep me going.
Abstract

This thesis presents a new framework that enables a better integrated and industry-wide approach to the sustainable design and operation of swimming pools in the UK. The framework addresses current issues in the swimming industry by proposing a restructuring of the regulatory and guidance structure to make use of existing pieces of UK legislation. A combination of a new approved code of practice for swimming pools incorporating risk-based assessments and changes to existing approved documents for building efficiency is proposed as an effective method of engaging all stakeholders.

The industrial setting of the research enabled a practical evaluation of the current UK guidance and regulation. The need for additional performance indicators to improve the management of compliance with recommendations is identified. The Water Exchange Deficit is proposed as a new performance indicator to support the water management of a facility. In addition, the relationship between activity type and the impact on water quality is examined and discussed. An enhanced methodology for the prediction of the water demand of a facility has also been generated. This methodology incorporates newly published findings in relation to the nature of bather contamination and operational variables relating to evaporation rates and chemical dosing.

In addition to the contributions above, the modelling of pool hydraulics was also undertaken to assess operational consequences of the existing implementation of industry guidance. A fundamental conflict was identified between the two key recommendations that should be adopted in relation to the design of pool hydraulics. Computational fluid dynamics and small-scale physical modelling approaches were used to show that the use of well-mixed hydraulics is effective at distributing chemicals but can also potentially increase the risk of exposure to disinfectant-resistant pathogens. The availability of new treatment technologies may present the opportunity for wholesale changes to the overall strategy of pool water treatment.
Statement of Originality

This thesis and the work to which it refers are the results of my own efforts. Any ideas, data, images or text resulting from the work of others, whether published or unpublished, are fully identified as such within the work and attributed to their originator in the text, bibliography or in footnotes. This thesis has not been submitted in whole or in part for any other academic degrees or professional qualification. I agree that the University has the right to submit my work to the plagiarism detection service TurnitinUK for originality checks. Whether or not drafts have been so-assessed, the University reserves the right to require an electronic version of the final document, as submitted, for assessment as above.

Signed:

Date:
Contents

Volume 1

Acknowledgements ........................................................................................................... i
Abstract .............................................................................................................................. ii
Statement of Originality ................................................................................................... iii
Contents ................................................................................................................................ iv
List of Figures ...................................................................................................................... xiii
List of Tables ...................................................................................................................... xxi
List of Abbreviations ........................................................................................................ xxii
Nomenclature .................................................................................................................... xxiii
Executive Summary .......................................................................................................... xxv

Chapter 1 – The Swimming Industry: A Critical Review

1.1 Introduction .................................................................................................................... 1-1

1.2 Current Structure of the UK Swimming Industry ......................................................... 1-3
1.2.1 The Client .............................................................................................................. 1-3
1.2.2 Pool Design ........................................................................................................... 1-4
1.2.3 Pool Construction ................................................................................................... 1-5
1.2.4 Pool Operation ....................................................................................................... 1-5
1.2.5 Pool Users ............................................................................................................. 1-6

1.3 UK Swimming Pool Guidance and Regulation ............................................................ 1-7
1.3.1 UK Legislation ...................................................................................................... 1-7
1.3.2 UK Codes of Practice and Standards ................................................................... 1-8
1.3.3 International Guidance ......................................................................................... 1-12
1.3.4 UK Training and Certification ............................................................................. 1-13
1.3.5 Sustainability-related Guidance .......................................................................... 1-15

1.4 Establishing a Framework to Assess the Current Knowledge Base ......................... 1-17
1.4.1 Evaluation of Swimming Pool Interactions ............................................................ 1-17
1.4.1.1 Swimming Pool Users ..................................................................................... 1-17
1.4.1.2 Swimming Pool Employees ............................................................................ 1-18
1.4.1.3 Swimming Pool Water Quality ..................................................................... 1-18
1.4.1.4 Swimming Pool Air Quality ........................................................................... 1-18
1.4.1.5 Swimming Pool Energy Consumption ......................................................... 1-19
1.4.2 Development of Framework ................................................................................ 1-19
1.5 Defining the Scope and Objectives of the Research Project ........................................ 1-22
   1.5.1 Definition of Water Quality for Swimming Pools ........................................ 1-22
   1.5.2 Evaluation of the Impact of Bather Interactions ........................................ 1-23
   1.5.3 Evaluation of the Environmental Impacts of Pool Operation .......................... 1-23
   1.5.4 Evaluation of the Significance of Pool Hydraulics in the Sustainable Design of Swimming Pools ................................................................. 1-24
   1.5.5 Recommendation of Modifications to Swimming Pool Guidance and Regulation to Enhance the Sustainability of the Industry ................................. 1-24

1.6 References ................................................................................................................. 1-26

Chapter 2 – An Assessment of the Water Quality Considerations Involved in Achieving a Healthy Swimming Pool Environment

2.1 Introduction .............................................................................................................. 2-1

2.2 Literature Review ................................................................................................. 2-4
   2.2.1 Health-Related Aspects ............................................................................... 2-4
      2.2.1.1 Microbiological Characteristics ....................................................... 2-4
      2.2.1.2 Chemical Characteristics ............................................................... 2-6
      2.2.1.3 Disinfection By-Products ............................................................... 2-7
      2.2.1.4 Exposure Routes ........................................................................... 2-13
   2.2.2 Operational Consequences of Microbiological and Chemical Aspects .......... 2-14
      2.2.2.1 Microbiological Characteristics ....................................................... 2-14
      2.2.2.2 Chemical Characteristics ............................................................... 2-14
      2.2.2.3 Organoleptic Characteristics ........................................................... 2-16
   2.2.3 Current UK Standards .................................................................................... 2-17

2.3 Surrey Sports Park Water Survey ........................................................................... 2-18
   2.3.1 Scope ........................................................................................................... 2-18
   2.3.2 Sampling Methods ....................................................................................... 2-20
      2.3.2.1 General Preparation ....................................................................... 2-20
      2.3.2.2 Pre-Sample Decontamination ....................................................... 2-21
      2.3.2.3 Water Sampling ............................................................................ 2-22
      2.3.2.4 Field Parameter Measurement ....................................................... 2-23
      2.3.2.5 Post-Sample Routine ..................................................................... 2-24
   2.3.3 Analysis Methods ......................................................................................... 2-24
      2.3.3.1 Field Analysis ............................................................................... 2-25
      2.3.3.2 Microbiological Analysis ............................................................... 2-26
      2.3.3.3 Chemical Analysis ....................................................................... 2-27

2.4 Water Survey Results ........................................................................................... 2-28
   2.4.1 Microbiological Analysis Results ............................................................... 2-28
   2.4.2 Chemical Analysis Results .......................................................................... 2-29
      2.4.2.1 Trihalomethane Concentrations ..................................................... 2-29
      2.4.2.2 Dissolved Metal Concentrations .................................................... 2-31
      2.4.2.3 Physical Chemistry ...................................................................... 2-33
Chapter 3 – An Assessment of the Impacts of Different Types of Activity on Swimming Pool Water Quality

3.1 Introduction ............................................................................................................. 3-1

3.2 Literature Review .................................................................................................. 3-2

3.2.1 Disinfection By-Product Precursor Prevention ......................................................... 3-2

3.2.2 Relationship between Pool Use and Water Quality ................................................ 3-3

3.3 Surrey Sports Park Activity Survey ........................................................................ 3-4

3.3.1 Scope .................................................................................................................. 3-4

3.3.2 Methodology ....................................................................................................... 3-5

3.3.2.1 Real-Time Water Monitoring ............................................................................. 3-5

3.4 Activity Survey Results .......................................................................................... 3-7

3.4.1 Bather Loading .................................................................................................. 3-7

3.4.2 Bather Behaviours .............................................................................................. 3-8

3.4.3 Chemical Analysis Results .................................................................................. 3-8

3.4.3.1 Pollutant Indicators ......................................................................................... 3-8

3.4.3.2 Disinfection By-Products ................................................................................. 3-9

3.4.3.3 Dissolved Metals ............................................................................................ 3-11

3.4.3.4 Operational Parameters .................................................................................. 3-12

3.4.4 Microbiological Analysis Results ........................................................................ 3-13

3.4.5 Onsite Measurements ........................................................................................ 3-14

3.4.5.1 Free and Combined Chlorine ........................................................................... 3-15

3.4.5.2 pH ................................................................................................................ 3-15

3.4.5.3 Conductivity .................................................................................................. 3-16

3.4.5.4 Temperature ................................................................................................. 3-17

3.5 Discussion .............................................................................................................. 3-18

3.5.1 Comparison of Grab Sample Results and In-Situ Results .................................... 3-18

3.5.2 Effect of Bather Numbers on Water Quality ....................................................... 3-18

3.5.3 Effect of User Behaviour on Water Quality ....................................................... 3-21

3.5.3.1 Uptake of Pre-Swim Showering ....................................................................... 3-22

3.5.3.2 Use of Accessories ....................................................................................... 3-23
Chapter 4 – An Assessment of the Impacts of Operational Aspects and Utility Consumption on the Sustainability of Swimming Pools

4.1 Introduction .................................................................................................................. 4-1

4.2 Literature Review ......................................................................................................... 4-2
  4.2.1 Energy Consumption ................................................................................................. 4-2
  4.2.2 Water Consumption ................................................................................................ 4-4
  4.2.3 Carbon Emissions ................................................................................................... 4-6

4.3 Operational Review of Surrey Sports Park Facility ..................................................... 4-7
  4.3.1 Facility Overview .................................................................................................... 4-7
  4.3.2 Facility Management ............................................................................................... 4-7
    4.3.2.1 Corporate Social and Environmental Responsibility ........................................... 4-8
    4.3.2.2 Bather Control and Management ...................................................................... 4-8
    4.3.2.3 Performance Monitoring ................................................................................... 4-9
  4.3.3 Operational Case Studies ......................................................................................... 4-10
    4.3.3.1 Equipment Corrosion Issue ............................................................................... 4-10
    4.3.3.2 Backwashing .................................................................................................... 4-12

4.4 Water Consumption Survey ......................................................................................... 4-15
  4.4.1 Scope ....................................................................................................................... 4-15
  4.4.2 Methodology ........................................................................................................... 4-15
    4.4.2.1 Prediction of Pool Water Evaporation ................................................................. 4-16
  4.4.3 Results ..................................................................................................................... 4-17
    4.4.3.1 Facility Water Consumption Overview ............................................................. 4-17
    4.4.3.2 Carbon Dioxide Emissions and Cost of Water at Surrey Sports Park .............. 4-18
    4.4.3.3 Swimming Pool Water Consumption ................................................................. 4-19
    4.4.3.4 Water Exchange Deficit .................................................................................... 4-20
    4.4.3.5 Impact of Inaccurate Bather Loads on the Recommended Water Consumption Values .............................................................................................................. 4-22

4.5 Energy Consumption Survey ....................................................................................... 4-24
  4.5.1 Scope ....................................................................................................................... 4-24
  4.5.2 Methodology ........................................................................................................... 4-24
    4.5.2.1 Weather Information .......................................................................................... 4-25
  4.5.3 Results ..................................................................................................................... 4-25
    4.5.3.1 Overall Fuel Consumption of Surrey Sports Park ............................................. 4-25
    4.5.3.2 Carbon Dioxide Emissions and Cost of Energy at Surrey Sports Park .......... 4-27
5.4.1.2 Boundary Conditions ........................................................................... 5-11
5.4.1.3 Computational Mesh ........................................................................... 5-12
5.4.1.4 Validation Methodology ....................................................................... 5-13
5.4.2 2D Single Jet Modelling Results .............................................................. 5-14
5.4.3 Sensitivity Analysis .................................................................................. 5-15
  5.4.3.1 Mesh Dependency .............................................................................. 5-16
  5.4.3.2 Turbulence Boundary Conditions Dependency .................................. 5-17
  5.4.3.3 Domain Size Dependency ................................................................ 5-21
5.4.4 2D Single Jet Modelling Conclusions ....................................................... 5-21
5.5 3D Single Free Jet Modelling ...................................................................... 5-23
  5.5.1 3D Single Jet Modelling Methodology ................................................... 5-23
    5.5.1.1 Geometry and Boundary Conditions ................................................. 5-23
    5.5.1.2 Mesh Generation ............................................................................. 5-23
    5.5.1.3 Turbulence Modelling .................................................................... 5-24
    5.5.1.4 Solver Settings and Convergence Criteria ....................................... 5-24
    5.5.1.5 Validation Methodology .................................................................. 5-24
  5.5.2 3D Single Jet Modelling Results ............................................................. 5-24
5.6 Single Shallow Jet Modelling ...................................................................... 5-26
  5.6.1 Single Shallow Jet Modelling Methodology ........................................... 5-26
    5.6.1.1 Geometry and Boundary Conditions ................................................. 5-26
    5.6.1.2 Mesh Generation, Turbulence Modelling and Convergence Criteria .......................................................... 5-27
    5.6.1.3 Validation Methodology .................................................................. 5-27
  5.6.2 Single Shallow Jet Modelling Results ..................................................... 5-27
5.7 Single Confined Jet Modelling .................................................................... 5-33
  5.7.1 Single Confined Jet Modelling Methodology ......................................... 5-33
    5.7.1.1 Geometry and Boundary Conditions ................................................. 5-33
    5.7.1.2 Mesh Generation, Turbulence Modelling and Convergence Criteria .......................................................... 5-34
    5.7.1.3 Validation Methodology .................................................................. 5-35
    5.7.1.4 Computational Fluid Dynamics Flow Visualisation .......................................................... 5-35
  5.7.2 Single Confined Jet Physical Modelling Methodology ............................ 5-36
    5.7.2.1 Experimental Apparatus ................................................................... 5-36
    5.7.2.2 Dye Injection ................................................................................... 5-37
    5.7.2.3 Experimental Procedure .................................................................. 5-37
  5.7.3 Start-Up Confined Jet Modelling Results ................................................ 5-38
    5.7.3.1 Computational Fluid Dynamics Plume Shape .................................. 5-40
    5.7.3.2 Reynolds Number Dependency ....................................................... 5-41
  5.7.4 Steady State Confined Jet Computational Fluid Dynamics Modelling Results .................................................................................. 5-42
    5.7.4.1 Jet Development ............................................................................. 5-42
    5.7.4.2 Dye Dispersion ............................................................................... 5-43
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7.5</td>
<td>Steady State Confined Jet Physical Modelling Results</td>
<td>5-44</td>
</tr>
<tr>
<td>5.7.5.1</td>
<td>Comparison of Computational Fluid Dynamics and Experiments</td>
<td>5-46</td>
</tr>
<tr>
<td>5.7.6</td>
<td>Single Confined Jet Modelling Conclusions</td>
<td>5-47</td>
</tr>
<tr>
<td>5.8</td>
<td>Multiple Confined Jet Modelling</td>
<td>5-49</td>
</tr>
<tr>
<td>5.8.1</td>
<td>Multiple Confined Jet Methodology</td>
<td>5-49</td>
</tr>
<tr>
<td>5.8.1.1</td>
<td>Dimensional Analysis</td>
<td>5-51</td>
</tr>
<tr>
<td>5.8.2</td>
<td>Multiple Confined Jet Physical Modelling Results</td>
<td>5-52</td>
</tr>
<tr>
<td>5.8.3</td>
<td>Multiple Confined Jet Computational Fluid Dynamics Results</td>
<td>5-53</td>
</tr>
<tr>
<td>5.8.3.1</td>
<td>Computational Fluid Dynamics Simulation without Base Outlets</td>
<td>5-53</td>
</tr>
<tr>
<td>5.8.3.2</td>
<td>Computational Fluid Dynamics Simulation with Base Outlets</td>
<td>5-57</td>
</tr>
<tr>
<td>5.9</td>
<td>Implications on Pool Design and Operation</td>
<td>5-59</td>
</tr>
<tr>
<td>5.10</td>
<td>Conclusions</td>
<td>5-60</td>
</tr>
<tr>
<td>5.11</td>
<td>References</td>
<td>5-62</td>
</tr>
<tr>
<td>6.1</td>
<td>Summary of Key Findings</td>
<td>6-1</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Existing Policy and Guidance</td>
<td>6-1</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Water Quality</td>
<td>6-2</td>
</tr>
<tr>
<td>6.1.3</td>
<td>User Aspects</td>
<td>6-4</td>
</tr>
<tr>
<td>6.1.4</td>
<td>Operational Aspects</td>
<td>6-5</td>
</tr>
<tr>
<td>6.1.5</td>
<td>Computational Fluid Dynamics Aspects</td>
<td>6-6</td>
</tr>
<tr>
<td>6.2</td>
<td>UK Policy Development Options</td>
<td>6-8</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Introduction of New Industry Focused Legislation</td>
<td>6-8</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Introduction of New Regulations under Existing Acts of Parliament</td>
<td>6-9</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Amendments to the Implementation of Existing Regulations</td>
<td>6-10</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Generation of New Voluntary Guidance or Informative Documents</td>
<td>6-11</td>
</tr>
<tr>
<td>6.3</td>
<td>Policy Development Recommendations</td>
<td>6-12</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Implementation of Policy Recommendations</td>
<td>6-14</td>
</tr>
<tr>
<td>6.4</td>
<td>Contributions to Knowledge</td>
<td>6-15</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Identification of the Relationship between Activity Type and Water Quality</td>
<td>6-15</td>
</tr>
<tr>
<td>6.4.2</td>
<td>Proposal of Water Exchange Deficit as a New Performance Indicator</td>
<td>6-15</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Proposal of an Enhanced Methodology for Calculating the Expected Water Consumption of an Indoor Swimming Pool</td>
<td>6-15</td>
</tr>
<tr>
<td>6.4.4</td>
<td>Proposal of a New Framework for Guidance and Regulation of the UK Swimming Industry</td>
<td>6-16</td>
</tr>
<tr>
<td>6.5</td>
<td>Further Work</td>
<td>6-17</td>
</tr>
</tbody>
</table>

Chapter 6 – Key Research Findings and Policy Recommendations for Integrating Sustainable Practices in the UK Swimming Pool Industry

6.1 Summary of Key Findings
6.1.1 Existing Policy and Guidance
6.1.2 Water Quality
6.1.3 User Aspects
6.1.4 Operational Aspects
6.1.5 Computational Fluid Dynamics Aspects

6.2 UK Policy Development Options
6.2.1 Introduction of New Industry Focused Legislation
6.2.2 Introduction of New Regulations under Existing Acts of Parliament
6.2.3 Amendments to the Implementation of Existing Regulations
6.2.4 Generation of New Voluntary Guidance or Informative Documents

6.3 Policy Development Recommendations
6.3.1 Implementation of Policy Recommendations

6.4 Contributions to Knowledge
6.4.1 Identification of the Relationship between Activity Type and Water Quality
6.4.2 Proposal of Water Exchange Deficit as a New Performance Indicator
6.4.3 Proposal of an Enhanced Methodology for Calculating the Expected Water Consumption of an Indoor Swimming Pool
6.4.4 Proposal of a New Framework for Guidance and Regulation of the UK Swimming Industry

6.5 Further Work
Volume 2

Appendix 1 – Research Papers and Documents

A1.1 The Effects of User Groups and Rest Periods on Swimming Pool Water Quality
A1.2 The Effects of User Groups and Rest Periods on Swimming Pool Water Quality: Microbiological Hazards
A1.3 Developing Swimming Pool Guidance Identification of Key Interactions
A1.5 Modifications for Water Management Guidance Based on an Assessment of Swimming Pool Water Consumption of an Operational Facility in the UK (In Review)
A1.6 An Analysis of Energy Consumption and Carbon Emissions Associated with Swimming Pool Operation at a Large Multi-Use Leisure Facility (In Review)
A1.7 Perceived health risks and benefits to children associated with the use of swimming pools (In Draft)
A1.8 Regulation of Swimming Pools, Water and Health (In Review)

Appendix 2 – Six–Monthly Reports

A2.1 6 Month Progress Report
A2.2 12 Month Progress Report
A2.3 18 Month Progress Report
A2.4 24 Month Dissertation
A2.5 30 Month Report
A2.6 36 Month Report
A2.7 42 Month Report
A2.8 48 Month Report

Appendix 3 – Surrey Sports Park Operational Documents

A3.1 Surrey Sports Park Technical Summary
A3.2 Surrey Sports Park Pool Schematic
A3.3 Surrey Sports Park Pool Plant Normal Operating Procedure
A3.4 Surrey Sports Park Swimming Pool Normal Operating Procedure

Appendix 4 – Other Supporting Documents

A4.1 Pool Water Sampling Procedure
A4.2 Surrey Sports Park Corporate Social Responsibility Review

Volume 3 (Digital Supplement)

Appendix 5 – Water Sampling and Operational Records

A5.1 – Field Sampling Data
A5.2 – Microbiological Sample Data
### Contents

A5.3 – Chemical Sample Data  
A5.4 – Sonde Collected Water Sampling Data  
A5.5 – Activity Survey Bather Data  
A5.6 – Surrey Sports Park Bather Numbers  
A5.7 – Energy Meter Records  
A5.8 – Water Consumption Data

### Appendix 6 – Computational and Physical Modelling Records

<table>
<thead>
<tr>
<th>A6.1</th>
<th>Single Jet Physical Modelling Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6.2</td>
<td>Multiple Jet Physical Modelling Records</td>
</tr>
<tr>
<td>A6.3</td>
<td>Free Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.4</td>
<td>Shallow Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.5</td>
<td>Confined Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.6</td>
<td>Multiple Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.1</td>
<td>Single Jet Physical Modelling Records</td>
</tr>
<tr>
<td>A6.2</td>
<td>Multiple Jet Physical Modelling Records</td>
</tr>
<tr>
<td>A6.3</td>
<td>Free Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.4</td>
<td>Shallow Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.5</td>
<td>Confined Jet Computational Modelling Records</td>
</tr>
<tr>
<td>A6.6</td>
<td>Multiple Jet Computational Modelling Records</td>
</tr>
</tbody>
</table>
List of Figures

Figure 0-1  Conceptual model for an indoor swimming pool ........................................ xxvii
Figure 0-2  A proposal for a new conceptual framework for the recreational water industry .......................................................... xxx
Figure 1-1  Historical structure of the UK swimming pool industry ........................................ 1-3
Figure 1-2  Key interactions in a swimming pool facility ..................................................... 1-20
Figure 1-3  Modified UK industry structure following adoption of modifications made by PWTAG ........................................................................ 1-21
Figure 2-1  Photos of pool tank (top right), traversable boom (left) and UV unit (bottom right) at Surrey Sports Park .................................................. 2-2
Figure 2-2  Potential microbiological pathogens in swimming pool water ............................... 2-5
Figure 2-3  Potential chemicals in swimming pool water ...................................................... 2-7
Figure 2-4  Sampling locations (A-M) at the Surrey Sports Park pool .................................... 2-18
Figure 2-5  Shallow water sampler used in the study ............................................................. 2-22
Figure 2-6  Illustration of inertial pump operation ............................................................... 2-23
Figure 2-7  Sample port on sand filter inlet ........................................................................ 2-23
Figure 2-8  Total THM concentrations for pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 .......... 2-30
Figure 2-9  Average THM concentration in A) the 231 pool water samples and B) the 21 source water samples taken during the water survey ............................................. 2-30
Figure 2-10 Aluminium concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ......... 2-31
Figure 2-11 Calcium concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ..... 2-32
Figure 2-12 Iron concentrations in shallow pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ...... 2-32
Figure 2-13 Metal concentrations for source water samples taken on each sampling date during the study running from April 2010 to September 2011 ..................... 2-32
Figure 2-14 Alkalinity of pool water and source water samples taken on each sampling date during the study running from April 2010 to September 2011 ................... 2-33
Figure 2-15 Calcium carbonate concentrations in pool and source water samples taken on each date in the study running from April 2010 to September 2011 .......... 2-33
Figure 2-16  pH of pool water and source water samples taken on each sampling date during the study running from April 2010 to September 2011 ................. 2-34

Figure 2-17  Conductivity of pool water and source water samples taken on each sampling date during the study running from April 2010 to September 2011 ............ 2-35

Figure 2-18  Bromate concentration in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 .... 2-35

Figure 2-19  Chlorate concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ..... 2-36

Figure 2-20  Chloride concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ..... 2-36

Figure 2-21  Nitrate concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ..... 2-37

Figure 2-22  Sulphate concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ..... 2-37

Figure 2-23  TON concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011 ................. 2-37

Figure 2-24  TOC concentrations in pool water and source water samples taken on each sampling date during the study running from April 2010 to September 2011 ................................................................................................................. 2-38

Figure 2-25  Temperature of pool water and source water measured on each sampling date during the study running from April 2010 to September 2011 .................. 2-38

Figure 2-26  Free chlorine concentrations in pool and source water measured on each sampling date in the study running from April 2010 to September 2011 ..... 2-39

Figure 2-27  Combined chlorine concentrations in pool and source water measured on each date in the study running from April 2010 to September 2011 ...................... 2-39

Figure 2-28  Field measurements of pH measured on each sampling date during the study running from April 2010 to September 2011 .................................................. 2-40

Figure 2-29  Field measurements of alkalinity measured on each sampling date during the study running from April 2010 to September 2011 ........................................ 2-40

Figure 2-30  Field measurement of calcium hardness measured on each sampling date during the study running from April 2010 to September 2011 ...................... 2-41

Figure 2-31  Field measurements of conductivity measured on each sampling date during the study running from April 2010 to June 2010 ............................. 2-41

Figure 2-32  Langelier saturation index for pool and source water calculated on each sampling date in the study running from April 2010 to September 2011 ..... 2-42
List of Figures

Figure 3-1 YSI sonde used for in-situ monitoring of pH, conductivity, temperature and free chlorine................................................................. 3-6

Figure 3-2 Bather load during the activity survey at Surrey Sports Park ..................... 3-7

Figure 3-3 Chloride, total organic carbon and total oxidised nitrogen concentrations in pool water at location A during the activity survey .................... 3-9

Figure 3-4 Chloride, total organic carbon and total oxidised nitrogen concentrations in pool water at location D during the activity survey .................... 3-9

Figure 3-5 Bromodichloromethane, chloroform and dibromochloromethane concentrations in pool water at location A during the activity survey ........ 3-10

Figure 3-6 Bromodichloromethane, chloroform and dibromochloromethane concentrations in pool water at location D during the activity survey ........ 3-10

Figure 3-7 Bromate, chlorate and sulphate concentrations in pool water at location A during the activity survey .................................................. 3-11

Figure 3-8 Bromate, chlorate and sulphate concentrations in pool water at location D during the activity survey .................................................. 3-11

Figure 3-9 Aluminium, calcium and iron concentrations in pool water at location A during the activity survey ..................................................... 3-12

Figure 3-10 Aluminium, calcium and iron concentrations in pool water at location D during the activity survey ..................................................... 3-12

Figure 3-11 Alkalinity, calcium hardness and conductivity of pool water at location A during the activity survey ................................................. 3-13

Figure 3-12 Alkalinity, calcium hardness and conductivity of pool water at location D during the activity survey ................................................. 3-13

Figure 3-13 Variation in concentration of microbiological indicators at location A during the activity survey ...................................................... 3-14

Figure 3-14 Variation in concentration of microbiological indicators at location D during the activity survey ...................................................... 3-14

Figure 3-15 Amperometric and photometric results of free and combined chlorine concentrations in the pool water during activities taking place in location A........................................................................ 3-15

Figure 3-16 Photometric results of free and combined chlorine concentrations in the pool water during activities taking place in location D .................... 3-15

Figure 3-17 In-situ pH measurements of the pool water during activities taking place in locations A and D .......................................................... 3-16

Figure 3-18 In-situ conductivity measurements of the pool water during activities taking place in locations A and D ............................................. 3-16
Figure 3-19  Pool water temperature measured at locations A and D during the different activities at the Surrey Sports Park ............................................................ 3-17

Figure 3-20  Combined chlorine concentration at the end of each indicated activity plotted against the total activity bather load ............................................................ 3-19

Figure 3-21  Total THM concentration at the end of each indicated activity plotted against the total activity bather load ............................................................ 3-20

Figure 3-22  Overlay of floor and boom movements onto pool water temperature data collected by the automated sondes at location A and location D ............................................. 3-26

Figure 4-1  Pool water and mains water chloride concentrations for A) April to November 2010 and B) March to September 2011 ............................................................ 4-11

Figure 4-2  The change in pool water chloride concentrations plotted against the mean daily water exchange rate ............................................................ 4-12

Figure 4-3  Water consumption at Surrey Sports Park from April 2010 to October 2011 ............................................................ 4-18

Figure 4-4  Actual and recommended volumes of fresh water added to the pool for various daily bather loads ............................................................ 4-19

Figure 4-5  Monthly-averaged actual and recommended daily refresh rates based on actual monthly bather numbers for Surrey Sports Park ............................................. 4-20

Figure 4-6  Actual and recommended cumulative water consumption and water deficit for Surrey Sports Park swimming pool between April 2010 and March 2012 .... 4-21

Figure 4-7  Actual and recommended cumulative water consumption and water deficit for Surrey Sports Park swimming pool between April 2010 and March 2012 with and without bather number correction applied ............................................. 4-22

Figure 4-8  Monthly energy consumption of the Surrey Sports Park for the first 18 months of operation following opening in April 2010 ............................................................ 4-26

Figure 4-9  Distribution of electrical consumption at Surrey Sports Park between April 2010 and September 2010 ............................................................ 4-27

Figure 4-10  Monthly carbon emissions and cost for energy consumption at Surrey Sports Park from April 2010 to September 2011 ............................................................ 4-27

Figure 4-11  Raw and modified BMS output data for the daily pool water heating load in June and August 2010 ............................................................ 4-29

Figure 4-12  Power demand profile for the swimming pool water treatment pumps using 15-minute measurements for the three weeks selected during the survey period ............................................................ 4-31
Figure 4-13  Daily electrical energy consumption for the swimming pool water treatment pumps from June 2010 to August 2010 based on 15-minute power consumption data................................................. 4-32

Figure 4-14  Power demand profile for the swimming pool air handling units using 15-minute measurements for the three weeks selected during the survey period ......................................... 4-33

Figure 4-15  Daily electrical energy consumption for the swimming pool air handling units from June 2010 to August 2010 based on 15-minute power consumption data................................................................. 4-33

Figure 4-16  Power demand profile for the swimming pool lighting using 15-minute measurements for the three weeks selected during the survey period........ 4-34

Figure 4-17  Daily electrical energy consumption for the swimming pool lighting from June 2010 to August 2010 based on 15-minute power consumption data .............. 4-35

Figure 4-18  Fortnightly moving average of daily bather numbers at the Surrey Sports Park swimming pool for May 2010 to April 2012......................................................... 4-37

Figure 4-19  Averaged instantaneous bather loads on Mondays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-38

Figure 4-20  Averaged instantaneous bather loads on Tuesdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-38

Figure 4-21  Averaged instantaneous bather loads on Wednesdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-39

Figure 4-22  Averaged instantaneous bather loads on Thursdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-39

Figure 4-23  Averaged instantaneous bather loads on Fridays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-39

Figure 4-24  Averaged instantaneous bather loads on Saturdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-40

Figure 4-25  Averaged instantaneous bather loads on Sundays at Surrey Sports Park during two selected periods from the 2011 and 2012 records ....................... 4-40

Figure 5-1  Schematic of a round jet issuing from a contraction nozzle (Ball et al. 2012) .................................................................................................................. 5-6

Figure 5-2  Comparison of computed and measured velocity profiles for a round jet; k-ω model (—), k-ε model (— - -), Wygnanski & Fiedler (1969)(o) ............. 5-8

Figure 5-3  Comparison of Computed and Measured Velocity Profiles for a Round Jet; k-ω model (—), k-ε model (— - -), RNG k-ε model (...), Wygnanski & Fiedler (o), Rodi (•) ........................................................................................................ 5-9
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-4</td>
<td>Outline of free round jet geometry</td>
<td>5-11</td>
</tr>
<tr>
<td>5-5</td>
<td>Figure showing structure of the 2500 cell mesh used in the 2D study</td>
<td>5-13</td>
</tr>
<tr>
<td>5-6</td>
<td>Centreline velocity variation for 2D free jet with distance from jet exit for various turbulence models</td>
<td>5-14</td>
</tr>
<tr>
<td>5-7</td>
<td>Comparison of computed axial velocity profiles against data from Wilcox (2006) and Wygnanski &amp; Fiedler (1969)</td>
<td>5-15</td>
</tr>
<tr>
<td>5-8</td>
<td>Output results for mesh dependency study</td>
<td>5-16</td>
</tr>
<tr>
<td>5-9</td>
<td>Centreline velocity decay of 2D k-ε model for different boundary conditions</td>
<td>5-19</td>
</tr>
<tr>
<td>5-10</td>
<td>Axial velocity profile of 2D k-ε model at x/D = 40 for different boundary conditions</td>
<td>5-19</td>
</tr>
<tr>
<td>5-11</td>
<td>Centreline velocity decay of 2D k-ω model for different boundary conditions</td>
<td>5-20</td>
</tr>
<tr>
<td>5-12</td>
<td>Axial velocity profile of 2D k-ω model at x/D = 40 for different boundary conditions</td>
<td>5-20</td>
</tr>
<tr>
<td>5-13</td>
<td>Geometry used for the 3D single free jet CFD simulations</td>
<td>5-23</td>
</tr>
<tr>
<td>5-14</td>
<td>3D Free jet centreline velocity variation with distance from jet exit for various turbulence models</td>
<td>5-25</td>
</tr>
<tr>
<td>5-15</td>
<td>Geometry used for the shallow jet CFD simulations</td>
<td>5-26</td>
</tr>
<tr>
<td>5-16</td>
<td>CFD generated centreline velocity profiles and experimental data for the shallow jet case at different values of h/d. (♂) Madina and Bernal (1994), (×) Shinneeb et al. (2011), (—is) CFD results, (---) Free Jet CFD results</td>
<td>5-28</td>
</tr>
<tr>
<td>5-17</td>
<td>Turbulent kinetic energy along the centreline for different values of h/d. (♂) CFD generated, (●) Shinneeb et al. (2011)</td>
<td>5-29</td>
</tr>
<tr>
<td>5-18</td>
<td>CFD generated velocity contours on the central vertical plan at Reynolds Number of 22,388 for different values of h/d</td>
<td>5-30</td>
</tr>
<tr>
<td>5-19</td>
<td>Comparison of geometric (solid symbols) and jet (hollow symbols) centreline velocities for shallow jets with h/d = 5, h/d = 10, h/d = 15 and h/d = 20</td>
<td>5-31</td>
</tr>
<tr>
<td>5-20</td>
<td>Centreline velocity profile for shallow jet at various Reynolds Numbers for a) h/d = 10 and b) h/d = 20</td>
<td>5-31</td>
</tr>
<tr>
<td>5-21</td>
<td>Geometry used for single confined jet CFD simulations</td>
<td>5-33</td>
</tr>
<tr>
<td>5-22</td>
<td>Graphical representation of the numerical mesh used for the single confined jet CFD simulations</td>
<td>5-34</td>
</tr>
<tr>
<td>5-23</td>
<td>Calibration images for the Ponceau 4R dye used in physical experiments</td>
<td>5-36</td>
</tr>
<tr>
<td>5-24</td>
<td>Schematic of single confined jet physical experimental apparatus</td>
<td>5-37</td>
</tr>
</tbody>
</table>
Figure 5-25  CFD generated images for a single confined jet with inlet velocity of 5.63 m/s................................................. 5-39
Figure 5-26  Experimental images for a single confined jet with inlet velocity of 5.63 m/s......................................................... 5-39
Figure 5-27  CFD generated images for a single confined jet with inlet velocity of 10.6 m/s.......................................................... 5-39
Figure 5-28  Experimental images for a single confined jet with inlet velocity of 10.6 m/s.......................................................... 5-39
Figure 5-29  CFD generated images for an inlet pressure of 100kPa ................................................. 5-40
Figure 5-30  Deep pool CFD images for an inlet pressure of 100kPa at τ=34 and τ=67 ...... 5-41
Figure 5-31  Centreline velocity profiles for shallow and confined jet case using the transient and steady state solvers for Re = 50,000. Transient confined jet τ = 113 (•), Transient confined jet τ = 625 (○), Steady state confined jet (□), Shallow jet h/d = 20 (Δ) ..................................................... 5-43
Figure 5-32  Still images taken from repeated physical modelling experiments for jet inlet Reynolds Number of Re 15701............................................ 5-45
Figure 5-33  Experimental Images at τ=20, τ=67 and τ=101. Left: Re=3224, Fr=2.59. Mid: Re=12497, Fr=10.03. Right: Re=15701, Fr=12.60............................................. 5-46
Figure 5-34  Comparison of CFD and experimental images for confined jet case at τ = 10 (top) and τ = 20 (bottom).......................................................... 5-46
Figure 5-35  Comparison of CFD and experimental images for the confined jet case following jet impingement with the wall at τ = 134........................................... 5-47
Figure 5-36  Photograph of the small scale pool tank, in 15 paired jet configuration, used for the physical dye visualisation experiments............................ 5-50
Figure 5-37  Geometry for the full scale swimming pool CFD modelling including base outlets........................................................................ 5-51
Figure 5-38  Comparison of the CFD generated images for dye spreading for the small scale multiple confined jet without base outlets case at τ = 20 for Reynolds Numbers 4,602 and 50,000.......................................................... 5-53
Figure 5-39  Experimental images for multiple jets with Reynolds number = 4,602 ........ 5-54
Figure 5-40  CFD generated images for multiple jets with Reynolds number = 4,602........ 5-54
Figure 5-41  Experimental images for multiple jets with Reynolds number = 5,589 ........ 5-54
Figure 5-42  CFD generated images for multiple jets with Reynolds number = 5,589....... 5-54
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-43</td>
<td>CFD generated volume contour plots showing volumes containing chlorine at various mass fractions (Fc) after 15 minutes of injection for the full scale pool, no base outlet scenario and a Reynolds number of 63,694.</td>
</tr>
<tr>
<td>5-44</td>
<td>A comparison between the modelled and theoretical proportion of original water removed from the full scale pool tank over time for a multiple confined jet scenario without base outlets.</td>
</tr>
<tr>
<td>5-45</td>
<td>CFD generated image showing areas of the pool tank without base outlets with a mass fraction of original water greater than 0.7 after 6 hours of injection.</td>
</tr>
<tr>
<td>5-46</td>
<td>A comparison between the modelled and theoretical proportion of original water exchanged from the full scale pool tank over time for the multiple confined jet scenario with base outlets operating at 75% of designed flow rate (406 m³/hr).</td>
</tr>
<tr>
<td>6-1</td>
<td>UK framework for domestic regulations.</td>
</tr>
<tr>
<td>6-2</td>
<td>A proposal for a new conceptual framework for the recreational water industry.</td>
</tr>
</tbody>
</table>
List of Tables

Table 1-1 Key interactions within a pool facility and the reasons for consideration...... 1-17
Table 2-1 Summary of recommended parameter limits for swimming pool water ..... 2-17
Table 2-2 List of parameters included in the water analysis........................................... 2-19
Table 2-3 Pool water survey sample descriptions......................................................... 2-21
Table 2-4 Look up table for the Langelier Saturation Index factors................................ 2-24
Table 2-5 List of methodologies and associated references used for water analysis.... 2-25
Table 2-6 Summary showing the number of positive microbiological results identified on each sampling date............................................................................................. 2-29
Table 2-7 Summary of pool water concentrations of parameters analysed in the second phase of the water survey between March and September 2011 .................. 2-46
Table 2-8 Summary of water quality parameters for the source water between April 2010 and September 2011....................................................................................... 2-48
Table 3-1 List of activities included in the Surrey Sports Park activity survey .............. 3-4
Table 3-2 Swimming pool schedule for Surrey Sports Park for the main study on Thursday 18th November 2010......................................................................................... 3-5
Table 3-3 Cumulative and average instantaneous bather loads for each pool activity ... 3-7
Table 3-4 Pre-swim shower use by each user group during the activity survey............ 3-8
Table 3-5 Summary of microbiological results of samples taken during the activity survey ...................................................................................................................... 3-13
Table 4-1 Evaporation rate (kg/hr/m²) look-up table for unoccupied pools based on the formulas proposed by Shah (2011)................................................................. 4-17
Table 4-2 Evaporation rate (kg/hr/m²) look-up table for occupied pools based on the formulas proposed by Shah (2011)................................................................. 4-17
Table 4-3 2010/11 pricing and CO₂ emission factors associated with the supply and disposal of water at Surrey Sports Park ................................................................. 4-18
Table 4-4 2010/11 pricing and CO₂ emission factors associated with the consumption of energy at Surrey Sports Park ................................................................. 4-24
Table 4-5 Heating degree days data for the study period and 20-year average as measured at the regional weather station calculated using a 15.5°C baseline ......................................................................................................................... 4-25
Table 4-6 Average monthly energy consumption, CO₂ emissions and cost for fuels used at Surrey Sports Park based on data from April 2010 to September 2011 ...... 4-28
### List of Tables

<table>
<thead>
<tr>
<th>Table 5-1</th>
<th>Number of computational iterations required for each mesh</th>
<th>5-17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5-2</td>
<td>Boundary condition settings for study</td>
<td>5-17</td>
</tr>
<tr>
<td>Table 5-3</td>
<td>Values of critical Reynolds number for the shallow cases with h/d values of 5, 10, 15 and 20</td>
<td>5-32</td>
</tr>
<tr>
<td>Table 5-4</td>
<td>Actual time at specified non-dimensional timesteps for experimental inlet velocities</td>
<td>5-44</td>
</tr>
</tbody>
</table>
## List of Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACOP</td>
<td>Approved Code of Practice</td>
</tr>
<tr>
<td>AF</td>
<td>Alkalinity Factor</td>
</tr>
<tr>
<td>APSE</td>
<td>Association for Public Sector Excellence</td>
</tr>
<tr>
<td>ASA</td>
<td>Amateur Swimming Association</td>
</tr>
<tr>
<td>BDCM</td>
<td>Bromodichloromethane</td>
</tr>
<tr>
<td>BISHTA</td>
<td>British and Irish Spa and Hot Tub Association</td>
</tr>
<tr>
<td>BMS</td>
<td>Building Management System</td>
</tr>
<tr>
<td>BREEAM</td>
<td>Building Research Establishment Environmental Assessment Methodology</td>
</tr>
<tr>
<td>BSPF</td>
<td>British Swimming Pool Federation</td>
</tr>
<tr>
<td>CF</td>
<td>Calcium Hardness Factor</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CFU</td>
<td>Colony Forming Units</td>
</tr>
<tr>
<td>CIMSPA</td>
<td>Chartered Institute for the Management of Sport and Physical Activity</td>
</tr>
<tr>
<td>CRC</td>
<td>Carbon Reduction Commitment</td>
</tr>
<tr>
<td>CSER</td>
<td>Corporate Social and Environmental Responsibility</td>
</tr>
<tr>
<td>DBCM</td>
<td>Dibromochloromethane</td>
</tr>
<tr>
<td>DBP</td>
<td>Disinfection By-Products</td>
</tr>
<tr>
<td>DCA</td>
<td>Dichloroacetic Acid</td>
</tr>
<tr>
<td>DCLG</td>
<td>Department for Communities and Local Government</td>
</tr>
<tr>
<td>DCMS</td>
<td>Department for Culture, Media and Sport</td>
</tr>
<tr>
<td>DEC</td>
<td>Display Energy Certificate</td>
</tr>
<tr>
<td>DEFRA</td>
<td>Department for Environment, Food and Rural Affairs</td>
</tr>
<tr>
<td>DPD</td>
<td>Diethyl-p-phenylenediamine</td>
</tr>
<tr>
<td>E&amp;FM</td>
<td>Estates and Facilities Management</td>
</tr>
<tr>
<td>GAC</td>
<td>Granular Activated Carbon</td>
</tr>
<tr>
<td>GCMS</td>
<td>Gas Chromatography Mass Spectrometry</td>
</tr>
<tr>
<td>HAA</td>
<td>Haloacetic Acids</td>
</tr>
<tr>
<td>HAN</td>
<td>Haloacetonitrile</td>
</tr>
<tr>
<td>HDD</td>
<td>Heating Degree Days</td>
</tr>
<tr>
<td>HSE</td>
<td>Health and Safety Executive</td>
</tr>
<tr>
<td>IQL</td>
<td>Institute of Qualified Lifeguards</td>
</tr>
<tr>
<td>ISPE</td>
<td>Institute of Swimming Pool Engineers</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler Velocimetry</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Meaning</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
</tr>
<tr>
<td>LSI</td>
<td>Langelier Saturation Index</td>
</tr>
<tr>
<td>MLSB</td>
<td>Membrane Lauryl Sulphate Broth</td>
</tr>
<tr>
<td>NOP</td>
<td>Normal Operating Procedures</td>
</tr>
<tr>
<td>NPLQ</td>
<td>National Pool Lifeguard Qualification</td>
</tr>
<tr>
<td>NPMQ</td>
<td>National Pool Managers Qualification</td>
</tr>
<tr>
<td>NPPO</td>
<td>National Pool Plant Operators Certificate</td>
</tr>
<tr>
<td>NTU</td>
<td>Nephelometric Turbity Units</td>
</tr>
<tr>
<td>PAC</td>
<td>Polyaluminium Chloride</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>PWTAG</td>
<td>Pool Water Treatment Advisory Group</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-Averaged Navier-Stokes</td>
</tr>
<tr>
<td>RCPEH</td>
<td>Robens Centre for Public and Environmental Health</td>
</tr>
<tr>
<td>RNG</td>
<td>Re-Normalisation Group</td>
</tr>
<tr>
<td>RO</td>
<td>Reverse Osmosis</td>
</tr>
<tr>
<td>RTD</td>
<td>Residence Time Distribution</td>
</tr>
<tr>
<td>SPATA</td>
<td>Swimming Pool and Allied Trades Association</td>
</tr>
<tr>
<td>SSP</td>
<td>Surrey Sports Park</td>
</tr>
<tr>
<td>SST</td>
<td>Shear Stress Transport</td>
</tr>
<tr>
<td>STA</td>
<td>Swimming Teachers Association</td>
</tr>
<tr>
<td>TCA</td>
<td>Trichloroacetic Acid</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
</tr>
<tr>
<td>TDSF</td>
<td>Total Dissolved Solids Factor</td>
</tr>
<tr>
<td>TF</td>
<td>Temperature Factor</td>
</tr>
<tr>
<td>THM</td>
<td>Trihalomethanes</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>TON</td>
<td>Total Oxidised Nitrogen</td>
</tr>
<tr>
<td>TVC</td>
<td>Total Viable Count</td>
</tr>
<tr>
<td>UF</td>
<td>Ultra-Filtration</td>
</tr>
<tr>
<td>UKAS</td>
<td>United Kingdom Accreditation Service</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra-Violet</td>
</tr>
<tr>
<td>WED</td>
<td>Water Exchange Deficit</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organisation</td>
</tr>
<tr>
<td>YEA</td>
<td>Yeast Extract Agar</td>
</tr>
</tbody>
</table>
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon )</td>
<td>Turbulent Dissipation</td>
<td>( m^2.s^{-3} )</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Dynamic Viscosity</td>
<td>( kg.m^{-1}.s^{-1} )</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Fluid Density</td>
<td>( kg.m^{-3} )</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Non-dimensional Time</td>
<td>-</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Specific Dissipation Rate</td>
<td>( s^{-1} )</td>
</tr>
<tr>
<td>( d )</td>
<td>Jet Diameter</td>
<td>m</td>
</tr>
<tr>
<td>( D_w )</td>
<td>Density of Saturated Air at Water Temperature</td>
<td>lb.ft(^{-3}) dry air</td>
</tr>
<tr>
<td>( D_r )</td>
<td>Density of Air at Room Condition</td>
<td>lb.ft(^{-3}) dry air</td>
</tr>
<tr>
<td>( E )</td>
<td>Evaporation Rate from Occupied Pool Surface</td>
<td>kg.hr(^{-1}) m(^{-2})</td>
</tr>
<tr>
<td>( E_0 )</td>
<td>Evaporation Rate from Unoccupied Pool Surface</td>
<td>kg.hr(^{-1}) m(^{-2})</td>
</tr>
<tr>
<td>( F_b )</td>
<td>Bather Count Correction Factor</td>
<td>-</td>
</tr>
<tr>
<td>( F_c )</td>
<td>Mass Fraction of Chlorine</td>
<td>-</td>
</tr>
<tr>
<td>( F_I )</td>
<td>Scaling Factor for the Geometry</td>
<td>-</td>
</tr>
<tr>
<td>( F_{ns} )</td>
<td>Proportion of Bathers Not Showering Before Swimming</td>
<td>-</td>
</tr>
<tr>
<td>( F_v )</td>
<td>Scaling Factor for Kinematic Viscosity</td>
<td>-</td>
</tr>
<tr>
<td>( Fr )</td>
<td>Froude Number</td>
<td>-</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravity</td>
<td>m.s(^{-2})</td>
</tr>
<tr>
<td>( h )</td>
<td>Tank Depth</td>
<td>m</td>
</tr>
<tr>
<td>( I )</td>
<td>Turbulence Intensity</td>
<td>-</td>
</tr>
<tr>
<td>( k )</td>
<td>Turbulent Kinetic Energy</td>
<td>( m^2.s^{-2} )</td>
</tr>
<tr>
<td>( l )</td>
<td>Tank Width</td>
<td>m</td>
</tr>
<tr>
<td>( l_t )</td>
<td>Turbulence Length Scale</td>
<td>m</td>
</tr>
<tr>
<td>( N )</td>
<td>Number of Bathers</td>
<td>-</td>
</tr>
<tr>
<td>( p_{aw} )</td>
<td>Air Water-Vapour Pressure, Air Saturated at Water Temperature</td>
<td>inches Hg</td>
</tr>
<tr>
<td>( p_r )</td>
<td>Air Water-Vapour Pressure, Air at Room Condition</td>
<td>inches Hg</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>Coefficient of Determination</td>
<td>-</td>
</tr>
<tr>
<td>( Re )</td>
<td>Reynolds Number</td>
<td>-</td>
</tr>
<tr>
<td>( SS_{res} )</td>
<td>Residual Sum of Squares</td>
<td>-</td>
</tr>
<tr>
<td>( SS_{tot} )</td>
<td>Total Sum of Squares</td>
<td>-</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
<td>s</td>
</tr>
<tr>
<td>( u )</td>
<td>Nozzle Velocity</td>
<td>m.s(^{-1})</td>
</tr>
<tr>
<td>( U )</td>
<td>Utilization Factor</td>
<td>-</td>
</tr>
<tr>
<td>( w )</td>
<td>Jet Width</td>
<td>m</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>$W_b$</td>
<td>Bather-Related Water Exchange Rate</td>
<td>l.bather$^{-1}$.day$^{1}$</td>
</tr>
<tr>
<td>$W_{bi}$</td>
<td>Bather-Related Water Exchange Rate for Initial Contaminants</td>
<td>l.bather$^{-1}$.day$^{1}$</td>
</tr>
<tr>
<td>$W_{bc}$</td>
<td>Bather-Related Water Exchange Rate for Continuous Contaminant</td>
<td>l.bather$^{-1}$.day$^{1}$</td>
</tr>
<tr>
<td>$W_c$</td>
<td>Chemical-Related Water Exchange Rate</td>
<td>l.day$^{1}$</td>
</tr>
<tr>
<td>$W_{ex}$</td>
<td>Water Exchange Rate</td>
<td>l.day$^{1}$</td>
</tr>
<tr>
<td>$W_{ev}$</td>
<td>Evaporation Rate of Pool Water</td>
<td>l.day$^{1}$</td>
</tr>
<tr>
<td>$W_p$</td>
<td>Pool Water Consumption</td>
<td>l.day$^{1}$</td>
</tr>
<tr>
<td>$W_r$</td>
<td>Humidity Ratio, Air at Room Condition</td>
<td>-</td>
</tr>
<tr>
<td>$W_w$</td>
<td>Humidity Ratio, Saturated Air at Water Temperature</td>
<td>-</td>
</tr>
<tr>
<td>$x$</td>
<td>Length Along Jet Axis</td>
<td>m</td>
</tr>
</tbody>
</table>
Executive Summary

Introduction

The swimming industry is facing increasing scrutiny as a consequence of a combination of tightening financial pressures and a rise in the profile of potential health issues associated with the activity. Historically the industry has been very loosely regulated with the main emphasis of management requirements placed on ensuring that participants are kept from physical harm. A growing awareness of the health implications associated with traditional pool water treatment practices has resulted in a multitude of new technological solutions and a greater interest in the exposure of bathers to chemicals to be developed (Oesterholt et al. 2009; PWTAG 2010).

Alongside this, the rise in utility prices, combined with the realisation of the environmental impact of energy use, has driven the industry to implement new efficiency measures for its facilities (Carbon Trust 2006). These developments have been piecemeal and poorly integrated to date, resulting in an industry relying on voluntary guidance that has formed organically over time. There is therefore a need to systematically appraise the current state of the industry, as a whole, and develop integrated guidance that considers all aspects related to swimming pool operation in order to ensure the sustainability of the industry as it develops.

The research presented in this thesis is the first to undertake a root and branch assessment of the industry. A strategy for addressing the major issues requiring resolution is recommended based on the analysis of primary data obtained through a series of targeted studies into the key interactions identified within indoor swimming facilities. The research was undertaken in conjunction with the Surrey Sports Park (SSP), the Department for Environment, Food and Rural Affairs (DEFRA) and the University of Surrey.

Identification of the Research Objectives

The initial phase of the research involved compiling all the interactions taking place within a swimming pool, as research published to date had focused on individual considerations in isolation. The interactions within the pool were categorised into five distinct aspects (Users, Employees, Water Quality, Air Quality and Energy Consumption) and a conceptual model for an indoor swimming pool facility was developed as shown in Figure 0-1.
Executive Summary

The generated conceptual model and these five aspects were used as the framework around which the initial scope of the research was formed. Key areas of existing knowledge that required strengthening in order to enhance current industrial guidance in the UK were identified through a review of existing guidance and in-depth discussions with the Pool Water Treatment Advisory Group (PWTAG), the primary body responsible for providing guidance to the industry.

The interactions relating to the water quality associated with swimming pools were considered to be of greatest importance during the literature review and discussions and were therefore selected as the focus for the research. These interactions included the relationship between user activity and water quality, as well as the impact of current UK guidance, prescribed for maintaining water quality, on the operational cost and environmental impact of a facility.

Employed Research Techniques

The broad nature of the area of research meant that a variety of research methods were required. An in-depth review of current guidance and regulation was required to gain an understanding of the existing information disseminated to the industry. To deepen the knowledge of the current state of the industry, several meetings and conversations with representatives of the industry were also undertaken. This provided a good insight into the challenges facing, and perceptions held by, practitioners in the industry. A review of academic literature relating to the sector was also undertaken to assess the existing supporting evidence available to the industry. As the industry has not been overly engaged with academic research, the range of pool-specific information available in academic journals was limited in many areas. To broaden the academic knowledge base from which to draw information, research findings based on closely-related industries, such as the drinking-water industry were also reviewed.
In addition to the review of available literature, primary data were collected during the research from a number of sources. Water quality data were generated by undertaking a programme of microbiological and chemical water sampling at an operational facility. Operational data for the facility were collected from the building management system installed at the facility as well as from the records held by the operational and maintenance teams. Statistical analysis of the data was undertaken and evaluation and discussion of the results were used to formulate conclusions in relation to the objectives set out in the scoping phase of the research. Computational software and small-scale physical experiments were also used to provide data which could be used to assess proposed hypotheses in relation to the impact of changes to operational aspects.

**Contributions to Knowledge**

Although a large amount of data has been reported in relation to swimming pool water quality to date, it has often been either reported with minimal information on the operational conditions of the facility or in relation to a restricted sample range (Lakind et al. 2010). In the current research, a substantial survey of the chemical and microbiological characteristics of the swimming pool water at Surrey Sports Park was undertaken, over an 18 month period, to generate the data required to assess the relationships between users and water quality. The range of parameters, sampling locations and sampling dates used in this survey, together with the access to associated occupancy and operational data, has provided a more substantial knowledge base than has been previously made available in the literature. This knowledge base enabled the impacts of different pool-based activities on water quality to be assessed. Activity type was found to be a factor in the degree of water contamination occurring during pool operation, not just the numbers of participants involved, as current guidance assumes. The relationship between activity type and water quality, as reported at the International Pool and Spa Conference held in Porto and the Engineering Doctorate Conference in 2011, is the first contribution to knowledge that was achieved during this research (Lewis et al. 2011a; 2011b).

The water quality survey also highlighted issues with the existing operational practices at the facility, namely the accumulation of dissolved non-reactive contaminants. Discussions with industry experts revealed that this issue was common throughout the industry and not specific to the facility involved in this research (PWTAG 2010). The investigation into operational practices at the research facility highlighted that a lack of performance indicators contributed to the mismanagement of the water replenishment. The Water Exchange Deficit, defined as the cumulative difference between the recommended and actual volume of
water exchanged, is proposed as a new performance indicator. This is the second contribution to knowledge generated through this research.

The assessment of operational practices and current industry guidance identified that they were not effective at encouraging designers and operators to make sustainable decisions. Swimming pool facilities are large consumers of water, however, very little consideration for methods of reducing water demand has taken place to date. The over-simplification of current water management guidance, as published by PWTAG (2009), was proposed as a contributing factor. The current water management guidance does not clearly present operators with the potential benefits of utilising opportunities for improvements in water efficiency. It is recommended that the industry moves away from the current strategy that is based on a simple fixed water exchange rate to one that takes into account variations in the contributing factors behind the need for fresh water addition. These factors include the rate of evaporation from the pool \((W_{ev})\), the amount of contaminants introduced by the users \((W_b)\) and the amount of contaminants introduced or formed as part of the water treatment process \((W_c)\). An enhanced relationship for water consumption \((W_p)\), as shown in Equation 0-1, is proposed in this research.

\[
W_p = (F_b \times N \times ((F_{ns} \times W_{bi}) + W_{bc})) + W_c + W_{ev} \quad \text{Equation 0-1}
\]

Where \(F_b\) is a factor accounting for errors in the calculation of bather numbers \((N)\) via the half-hourly head count method, \(F_{ns}\) is the proportion of bathers not showering prior to participation and \(W_{bi}\) and \(W_{bc}\) are the water exchange requirements associated with the initial and continuous contaminants introduced by the bathers respectively. This is the third contribution to knowledge that has been made during this research.

The final contribution to knowledge that has resulted from the current research is in relation to the overall structure of the UK swimming industry. The disjointed and un-regulated approach of the industry to date has not been effective in delivering sustainable swimming pools that minimise the life cycle cost and associated health risks of facility operation whilst continuing to offer a welcoming environment and varied activity schedule to the public. A new framework for the industry has been proposed in this thesis.
The developed framework, shown in Figure 0-2, is based on the integration of the use of new approved documents under existing legislation with improved stakeholder collaboration and information sharing through a new knowledge gateway. The aim of the new framework is to encourage collaborative innovation and improved facility operation by enforcing minimum standards for fundamental aspects of the industry, such as requirements for training and water quality parameters, whilst leaving other aspects unrestricted, such as water treatment methodologies. One aspect that has been identified as needing substantial improvement is the promulgation of information to all stakeholders. Although the generation of industry guidance and regulation may be sufficient for those stakeholders who keep a close interest in industry publications, such as pool design companies, others will require active targeting and education, especially the general public. The addition of the requirement for user inductions and the formation of stakeholder engagement bodies as part of the proposed policy framework aims to address this issue. The framework also looks to encourage the use of risk-based assessments in the swimming industry through the adoption of Water Safety Plans similar to those used for drinking-water (WHO 2009).
Other Industry-Related Contributions

Aside from the four contributions mentioned above that are relevant to the industry as a whole, the research also involved studies that resulted in the development of the understanding of aspects relevant to the case of the Surrey Sports Park or the basis upon which future contributions to the industry could be made.

The research into the potential for modelling techniques to support the design and optimisation of swimming pool facilities was undertaken using the Surrey Sports Park as a test case. Both computational and physical modelling experiments were used to develop an initial modelling strategy for the swimming pool context. The modelling strategy enabled the existing hydraulics of the Surrey Sports Park swimming pool to be examined. More specifically, the ability for the current circulation rate to distribute disinfectants effectively and to remove water in a uniform fashion within the pool tank was investigated.

The distribution of disinfectant within the tank was simulated in the computational fluid dynamic modelling using a multi-phase time-accurate solver together with a Reynolds-averaged Navier-Stokes (RANS) based turbulence model. The results were validated using a combination of published data for several jet flow scenarios and dye visualisation results generated using physical experiments on a 1:50 scale model of the pool tank. The modelling showed that the current hydraulic strategy of the pool was effective at achieving disinfectant distribution throughout the tank within the currently recommended maximum time of 15 minutes. The pool turnover rate, defined as the time taken to exchange the water volume, was observed to be far longer than the estimated time calculated using the current guidance method. This is because of the guidance method assuming that the pool hydraulics is plug flow in nature whilst the requirement for disinfection distribution leads to well-mixed hydraulics to be adopted. The contradiction between the two recommendations in the current guidance needs to be addressed. The recent increase in implementation of ex-situ treatment technologies, such as UV and ozone, within the treatment plant opens the possibility to change the strategy used for pool hydraulics fundamentally as less emphasis is placed on traditional disinfection techniques within the main pool tank.

The specification of a modelling approach for the swimming pool requires further development in order to increase the confidence that can be placed on pool tank flows generated in this way. The work undertaken in this study provides a basis for this recommended future work. It is also advised that greater engagement with
industries that currently use the technique in design processes is achieved to improve knowledge transfer into the swimming industry on a practical level. The addition of chemical reactions into the hydraulic simulations would be a useful tool to enable risk-based analysis of pool design and operation options.

The utility consumption of the entire facility was also evaluated during the research in order to put the swimming pool operation into the wider context of an entire multi-use leisure facility. Electrical consumption was observed to be the most significant factor in the overall cost of operating the SSP facility. The swimming pool was identified to contribute approximately 25% of the electrical consumption with water circulation and air conditioning making up the majority of this demand. The heating of the water in the facility is achieved using a biomass boiler which, although associated with a higher fuel cost, effectively reduced the carbon emissions of the facility. The reductions achieved were small compared to the emissions of the facility attributed to the electrical consumption. This high level review indicates that it could potentially be more beneficial to prioritise financial investment on the aspects that reduce the electrical demand of the facility. As water circulation is a fundamental requirement of swimming pool management and the facility already employed variable speed drives on the pumps, the opportunity to reduce the electrical consumption of this aspect further was limited. The evidence collected in the activity survey did indicate that it may be possible to use lower circulation rates during some activities, however, further research into the impacts of reduced circulation rates is required.

The review of operational procedures of the facility also showed that there were potential opportunities for efficiency savings to be realised through improving the understanding of the use of the facility in more detail. Trends in bather visits were analysed and the results showed that applying a uniform approach to pool management at the facility was not an efficient practice. The facility was observed to have a highly varied usage profile. The number of bathers using the pool followed both schedule-based variation and seasonal variation. Adapting the operating procedures to account for this variation could result in efficiency savings by modifying treatment intensity to suit pool usage. Again further research into the impacts of reduced treatment intensity is required alongside this recommendation.

The case study showed therefore that although water quality-related aspects are of importance when considering the welfare of bathers, the operational sustainability of large facilities is more affected by aspects that are related to the air handling system. Opportunities to improve the sustainability of SSP were identified during the research and were used to formulate a sustainability review for the facility. The documented opportunities included those that involved the modification to the
infrastructure of the facility as well as those that focused on using the existing infrastructure in a more efficient manner. Key recommendations included the installation of a pool cover, the installation pool side controls for the treatment systems, the reuse of backwash water, the enforcement of pre-swim showers and increasing the temperature differential between water and air to 2°C. The combination of these opportunities could realise cost savings of over £20,000 per year to the facility. The review also recommended that the potential for solar collectors, either for hot water or electricity generation, to be installed on the roof was re-assessed. The onsite generation of renewable electricity is likely to be the only way to make significant improvements in the environmental performance and operational cost of the facility.

Assessing the Research in the Context of the Engineering Doctorate in Sustainability for Engineering and Energy Systems

The research objectives and contributions to knowledge were also assessed in the context of the requirements for the Engineering Doctorate in Sustainability for Engineering and Energy Systems. The research objectives aimed to address the current challenges relating the sustainability of swimming pool facilities by evaluating the impacts of existing guidance and assessing the potential for policy developments to improve the efficiency of facility operation through the use of “industry-focused engineering” research. It is therefore considered that this work has met the requirements of the Engineering Doctorate in Sustainability for Engineering and Energy Systems by addressing both the “Engineering for Sustainability” and “Sustainable Energy and Low Carbon Systems” research themes.
References


Chapter 1 – The Swimming Industry: A Critical Review

1.1 Introduction

Swimming is one of the most popular sports in the UK, with almost a third of adults and half of children visiting a pool annually (DCMS 2011). The provision of swimming pools, or lack thereof, has been largely left as a topic of local concern until recently. The preparation for the 2012 Olympics in London helped generate a broader interest in sports infrastructure throughout the UK. The UK government had already recognised both the sporting benefits and the health benefits associated with an increased participation in swimming and had promoted the sport through various initiatives (DCMS 2008). These initiatives aimed to improve access to swimming pool facilities and, together with an increase in publicity of the sport following unprecedented successes by British athletes at the Beijing Olympics, resulted in an increase in the numbers of people swimming towards the end of the last decade (DCMS 2010).

The participation in swimming, however, was not found to grow as predicted in the run up to the London Olympics and therefore a more in-depth interest into the swimming industry was generated. The confidence in continued participant growth had been based on positive reports regarding the improving provision of swimming facilities and the presence of funded initiatives (British Swimming 2012a; DCMS 2012). The 2010 UK State of Industry Report (Leisure Industry Company 2009) was the first attempt to take stock of the swimming infrastructure throughout the UK. This report provided an in-depth review of the quantity and nature of both existing and new swimming pool facilities. It did, however, fail to consider the number of recent or imminent pool closures and therefore the true state of the industry had not been reported. Pool closure is a very important topic for the UK government at present, as not only is it a significant factor determining the participation in swimming, but is also often a highly emotive issue amongst local populations and contradicts the national agenda for improved sports provision.

In general, pool closures appear to take place as a result of one of three reasons (PWTAG 2010). The first is that the opening of a new facility has made an existing facility obsolete. Pool closure can also occur following the investigation of an incident that endangered the health or safety of its staff or visitors, for example, following an illness outbreak. Although many incidents result in only temporary closures, investigations can identify failings in the design, maintenance or management of the pool that require significant remedial actions. Permanent
closure can subsequently take place where either it is not feasible to address the issues or the costs associated with the temporary closure and remedial actions are too great for the owner or operator. The cost of addressing incidents and associated remedial work is only one financial reason for a pool facility to close. The third, and largest, contributor to the number of pool closures in the UK is the inability for an operator to continue to afford the ongoing maintenance and operational costs of the facility. Whilst the first of the three reasons may raise concerns within local communities, it is the other two reasons that present significant challenges to the swimming industry as a whole;

1. The reduction of risks associated with the use of swimming pools
2. The minimising of facility operation and maintenance costs

Aside from the desire to prevent pool closures and to increase participation in swimming, additional pressure for the industry to become more efficient is starting to build. Building-related energy use is already a significant concern for the aquatic leisure industry and, with the UK national carbon reduction targets affecting large parts of the leisure industry, is likely to become even more so (Carbon Trust 2006). Swimming pool facilities are often the major contributor to the overall energy use of a leisure facility. Up to 65% of the energy burden for a leisure facility can be associated with the pool as many aspects of swimming pool operation involve substantial energy use (Carbon Trust 2006). Increasing the number of people using swimming pool facilities has the potential to exacerbate these issues if they are not managed effectively (HSE 2007).

The research presented in this thesis assesses whether the current swimming industry is equipped to tackle these increasingly difficult challenges and provides novel contributions to the knowledge base that is used to determine best practice and regulatory benchmarks. In order to make this assessment, a detailed understanding of the entire swimming industry is needed. The key stakeholders involved and the way they interact with each other can have a significant impact on the ability to determine solutions for the challenges facing the swimming industry in the UK. The structure of the industry was therefore examined.
1.2 Current Structure of the UK Swimming Industry

The swimming industry in the UK comprises a broad range of facilities offering a wide variety of activities that have developed with minimal external influence over a long period of time. This expansive industry encompasses not only large facilities used for learning, competition and leisure purposes, but also smaller facilities used for wellbeing and rehabilitation. The combination of high participant numbers, a broad range of physical and health risks, high capital costs and significant ongoing energy and resource demands, creates an industry that is more complex than other recreational industries. Despite this, the swimming industry is structured largely in line with other recreational industries. There are five broad sectors within the industry; Investors, Designers, Builders & Equipment Suppliers, Operators and Users (PWTAG 2010). These sectors have historically operated in relative isolation to each other in predominantly a “top down” manner as illustrated in Figure 1-1.

![Figure 1-1 - Historical structure of the UK swimming pool industry](image)

Although this simple structure may appear logical at first glance, inherent issues are soon highlighted when the industry is examined in greater detail. The structure of the industry is far more fractured than indicated by the above model. Each of the sectors shown in Figure 1-1 is often a complex mixture of independent organisations (Devin 2010).

1.2.1 The Client

As a result of the significant cost of building swimming facilities, the “client” is frequently a combination of investors and can include public sector, private sector
and charitable organisations. The “client” can therefore have no involvement in the operational or use phase of the pool (Devin 2010). This detachment between those initially investing in the facility and those operating the facility presents a significant challenge to the industry, as there is no incentive to design and build facilities based on a whole life cost rather than initial capital expenditure. The inclusion of sustainability requirements within the planning process has helped to address the issue, however, the weighting schemes used in the available assessment tools make it possible to achieve these requirements without fully considering the operational phase of the building (Devin 2010). In the Building Research Establishment Environmental Assessment Methodology (BREEAM), for example, consideration of life cycle servicing costs and the use of energy efficient equipment only accounts for 1.65% and 1.12% of the overall score respectively (RIBA 2011). It is therefore possible to achieve the 45% needed for a “Good” BREEAM rating, the minimum requirement for many planning applications (BRE 2014), without taking operational costs into account. The disconnection between the client and the operator can also mean that the final operators have little influence on the brief given to the pool designers.

1.2.2 Pool Design

Those involved in the design and construction process of a swimming pool can vary from project to project. The scale and budget of the project can influence the makeup of the design team as well as whether it is a new build or a refurbishment project (Devin 2010). The terms “pool designer” and “pool builder” are rather vague in the pool industry as different aspects of a facility are designed and built by different parties. In large projects, it is common that one company, usually an architect, oversees the design process and designs the overall structure of the facility including the pool hall, pool tank, changing rooms and ancillary facilities and services. A second company will be responsible for designing the pool water treatment system and a third the ventilation system for the pool hall. The level of integration of these three main aspects of design is often low, with each aspect considered in a modular manner (Devin 2010). For example, the water treatment plant is commonly designed based on the budget, pool tank volume and available building services specified by the architect, together with the rules of thumb available in design guidance. Similarly, the ventilation system is often designed based solely on the air volume and published guidance. The extraction and delivery locations for the pool water and air are, however, often left to the discretion of the architect (Devin 2010). Treating the air and water handling services as standalone components in this manner can mean that opportunities to improve the sustainability of the facility through design can be missed.
1.2.3 Pool Construction

As the project enters the construction phase, different combinations of companies are usually responsible for delivering the outputs of the design process (Devin 2010). For large or new build projects, the building contractor is commonly given the primary responsibility because of the significant amount of building works associated with the facility construction. The demand to complete the project within the desired timescales and budgets can lead to decisions being made by the principle contractor that fail to take into account the potential impact on the sustainability of the final swimming pool facility. The removal of building components that are surplus to the requirements of the investors intended use are the most likely to be cut when savings are required (Devin 2010). This is a significant issue within the industry because options for future modification of pool facilities are limited by the initial building construction as, once built, alterations to the fabric of the building are often prohibitively costly (PWTAG 2010). It is also common for the installation of ventilation systems and water treatment systems to be passed on to sub-contractors who often have their own preferred equipment suppliers (Devin 2010). As the scale of the project reduces, the line between pool design and installation can be blurred, as contractors can start to take on the design roles. The preferences of the individual contractors can then start to have a significant influence on the final design of the pool air and water handling systems. These may not be in line with the initial objectives of the investor or the design teams.

1.2.4 Pool Operation

The complexity continues as a pool facility moves into the operational phase. The operational management structure of a facility can vary hugely (PWTAG 2010). Some facilities are operated by the original client, although this is usually limited to smaller privately owned facilities, such as health clubs. The majority of larger facilities in the UK are run by a third party operator (Leisure Database Company 2009). These operators have often had no involvement in the design of the facility but are responsible for delivering the ongoing operational and maintenance activities. This is where the greatest issues exist in the current industry structure (PWTAG 2009). The operators are given a set of specifications prescribed by the pool builders and equipment suppliers based on the nature of use specified by the client. Although pool facilities are designed and built with a particular type of use in mind, operators often find that the users demand other activities in addition to those originally considered in the design stage. It is therefore becoming more common that facilities are designed to be suitable for a broader range of activities (Devin 2010). This is often achieved through the use of moveable floors and booms to adjust the configuration of the pool tank. Many other aspects of the pool...
operation, such as water treatment rates and air turnover rates, are starting to be
designed to provide the ability for operators to adjust them as required to suit
different users.

1.2.5 Pool Users

The final sector of the swimming industry is arguably the most important. As a
recreational industry the primary focus is always going to be on the facility users.
The industry historically referred to the users of a swimming pool by the generic
term of “bathers” (PWTAG 2010). This is an over simplification and no longer
reflects the activities that take place within a modern pool facility. Visitors to a pool
can be taking part in the traditional act of swimming, the increasingly popular
fitness and rehabilitation activities, as well as more obscure activities, such as scuba
diving or kayaking. The demands on the facility can vary significantly even between
users within seemingly similar activities. For example, competition swimmers,
leisure swimmers and learner swimmers all present their own specific requirements
on a pool facility (Mansi 2010). Competition swimmers prefer colder water than
leisure swimmers because of the difference in the level of physical exertion they are
undertaking. The type of user can also present different requirements from a
management perspective. Competition swimmers are usually highly regular visitors
to the pool, attending multiple times a week, whilst leisure swimmers may only visit
very infrequently, perhaps only a couple of times a year (Mansi 2010). The
operators therefore face a very difficult challenge when attempting to balance the
operational costs with the often conflicting demands of their visitors.
1.3 UK Swimming Pool Guidance and Regulation

The complex nature of the swimming pool environment, and the significant consequences that can occur if things go wrong, results in a strong need by those within every sector for guidance on which to base their decisions. This demand for guidance, together with such a fragmented and complex industry structure, has encouraged a large number of organisations to generate guidance for the swimming industry. These organisations include those that focus on the sporting and leisure aspects, the Amateur Swimming Association (ASA) for example, those that focus on operational aspects, such as the Pool Water Treatment Advisory Group (PWTAG), and those focusing on the management and training aspects, for example the Chartered Institute for the Management of Sport and Physical Activity (CIMSPA), amongst many others. Each organisation has historically worked fairly independently of one another with the aim of providing guidance to one or more of the five sectors discussed above. British Swimming, the UK’s governing body for the sport, compiled a list of guidance relevant to the industry in 2012 (British Swimming 2012b). The list extended to almost 300 guidance documents and standards published by 12 separate organisations. In relation to pools designed for competitive use, the ASA are responsible for informing the UK industry of requirements that ensure a facility does not affect, beneficially or adversely, the performance of the swimmers. Many of the regulations have little effect on the operation of the pool facility, however, water circulation, temperature and pool hall lighting levels are three key exceptions. All competition pools must comply with the requirements in order for events held at them to be valid, however, there is no requirement for facilities to adhere to these requirements during non-competition periods. This is a significant detail as modern facilities are increasingly being used for a wide range of activities (PWTAG 2010).

The industry today is far more complex than the one for which initial UK guidance was developed. The addition of internal structures and alternative treatment systems has resulted in pool designs that are far more diverse than the simple chlorine-treated, steady-state, rectangular tanks on which the traditional science of pool design and operation has been based. Recent revisions in published guidance have been made to attempt to keep the guidance relevant, however because of the fast changing nature of the industry, it is important to review the guidance that is currently available to the industry and the knowledge base on which it is founded.

1.3.1 UK Legislation

The design and operation of swimming pool facilities is largely unregulated in the UK. Although there are not any regulations specifically aimed at the swimming
industry, some key aspects are covered by the general requirements of current UK legislation. Historically the Health and Safety at Work etc. Act 1974 and its associated regulations have been the primary concern for the industry because of the direct implications they have on operational practices (PWTAG 2010). This act places a responsibility on employers not only to “ensure the health, safety and welfare of their employees” but also to “ensure persons not in his employment who may be affected thereby are not thereby exposed to risks to their health or safety” (HMSO 1974). In addition to these duties placed on employers the act also places responsibility for health and safety on a company’s employees. In the context of public swimming pools, both the facility operator and their employees, such as lifeguards, are legally responsible for the health, safety and welfare of visitors to the facility as they are directly affected by their actions. Incidents that result in the illness or injury of bathers may therefore leave operators and employees open to prosecution under section 33 of the Health and Safety at Work etc. Act 1974.

Other pieces of legislation with significant relevance to the UK swimming industry include the Occupiers' Liability Act 1957 and 1984 and the Building Act 1984 (HMSO 1957, 1984a, 1984b). The Occupiers' Liability Act 1957 requires those responsible for the facility to ensure that visitors “will be reasonably safe in using the premises for the purposes for which he is invited or permitted by the occupier” (HMSO 1957). This is clearly relevant for the industry as its main purpose is to provide the facilities for public use. The Occupiers’ Liability Act 1984 broadens the responsibilities beyond permitted visitors to include any other person that “may come into the vicinity of the danger….whether the other has lawful authority for being in that vicinity or not” (HMSO 1984a). It is very rare that swimming pools are operated continuously. Many facilities, such as lidos, are closed for significant periods of time. The inherent risks with these facilities means that the management of closed facilities is a significant duty for owners and operators. The Building Act 1984 is the primary legislation that enables the setting of regulations prescribing the requirements for many aspects of the built environment in the UK (HMSO 1984b). Although the act itself may not place any duties directly on those involved in the industry, it enables various statutory bodies to do so. The potential legal consequences of incidents in the pool environment have therefore driven the development of the guidance for the industry to date (PWTAG 2010).

1.3.2 UK Codes of Practice and Standards

There are a large number of statutory instruments that expand on the general duties placed on the various sectors of the industry by the above Acts. This creates a very complex collection of legal documents that have a relevance to the industry
The complexity makes it difficult for organisations to identify their legal obligations or restrictions directly from these regulations. The industry therefore relies on the guidance generated by various bodies to distil the legal aspects into a more manageable form (PWTAG 2010). The Health and Safety Executive (HSE) has published guidance specifically aimed at consolidating the legal requirements for health and safety that are relevant to designers and operators of swimming pool facilities. The HSE first issued guidance in 1988 and has amended the contents of the guidance over the years in order to incorporate the various developments in health and safety law, pool design, treatment technologies and pool use. The latest edition of the guidance, “Managing Health and Safety in Swimming Pools” (HSG179), was published in 2007 and provides an example of how complex the structure of relevant UK legislation can be for the swimming industry (HSE 2007). HSG179 highlights the following regulations under the Health and Safety at Work Act 1974 to be of significant relevance to the swimming industry:

- Management of Health and Safety at Work Regulations 1999
- Workplace (Health, Safety and Welfare) Regulations 1992
- Provision and Use of Work Equipment Regulations 1998
- Construction (Design and Management) Regulations 2007
- Electricity at Work Regulations 1989
- Control of Substances Hazardous to Health Regulations 2002
- Reporting of Injuries, Diseases and Dangerous Occurrences 1995
- Health and Safety (Safety Signs and Signals) Regulations 1996
- Diving at Work Regulations 1997
- Confined Spaces Regulations 1997

In addition to directing organisations to the most relevant legal documents, HSG179 aims to provide guidance on best practice methods of meeting the obligations contained within them. The guidance covers four main aspects of pool design and operation; The Physical Environment, Supervision Arrangements, Maintenance of Plant and Equipment and The Water Treatment System. The guidance is primarily focused on the physical hazards, such as slips, trips, drowning and entrapment, associated with the design and management of a facility. The microbiological and chemical hazards associated with faecal fouling and disinfectant by-products are also highlighted as aspects that need consideration. As there is an absence of specific health and safety regulations on swimming pool air and water quality, the HSE have limited the guidance to recommending operators to seek further advice in relation to best practice.
Best practice guidance for the swimming industry has been available in some form for many years. The current guidance published in the UK has evolved over a number of decades as the industry has developed. The first UK swimming pool guidance was published in 1929 by the Ministry of Health and focused solely on best practice surrounding basic disinfection methods (HMSO 1929). This guidance for pool water disinfection was developed further to include a broader range of aspects in 1951 and again in 1975 following the introduction of the Health and Safety at Work Act. The guidance for pool operators continued to develop as the concept of water quality for pools started to be developed (HMSO 1984c). The Pool Water Treatment Advisory Group (PWTAG) was formed by the Department of Environment as an independent organisation in 1984 and took over responsibility for developing the UK guidance for the swimming industry. Throughout the 1980s and 1990s the increase in awareness of issues relating to the swimming pool environment enabled the guidance to be expanded and developed. This resulted in the publication of "Swimming Pool Water" in 1999 which provided the UK swimming industry with its first widely available benchmark for not only the treatment of pool water, but also for aspects of the design of swimming facilities and their treatment systems (PWTAG 1999).

As health and safety issues were the primary driver for the industry during the time the guidance was being developed, the book focuses on the aspects of pool design and operation from this perspective. The recommendations made by PWTAG in their book cover a wide range of topics from design of the pool tank to acceptable water quality ranges for swimming pools. The standards can be broadly segregated into 3 distinct focus areas; Pool Design, Water Quality, Treatment Plant Design. The form of the guidance is more specific than that contained within HSG179 and provides designers and operators with recommended design parameters and operational ranges for key aspects. The standards are soundly based on empirical knowledge in a few areas, however the majority are derived from inferred knowledge from the operational experience of its constituent members and therefore the support behind the standards is not definitive. In addition, as PWTAG is responsible for providing guidance to the entire industry, the guidance does not simply convey best practice for new pool design and operation, but also attempts to provide more generic advice for those operating older facilities that are not consistent with best practice design. This has the result of making the guidance open to interpretation by addressing some aspects in a generic fashion.

Despite this, the information in the guidance was used as the basis on which a number of British Standards have been developed. Although not legal requirements in their own right, British Standards are often considered as the minimum standards...
that should be achieved in order to comply with legislation. Compliance with British Standards does not exempt organisations from prosecution, however failure to comply with them can make avoiding prosecution following an incident almost impossible. The first British Standard aimed specifically at the swimming industry was “BS EN 13451: Swimming Pool Equipment” and was created in response to repeated incidents of entrapment and other serious injuries associated with pool components (BSI 2001). It was published in 2001 and covers safety requirements and testing procedures for specific pool equipment. Because of the variety of pool equipment, the standard is segregated into 11 parts, each focusing on a different type of equipment. These standards focus solely on the prevention of injury to users and operators from various items of pool equipment, however some of the restrictions and specifications prescribed also have a direct impact on other aspects, such as water circulation within the pool. Part 11 of the standard, for example, prescribes specific requirements and testing protocols for moveable floors and booms. These structures present a range of significant risks including becoming trapped by the structures during their movement. The standard requires that accidental access underneath such structures is prevented and that the structures move through the water at a maximum speed of 0.5 m/min for floors and 3 m/min for traversable booms. There is, however no requirement to ensure that these structures do not have a significant impact on the water circulation in the pool tank.

The adoption of formalised standards for pool equipment led to the development of an approved code of practice for the management of swimming pool water treatment, heating and ventilation systems, “PAS 39” (BSI 2003). The code of practice was based on the recommendations published by PWTAG. A second code of practice, “PAS65”, for the general management of swimming pools, was developed by the Institute of Sport and Recreation Management, now known as CIMSPA (BSI 2004). This code of practice aimed to standardise the way in which operators manage a facility and its associated staff. The uptake of new technologies, such as ultraviolet and ozone disinfection systems, in the pool water treatment process led to the development of a new 2 part European Standard, “BS EN 15288: Swimming Pools” that outlines the formal procedures designers and operators should have in place to ensure facilities are built and managed correctly (BSI 2008a, 2008b). This new standard supersedes the former code of practice for pool management, however the standard does not, with the exception of undertaking dye tests, contain details on best practice procedures and therefore additional guidance is still required to supplement it. Critically, compliance to this particular European Standard does not meet the minimum requirements set out in
other UK guidance, such as PAS 39 or HSG 179. It is therefore insufficient for
designers and operators to only comply with this standard in the UK.

The continued development in pool designs and technological advancements in
treatment equipment resulted in a revised edition of the PWTAG guidance,
“Swimming Pool Water: Treatment and quality standards for pools and spas”, to be
published in 2009 (PWTAG 2009). This book is currently considered the primary
source of design and operation best practice for the industry, however as it
attempted to provide guidance for an even broader range of treatment options, the
best practice principles are less clear. The broad nature of “Swimming Pool Water”,
and the lack of detail within the standards and codes of practice mentioned
previously, encouraged other organisations involved with the swimming industry to
produce guidance for the sectors they engage with. A few of these organisations
have generated pieces of guidance that have had a significant influence on the
current practices within the swimming industry. The most significant of these are
the World Health Organisation (WHO), the Chartered Institute for the Management
of Sport and Physical Activity (CIMSPA) and the Carbon Trust.

1.3.3 International Guidance

The WHO published guidance to address the significant risks associated with the
interaction of people and large bodies of water. The “Guidelines for Safe
Recreational Water Environments” was published in 2006 and provides a
referenced review and assessment of the health related issues associated with
recreational water environments (WHO 2006). The first volume is concerned with
the health hazards of coastal and fresh water environments and is of limited
relevance to this research project, whilst the second volume is specific to the
hazards of swimming pool environments. The guidance is segregated into 3 sections
that cover the main types of hazard present in a swimming pool facility: Drowning
and Injuries, Microbial Hazards and Chemical Hazards. Each of these sections
contains a topic specific review of current knowledge and recommended best
practices that have been implemented around the globe. Unlike the majority of
guidance available for the swimming industry, the “Guidelines for Safe Recreational
Water Environments” references published academic and industrial research and
therefore the support behind the recommendations within is much stronger.

The health implications associated with the presence of microbiological pathogens
and chemical compounds within the pool environment is a significant concern for
the industry. These substances can present a range of hazards to the users through
different exposure routes including ingestion, inhalation or through dermal contact.
The “Guidelines for Safe Recreational Environments” provides the most
comprehensive review of these health risks and, where data are available, provides information with regards to the relative importance of particular hazards. The guidance also identifies a list of substances that can be monitored to provide a good indication as to the presence of other water-borne hazards. In order to ensure the swimming pool is safe to use, regular monitoring of the microbial activity and chemical composition of the water is required. It is currently impractical for operators to monitor every pathogen or substance that may be present in the water and therefore this list of indicators is of great importance to the industry.

Good management and supervision is highlighted as critical to the safety of swimming facilities. It is claimed, for example, that over 80% of drowning incidents could have been prevented by increased levels of supervision (WHO 2006). The final section of the WHO guidance contains recommendations on policies that operators should adopt when managing a swimming pool environment. The enforcement of management best practices varies greatly from country to country. However, there is general agreement that good management of pool facilities is essential in providing a safe and welcoming swimming environment. The WHO guidance references the British Standards and Codes of Practice for pool management, mentioned previously, as the most complete management guidance available. Therefore the information in this guidance is very similar to that presented in these other documents and remains as generic concepts rather than definitive requirements.

1.3.4 UK Training and Certification

The management and operation of swimming pool facilities by a “competent” person is a common concept referred to within all of the available management guidance. There is, however no specific definition of what constitutes a “competent” person for the swimming industry within these documents. CIMSPA is one organisation in the UK that has attempted to address this issue to date. CIMSPA has developed a training and assessment course, “The National Pool Plant Operators Certificate” (NPPO), that aims to measure the competency of individuals working in the aquatic leisure industry against a common benchmark (CIMSPA 2012). The qualification acts as a certificate of competency that operators can use to help comply with the requirements of the management standards and codes of practice. In order to ensure ongoing competency, those holding the certificate are required to attend a refresher course every 3 years. The current syllabus for the NPPO certificate is based predominantly on the guidance published by PWTAG in the 2009 edition of “Swimming Pool Water”. This re-enforces the need for the PWTAG guidance to be carefully scrutinised to ensure that the workforce in the UK
is being trained appropriately. In general, there have not been any significant changes to pool operational guidance in the UK in recent years with the exception of the prevention and management practices in relation to cryptosporidiosis outbreaks and other faecal contamination incidents (PWTAG 2014).

The significant hazards facing those taking part in water-based activities requires those supervising the activities to have a wide range of specialist skills. The National Pool Lifeguard Qualification (NPLQ) was developed to address this by the Institute of Qualified Lifeguards (IQL) initially in collaboration with CIMSPA (IQL 2012). The NPLQ is now solely managed and delivered by the IQL and focuses on the specific physical hazards, and methods for preventing and responding to injuries, associated with pool based activities. It does also briefly cover the general issues in swimming pool facilities including disinfection requirements. The IQL also identified shortcomings in the syllabus of the NPPO with regards to the overall management of pool facilities and developed the National Pool Managers Qualification (NPMQ) to address this (IQL 2012).

Other organisations such as The Institute of Swimming Pool Engineers (ISPE) and The British Swimming Pool Federation (BSPF) have also attempted to address the “competency” issue for specific sectors of the industry. ISPE is an organisation for professionals in the design, installation and maintenance of swimming pools and associated equipment. It operates its own certification process, similar to CIMSPA’s NPPO certification, for the technical competency of individuals within the swimming pool industry through its training courses (BSPF 2012). The BSPF is an overarching organisation that is comprised of three separate associations of the swimming pool industry: The Swimming Pool and Allied Trades Association (SPATA), The Swimming Teachers Association (STA) and the British and Irish Spa and Hot Tub Association (BISHTA). SPATA runs training courses and provides guidance to over 175 UK companies working in the swimming industry. The STA is an independent organisation that provides guidance and training courses for those in the swimming industry. They deliver and manage over 20 different qualifications for a wide range of swimming-related aspects including swim teaching, pool operation and lifeguarding.

The availability of multiple qualifications that claim to certify the competency of individuals is not an issue in itself as long as they are working to a comparable syllabus. The lack of a clearly defined body responsible for the swimming industry has resulted in a disjointed structure for the training of professionals in the industry to date. For example, the continual development in technologies and knowledge base within the industry has resulted in the production of a number of standalone technical notes that update the best practices on specific issues. Because of the
independence of the organisations generating guidance and delivering training there is little consistency with regards to the uptake of new guidance as CIMSPA and STA can determine the frequency at which they review and update their own course syllabuses. PWTAG has recently attempted to start the process of addressing this issue through the publication of a new Code of Practice in 2013 (PWTAG 2013). This Code of Practice is the first attempt not only to provide best practice recommendations for pool design and operation but also to specify requirements for the contents and structure of a pool operator and management training courses. Organisations wishing to provide PWTAG accredited qualifications would be required to plan and deliver their training in accordance with the contents of the Code of Practice. Similarly pool owners and operators that wish to obtain accreditation from PWTAG for their facilities must also operate in accordance with the best practices contained within the Code of Practice. Although this is a significant development in the guidance landscape in the UK, whether the Code of Practice will achieve its aim of ‘standardising the industry’ will depend on the voluntary cooperation from the individual companies within the industry, as there is no legal requirement for training organisations to adopt the Code of Practice or for operatives to hold a PWTAG accredited certification. The lack of an organisation in the UK with the legal authority to enforce standards within the swimming industry means that coherent implementation of improvements within the industry practices are currently reliant on the voluntary actions of a number of organisations across the industry. The recent increase in interest in energy efficiency and carbon reduction policies is a good example showing the challenges associated with this approach.

1.3.5 Sustainability-related Guidance

A number of organisations have begun to publish energy-related guidance to the swimming industry following the increased interest in environmental and economic concerns associated with current practices across UK industries. The Carbon Trust has been the primary organisation promoting this topic to date and published advice aimed specifically at the sports and leisure industry in 2006 (Carbon Trust 2006). The Carbon Trust identified five key areas that should be evaluated when assessing the efficiency of energy use within a leisure facility: Heating, ventilation, lighting, electrical equipment and swimming pools. Swimming pools were also identified as the least efficient aspect within a typical facility in terms of energy use. The guidance recommends measures that designers and operators could implement to improve the sustainability of swimming pool facilities. These recommendations include changes to infrastructure, such as installing pool covers or heat recovery systems, as well as operational changes, such as reducing backwash volumes or
reducing the circulation pump speeds when the facility is closed. The production of
guidance by an organisation that did not have an in-depth understanding of the
swimming industry has resulted in a significant issue. Although the guidance refers
to the potential savings in running costs that the adoption of the proposed
measures could deliver, the potential impacts of water and energy saving measures
on other critical aspects of pool management, such as water quality and the
associated health risks, are not considered at all. This is significant as different
organisations within the industry may adopt the measures with varying amounts of
consideration for the detailed implications. The ability for optimal pool design and
operational specifications to be developed requires a more integrated approach to
the guidance.

The availability of broad sweeping guidance such as “Swimming Pool Water”
(PWTAG 2009) and Sport England’s “Design Guidance Note for Swimming Pools”
(Sport England 2008) enables pool designers and operators to have easy access to
an overview of the industry guidance. The guidance published by Sport England
collates information from guidance published by PWTAG, the ASA, The Carbon Trust
and the HSE amongst others to attempt to provide a one-stop shop for pool
designers and operators (Sport England 2008). These collated documents are the
closest thing the industry has to integrated design and operation guidance,
however, in order for the guidance to be further developed a more in-depth
knowledge base is required.
1.4 Establishing a Framework to Assess the Current Knowledge Base

1.4.1 Evaluation of Swimming Pool Interactions

Prior to being able to assess the areas in which the knowledge base requires developing, it is first important to identify the key interactions within the swimming pool environment. Each of the five main aspects important to pool operators that were identified during the review of UK guidance (users, employees, water quality, air quality and energy consumption) was examined in turn. A summary of the key interactions for each of aspects and the reasons for their consideration is shown in Table 1-1 below.

Table 1-1: Key interactions within a pool facility and the reasons for consideration

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Interaction</th>
<th>Reasons For Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathers</td>
<td>Pool Structure</td>
<td>Injuries, Biofilm Formation</td>
</tr>
<tr>
<td></td>
<td>Pool Water</td>
<td>Illnesses, Source of Contaminants</td>
</tr>
<tr>
<td></td>
<td>Pool Air</td>
<td>Illnesses</td>
</tr>
<tr>
<td>Employees</td>
<td>Pool Air</td>
<td>Illnesses</td>
</tr>
<tr>
<td></td>
<td>Plant Room Equipment</td>
<td>Injuries</td>
</tr>
<tr>
<td>Water Quality</td>
<td>Treatment Method</td>
<td>Disinfection By-Products (DBPs), Removal of Pathogens</td>
</tr>
<tr>
<td></td>
<td>Hydraulic Design</td>
<td>Circulation, Distribution of Disinfectants</td>
</tr>
<tr>
<td></td>
<td>Refresh Rate</td>
<td>Accumulation of Dissolved Chemicals</td>
</tr>
<tr>
<td>Air Quality</td>
<td>Hydraulic Design</td>
<td>Circulation, Distribution of DBPs Leading to Potential Health Hazards</td>
</tr>
<tr>
<td></td>
<td>Pool Water</td>
<td>Evaporation, Source of DBPs</td>
</tr>
<tr>
<td></td>
<td>Refresh Rate</td>
<td>Humidity, Accumulation of DBPs</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>Plant Room Equipment</td>
<td>CO₂ Emissions, Cost</td>
</tr>
<tr>
<td></td>
<td>Operational Settings</td>
<td>Water Quality, Air Quality, Bather Comfort</td>
</tr>
</tbody>
</table>

1.4.1.1 Swimming Pool Users

Users interact with the pool environment in four significant ways. The first is the physical interactions with the pool facility and associated structures such as slipping on wet surfaces, tripping on raised ledges, entrapment in and between objects and accidental impacts (HSE 2007). The second interaction of concern is the exposure of users to microbial and chemical hazards in the pool water that have the potential to lead to bathers developing both communicable and non-communicable diseases.
The Swimming Industry: A Critical Review

(Lakind et al. 2010; Pond 2005; Richardson et al. 2010). Similarly, the exposure of users to chemical hazards in the air is another interaction of concern because of the potential for it to cause acute and chronic health issues (Meek et al. 2002; WHO 2004). The final significant interaction between users and the pool environment is the potential for a wide variety of contaminants to be introduced to the pool water including infectious material as well as compounds that can enable harmful chemicals to be formed (Keuten et al. 2012; Santos et al. 2012).

1.4.1.2 Swimming Pool Employees

The employees of a swimming pool facility often have the same exposure to the hazards identified for bathers, however there are two significant differences in their interactions. The employees spend a much longer time in the pool environment compared to the bathers or spectators. This has the potential to result in much greater exposure to harmful chemicals in the pool air (Fantuzzi et al. 2010). The second significant difference is the additional interactions with the pool plant equipment which can introduce hazards such as contact with moving machinery, exposure to noise, electrical hazards and exposure to strong chemicals (HSE 2007).

1.4.1.3 Swimming Pool Water Quality

In order to maintain a safe environment for bathers, the pool water quality needs to be monitored and controlled. As mentioned previously, the bathers present a direct source of contaminants to the pool water and therefore a treatment system is required to maintain the water quality. There are a number of methods of treatment available to pool operators and each of these methods can have a range of benefits and drawbacks (DWI 2010; Weng et al. 2012). The effect of a treatment methodology on the water quality entering the pool is therefore an interaction of significant interest. The second key interaction is the ability of the hydraulic design of the facility to generate sufficient circulation to distribute disinfectants and remove suspended contaminants. The removal of some dissolved contaminants and chlorine-resistant pathogens can only be achieved through the disposal of pool water (PWTAG 2009). The effect that the amount of fresh water added to the pool, known as the refresh rate, has on the accumulation of dissolved contaminants in the pool water is of interest, as the exchange of water is a key contributor to the operational costs of the facility (Carbon Trust 2006).

1.4.1.4 Swimming Pool Air Quality

The interactions that need to be considered in relation to the air quality within a pool are similar to those for the pool water quality. The design of the ventilation system needs to ensure that sufficient air circulation is achieved in order for
contaminants to be effectively removed from the pool hall (Hsu et al. 2009). The velocity of the air movements in the pool hall can also affect the rate at which evaporation occurs from the pool water surface (Asdrubali 2009; Moghiman and Jodat 2007; Shah 2003). This will have a direct impact on the level of exposure experienced by both bathers and employees and is therefore a significant interaction. The significance of evaporation will also depend on the pool water quality and the presence of harmful volatile compounds. In addition to controlling the contaminant concentrations in the air, the addition of fresh air is also required to control the humidity within the pool hall (PWTAG 2009). The condition of the air in an indoor pool is important as it can have an impact on both the rate of evaporation from the pool and also the integrity of the structure of the facility (Gonzalez and Andrade 1982; Houska and Fritz 2005; Sun et al. 2011).

1.4.1.5 Swimming Pool Energy Consumption

A swimming pool facility has a vast array of components that are associated with an energy demand. The specific components are dependent on the design of the facility, however the energy demands can be broadly grouped into five categories; general, air handling, water circulation, water heating and water treatment (Trianti-Stourna et al. 1998). The first category is for generic building-related components that have an energy demand such as lighting. The energy consumed by the air handling equipment depends on the amount of dehumidification, heating and circulation required to maintain the desired air quality in the facility. The energy demand associated with the circulation of water through the pool tank and associated treatment plant is dependent on the structural design as well as the operational parameters selected. The energy demand for heating the pool water is dependent on operational parameters, such as the refresh rate and water temperature, and external factors, such as the source water temperature. The design of a water treatment system can vary widely and therefore the energy demand associated with different options is of significant interest. In order for energy considerations to be incorporated within the generation of sustainable pool design guidance, the energy interactions within each of these categories needs to be understood in detail.

1.4.2 Development of Framework

During the exploration of interactions within a pool environment, it became clear that it is not feasible to make recommendations on one aspect without understanding the interactions it has on other aspects. A conceptual model for a swimming pool was developed by compiling the interactions relevant to each of the five key aspects discussed above. The resulting conceptual model is shown in Figure
The conceptual model was used as a framework around which the knowledge base required for an integrated guidance document can be formed.

Figure 1-2 - Key interactions in a swimming pool facility

The review of the current guidance highlighted that the knowledge base on which it has been developed largely consists of a combination of historical anecdotal evidence and commonly-held assumptions. Remarkably, little scientific and experimental support has been referenced throughout the guidance. A wide range of research with relevance to the swimming industry has taken place in various countries around the world. As the swimming industry itself has not had a strong academic focus historically, the dissemination of this research has been limited (PWTAG 2010). The broad range of interactions within the swimming pool environment also creates opportunities for knowledge from other industries to assist with developing the knowledge base.

The transfer of knowledge between countries and from other industries is something that has not taken place to a great extent to date. The lack of a cohesive structure to the industry guidance within the UK or elsewhere is considered to be a major contributor to this issue (PWTAG 2010). PWTAG has recently attempted to address this issue through the generation of an international research database, the International Pool and Spa Forum. This forum aims to encourage research to take place on all aspects of the swimming industry to be collated in a central location. However, since its launch in 2011, there has been very little contribution from the various international research groups to the forum. The creation of a central knowledge database that a Code of Practice can draw upon would help the transition to a new industry structure which is more able to result in the sustainable design and operation of swimming pools. Figure 1-3 shows the result of incorporating the changes that PWTAG has made into the UK industry structure.
This improved structure would provide a clear pathway for organisations to influence the development of the industry guidance whilst minimising the risk of unintended consequences arising within aspects about which they are not informed about.

Figure 1-3 - Modified UK industry structure following adoption of modifications made by PWTAG
1.5 Defining the Scope and Objectives of the Research Project

The lack of a strong knowledge base means that it is not possible at present to produce a well-supported methodology for optimising swimming pool design and operation. It is therefore important first to enhance the rigour of the knowledge base through empirical research. The review of literature identified a large number of areas that are in need of improved understanding. The most significant areas were in relation to the interactions associated with water quality. The basis for this decision is the fact that the overarching objective for the swimming industry is to provide an environment that does not endanger the health or safety of the users. This priority means that the water quality is a fundamental aspect that must be considered in all design or operational decisions.

This research project aims to help develop the understanding of key interactions that have an influence on the swimming pool water quality through investigations undertaken in partnership with the University of Surrey and the Surrey Sports Park, a fully operational leisure facility containing a multi-use swimming pool. In particular the research aims to assess the effects of user behaviour and common energy efficiency measures on the water quality.

1.5.1 Definition of Water Quality for Swimming Pools

In order to make assessments regarding the significance of any effects resulting from the various interactions, it is first essential that a clear definition of what acceptable water quality is for the purposes of swimming. Water quality is a ‘pseudo-property’ that has been referred to as a combination of physical, chemical, biological and organoleptic characteristics of water (UNSD 1997). Various guidance documents outline some water quality indicators that are recommended to be used to assess the suitability of swimming pool water (ISRM 2010; PWTAG 2009; WHO 2006). The water quality targets presented in the guidance have evolved as user expectations have changed and as additional information about substances present within the pool environment has become available. It is not possible to confidently determine the risks associated with pool water without having a good understanding of its composition. It is therefore important to undertake a broad examination of the water composition found within swimming pools. An in-depth study of the composition and associated risks of pool water was undertaken. It included a review of currently published information as well as the analysis of primary data collected from the operational swimming pool facility. The research undertaken on this topic is presented in Chapter 2.
1.5.2 Evaluation of the Impact of Bather Interactions

Following the specification of a target water quality and the identification of the pool water composition, it was then possible to start developing methodologies for achieving the target water quality. Clearly, minimising the amount of unwanted material entering the pool water is the easiest way of maintaining the water quality. Reducing the primary sources of unwanted substances can reduce the opportunities for secondary unwanted substances being generated. The primary sources of contaminants include the source water and the use of chemicals for disinfection or cleaning, however the most significant source is the pool users. Because of the large number and variety of people using a pool facility, the effect of user behaviours on the water quality is of high importance to those responsible for specifying the treatment system.

Aside from the introduction of contaminants to the pool water, the users also have a significant influence on other aspects of a facility's operation. The perception of risk can be significantly different from the statistical probability of risk. The perception of the public regarding swimming is an important factor when assessing the potential impacts any changes to the industry could make. A number of studies were undertaken in collaboration with the Surrey Sports Park to assess not only the common actions of bathers and their potential impacts on the water quality, but also the perceptions of users regarding the benefits and risks of swimming. These aspects of the research are discussed in Chapter 3.

1.5.3 Evaluation of the Environmental Impacts of Pool Operation

It is impossible for all sources of contamination to be prevented and therefore there will always be a requirement for some form of water treatment. The options for water treatment range from low-tech solutions, such as water exchange, to high-tech solutions, such as reverse-osmosis. Each of these methods presents its own benefits and drawbacks in relation to water use, energy use, ease of operation and effects on water quality. It is therefore important to have an understanding of the impacts of different technologies on these aspects in order to assess the sustainability of each option. An additional layer of complexity is added to this as a result of the impacts of a treatment plant being dependent on the way it is operated. The performance of a treatment system in different modes of operation is not an area that has been covered in much detail to date. The collaboration with the Surrey Sports Park presented the opportunity to identify the challenges of addressing sustainability issues from an operator’s perspective, collect the primary data required to enable assessment of the options installed at the facility and to
The Swimming Industry: A Critical Review

examine the potential for reducing the running costs of the facility. The operational studies undertaken are discussed in Chapter 4.

1.5.4 Evaluation of the Significance of Pool Hydraulics in the Sustainable Design of Swimming Pools

Although the components of a pool water treatment system can vary significantly from one pool to another, one fundamental issue that applies to all systems is that it can only effectively remove contaminants if they are exposed to the treatment. Therefore the nature of the pool tank hydraulics has significant influence on the ability to maintain the water quality. A significant issue for pool designers is that once built, pool structures are very expensive to modify (Dev in 2010). To date, designers have based design decisions on observations taken from existing pool facilities, however the options that can be explored through examination of built structures are limited. The opportunity to identify innovative design solutions for the challenges of creating sustainable pools therefore requires new tools to be used in the design stage. One such tool that has the potential to address the issue with regards to pool hydraulics is computational fluid dynamics (CFD).

CFD is widely used in many different industries to inform design decisions, however it is not common practice within the swimming industry. There are a number of different commercially available methods within the field of CFD. Improper use of simulation methodologies can result in inaccurate representations of the system being modelled. It is therefore important that a robust and validated approach for the use of CFD is developed for the swimming pool environment. A series of physical and CFD experiments were undertaken to develop a suitable methodology that could be subsequently applied to a case study based on the Surrey Sports Park pool. Chapter 5 presents the work undertaken in developing the methodology together with the outcomes of the case study.

1.5.5 Recommendation of Modifications to Swimming Pool Guidance and Regulation to Enhance the Sustainability of the Industry

The development of an improved knowledge base through research, such as that presented in Chapters 2 to 5, will help to generate more integrated guidance for the UK industry, however, as there is currently very little relevant legislation, it still remains dependent on the organisations in the UK swimming industry to adopt it voluntarily. The ability to reduce operating costs is an incentive for some aspects of the guidance, however other parts have inherent costs associated with them and are therefore less attractive to organisations. Legislation is often slow to evolve because of the complex approval process and can therefore hinder progress in an industry if it is too prescriptive. The enforcement of legislation can also be costly...
and, as the UK government adopts the ‘beneficiary pays’ principle, these costs would be passed on to the industry. Finding a balance between legislation and incentive for the swimming industry is therefore a crucial factor for addressing the sustainability challenges. The final chapter draws together the findings of all aspects of the research project and explores the role policy mechanisms have in assisting the development and implementation of integrated guidance within the UK swimming industry.
1.6 References


The Swimming Industry: A Critical Review


Chapter 2 – An Assessment of the Water Quality Considerations Involved in Achieving a Healthy Swimming Pool Environment

2.1 Introduction

‘Water Quality’ has been defined as a ‘pseudo-parameter’ that is used to describe the overall condition of water encompassing its physical, chemical, biological and organoleptic characteristics (UNSD 1997). This study considers that, in general, “good” quality water is one that does not exhibit characteristics that negatively affect any aspect of its intended application. These could include characteristics that are hazardous to health, present operational or maintenance issues or impact the environment. The concept of water quality is therefore completely dependent on its application. For instance, the requirements for a “good quality” water to be used in an industrial setting can be very different from that intended for human consumption. Therefore, the specific water quality “standards” for one application may not be appropriate for another. Manipulating the condition of water can be difficult and expensive. As a result, the quality benchmarks to which the water is compared can have important repercussions. This chapter aims to explore this area by examining the current understanding of water quality in relation to swimming pools and reviewing it through the use of published literature and data collected during a water survey of an operational facility.

In the case of swimming pools, the characteristics that have relevance to determining the quality of water are wide ranging. It is important not only to consider the potential for the water to impact the integrity of the infrastructure and equipment but also the potential for the water to affect the health of those using the facility. In addition, the aesthetics of the water are also important as swimming pools are social venues and users desire a pleasant environment. There are currently a number of guidance documents that outline some water quality indicators that are recommended to be used to assess the suitability of swimming pool water (ISRM 2010; PWTAG 2009; WHO 2006). The main focus of these documents is on the health-related aspects of water quality, however, some operational and aesthetic considerations are also referred to. The historical interest in the health effects of water consumption has generated a large amount of literature on the subject.

A recent increase in interest in health effects associated with recreational water has added to this body of knowledge and has also been the driver for pool designers to
develop alternative approaches to the traditional chlorine disinfection techniques (Oesterholt et al. 2009). These alternatives range from the use of oxidation methods, such as UV irradiation and ozone, to physical techniques, such as reverse osmosis and ultrafiltration (Skibinski and Uhl 2011). Each treatment technique has the potential to affect the characteristics of the pool water differently. It is therefore important to understand the impact each has on the concentrations of substances within the water. A review of literature published in relation to the characteristics of pool water, the effects of treatment techniques and their associated health and non-health related issues is presented in Section 2.2. The current water quality standards published for UK swimming pools are also summarised in this section, however, it is often found that no consistent requirements for water treatment exist (de Man et al. 2014).

In order to assess the effectiveness of current pool water quality standards in minimising the potential impacts on a swimming facility and to identify opportunities for improvement, it is first important to have a good understanding of the characteristics of pool water in an operational facility. An in-depth survey of the pool water and source water at the Surrey Sports Park was therefore undertaken.

**Figure 2-1 - Photos of pool tank (top right), traversable boom (left) and UV unit (bottom right) at Surrey Sports Park**

The Surrey Sports Park at the University of Surrey incorporates an indoor 50m 8-lane deck level swimming pool that is fitted with a traversable boom and a
moveable floor. The water treatment process incorporates sand filtration with a polyaluminium chloride (PAC) coagulant, medium-pressure UV irradiation and sodium hypochlorite injection. Hydrochloric acid is used to maintain the pH level of the pool water. To enable research, the pool plant has been designed to include sampling points at strategic locations, allowing data to be collected in a controlled manner. The facility presented the opportunity to begin collecting data at the commissioning stage prior to the public opening of the new pool and therefore to enable a better understanding of the transient nature of the various aspects of pool water quality. The scope and methodology of the survey is described in Section 2.3. The results of the water survey are presented in Section 2.4 whilst the subsequent analysis of the results and the findings of the survey are discussed in Section 2.5.
2.2 Literature Review

This section contains a critical review of the published literature on topics relating to swimming pool water quality. There are a wide range of characteristics that need to be considered for swimming pool water. These can largely be categorised as health-related aspects and non-health related aspect.

2.2.1 Health-Related Aspects

The swimming pool water has the potential to present a wide range of health-related hazards to both staff and visitors. The exposure to substances in the water can be through dermal contact, ingestion or inhalation. The health hazards can be associated with microbiological pathogens as well as chemical substances.

2.2.1.1 Microbiological Characteristics

Microbiological pathogens can be introduced to the swimming pool water directly through accidental releases from infected users, through shedding from contaminated equipment and clothing or from contaminated source water. The interaction of animals with water can be an additional source of pathogens for outdoor pools. The microbiological pathogens that are associated with swimming pool water, together with their potential impacts on human health and methods for control, have been well researched and documented (HPA 2011; HSE 2006; Pond 2005; PWTAG 2009; WHO 2006). There is a wide range of pathogens that may be present within pool water. These include faecally-derived hazards, such as Cryptosporidium and E. coli O157, and non-faecally-derived hazards, such as Pseudomonas aeruginosa and Staphylococcus aureus (De Man 2014; Pond 2005). A summary of microbiological pathogens that have been associated with swimming pool water was compiled by the World Health Organisation (WHO) and is shown in Figure 2-2.
Figure 2-2 - Potential microbiological pathogens in swimming pool water (WHO 2006)

A large surveillance study of the microbiological quality of swimming pool water was undertaken by Martins et al. (1995) and showed that there was a strong correlation between the concentrations of many microbiological pathogens often found within recreational waters. The study supported the use of relatively inexpensive and straightforward testing for total coliforms and heterotrophic bacteria as indicators for microbiological water quality. Another large study undertaken by Papadopoulou et al. (2008) identified the presence of a range of antibiotic-resistant faecally-derived and non-faecally-derived pathogens. The potential for both to be present in swimming pool water means that both faecal and non-faecal indicators are ideally required to assess the water quality. This may not always be practical because of the cost or availability of testing facilities. The absence of an indicator also does not guarantee the absence of other pathogens, especially those that are more resistant to the disinfection treatment being used (WHO 2006).

Common health effects of exposure to microbiological pathogens include eye infections, skin infections and gastrointestinal illnesses. Guidelines for the maximum permissible microbiological concentrations for swimming pools have been derived from the findings of numerous studies into the infective doses of each pathogen (WHO 2006). Studies show that acute gastrointestinal illnesses are more likely where swimmers have submerged their heads (Boehmer et al. 2009; Causer et al. 2006). The successful control of many common microbial pathogens can be achieved through well-designed pool structures and good management that enable the entire water body to be effectively treated by a disinfectant. However, the
potential presence of disinfectant resistant pathogens, such as *Cryptosporidium parvum*, introduces an extra requirement of ensuring the entire water body passes through additional treatment processes within a relatively short timescale (PWTAG 2011; Rose 1997). *Cryptosporidium* oocysts present a significant challenge for the swimming industry because of the combination of its high resistance to disinfection, small size and low infectious dose (HPA 2011; RSC 2001). The continued occurrence of swimming pool-related outbreaks of Cryptosporidiosis has resulted in significant interest in the presence, transport and fate of *Cryptosporidium parvum* oocysts within recreational water (Lu *et al.* 2013). Cryptosporidium oocysts have, however, been identified to be susceptible to UV and ozone in various studies (Craik *et al.* 2001; Korich *et al.* 1990; Rennecker *et al.* 1999; Zimmer *et al.* 2003). Many pools have also been shown to exceed national legal limits for microbiological quality, see for example Mavridou *et al.* (2014).

2.2.1.2 Chemical Characteristics

Chemicals identified in swimming pool water can originate from a number of sources. Chemical substances can be added directly to the water as part of the treatment process, present in the source water or introduced to the water by the users. In most cases in the UK, source water is taken from the mains drinking-water supply and therefore should not contain substances harmful to health. Similarly, the majority of chemicals introduced to the pool by the bathers, for example cosmetics, do not present a significant health risk in their own right at the quantities expected to enter the pool. Therefore, the most significant of the primary sources, in relation to potential health risks, are the chemicals used in the water treatment process.

These can include chemicals used as coagulants to aid the removal of suspended material, chemicals added to manipulate the pH of the water and chemicals used as disinfectants. Many of the chemicals used for these purposes are delivered and stored at high concentrations and then diluted for the final application. Careful management and control of access to these chemicals and their use is required as a result. Exposure to the chemicals at high concentrations can cause significant harm ranging from irritations to the eyes and skin to very severe burns or even death depending on the nature of the exposure. Those presenting the greatest health risks in a swimming pool environment are often those containing chlorine, such as sodium hypochlorite or hydrochloric acid, as at high concentration they present significant hazards through dermal exposure or ingestion and their misuse can also potentially liberate the chlorine to present a significant inhalation hazard. If done correctly, the final application of chemicals for the management of pool water does not present health risks to the users.
In addition to the chemicals introduced to the water through one of the three primary sources, there is also the potential for secondary chemicals to be formed within the pool water. These chemicals have been collectively termed disinfection by-products (DBPs) as many of them are formed through the reaction between a precursor and the disinfectant (WHO 2006). A wide range of DBPs that are potentially hazardous to health, including chloramines, trihalomethanes (THMs) and haloacetic acids (HAAs), can be generated through the reactions between disinfectants and precursors within the pool water (Lakind et al. 2010; White 1986; Xie 2004). The range of substances that can act as DBP precursors is vast and includes both organic and inorganic material. Keuten et al. (2012) and Kim et al. (2002) reported that the majority of precursors are commonly considered to be introduced to the pool water by bathers in the form of sweat, urine, hair and cosmetics. DBP precursors, however, can originate from all of the primary sources or even from other DBP reactions. A summary of key chemicals that should be considered in the pool environment was compiled by the WHO and is shown in Figure 2-3. The presence of DBPs and the potential health effects has been the subject of a substantial amount of recent research. A review of current knowledge about the presence and health effects of DBPs is discussed in the following section.

![Figure 2-3 - Potential chemicals in swimming pool water (WHO 2006)](image)

2.2.1.3 Disinfection By-Products

Since the initial identification of the existence of chloroform in chlorinated waters in the early 1970s, research into the presence of disinfection by-products (DBPs) has been undertaken in many countries [Xie 2004]. The drinking-water industry has been the driver for this research, with the predominant concern being the provision...
of safe water for human consumption. Chlorination is the most common form of water treatment used to remove microbiological pathogens from both drinking and swimming pool water, however many of the by-products formed during this process are also harmful to human health, as discussed by Connell (2002). The extent of potential exposure of chlorination by-products to bathers has subsequently been widely studied (Aggazzotti et al. 1993; Caro et al. 2007; Hery et al. 1995; Lahl et al. 1981; Lourencetti et al. 2012; Zwiener et al. 2007). The presence of chloramines, HAAs, and THMs in chlorinated waters is now very well documented (Chu and Nieuwenhuijzen 2002; Feyen and Appel 2011; Maliliarou et al. 2005; Ribeiro et al. 2011; Silva et al. 2011; Weaver et al. 2009). Potential health implications of exposure to these DBPs has also been widely reported, including evidence of asthma and other illnesses, such as eye and skin irritations (Bernard et al. 2003; IPCS 2004; Jacobs et al. 2007; Moriera 2011; Päivinen et al. 2010; Thickett et al. 2002; Weaver et al. 2009; Weisel et al. 2009) however the review by Villanueva (2012) reported that conclusions have been often conflicting. Attempts to understand the uptake routes and rates of these substances have been undertaken through various epidemiological studies (Caro and Gallego 2007; Erdinger et al. 2004; Xu and Weisel 2005). These studies highlighted the potential for DBP exposure to occur through dermal adsorption, inhalation and ingestion. Hery et al. (1995) undertook air sampling at a number of different pools to provide information relating to the air-borne concentrations of chloramines. To date over 100 different disinfection by-products have been identified in swimming pool water (Richardson et al. 2010). However, there has only been a significant amount of research into those that are found most commonly in substantial quantities, such as chloramines and trihalomethanes (Lakind et al. 2010).

A wide range of DBPs are formed through the oxidation reactions between free chlorine and inorganic and organic materials in the water (WHO 2006). When analysed, samples from chlorinated water are often only examined for a narrow range of common DBPs. Many of the DBPs that are theoretically possible are therefore not identified especially if they are only present in very low concentrations. White (1986) reported that many potential DBPs would not be easily identified as a result of the continual reaction of DBPs in treated water systems. Many trihalogenated DBPs readily degrade via hydrolysis yielding other DBPs. Similarly, monochlorinated and dichlorinated DBPs are intermediates and can be involved in further chlorination reactions to form other DBPs. Xie (2004) explains that chloroacetic and dichloroacetic acids are notable exceptions to this. It has been widely reported that the formation of DBPs is time dependent (White 1986; Xie 2004). In the swimming pool industry, the chlorine residual is maintained and the
Water Quality Considerations for a Healthy Pool

Water is constantly re-circulated for a long period of time, up to 30 weeks. It is therefore assumed that DBP formation reactions will not be limited by chlorine supply or reaction time and that only reaction end products need to be considered. In addition to the commonly referenced chemicals discussed in the following sections, the use of modern treatment technologies, such as UV and ozone, have been reported to increase the formation of more complex and potentially toxic DBPs (Karanfil et al. 2008; Santos et al. 2012).

Chloramines

Chloramines have historically been associated with swimming pools as they are formed through the reaction between hypochlorous acid and ammonia. Mono-, di- and trichloramine can be formed, however, at low ratios of chlorine to ammonia in the pH range of 7.2 and 7.8, the operational range for pools, monochloramine is the predominant compound formed as a result of its favourable reaction kinetics. Higher ratios of chlorine to ammonia and lower pH conditions are known to lead to the increased formation of di- and trichloramine. Chloramines are known to be strong respiratory irritants (IPCS 2000b). Common symptoms of exposure to chloramines include soreness to eyes and coughing. Monochloramine is considered relatively non-toxic at levels below 3 mg/l (WHO 2008). Trichloramine, commonly known as nitrogen trichloride, is highly volatile and is the strongest irritant of the chloramines. Thicket et al. (2002) reported that repeated exposure to nitrogen trichloride can cause the onset of respiratory conditions such as asthma. It has been suggested that a maximum long-term exposure limit of 0.5 mg/m³ for nitrogen trichloride should be adopted for indoor pool environments based on respiratory responsiveness tests (Henry et al. 1995; Massin et al. 1998).

Trihalomethanes (THMs)

Chloroform has often been identified as the most prevalent DBP in chlorinated swimming pool water and has therefore been the focus of the majority of research to date. Similarly, bromoform is the dominant DBP in brominated swimming pool water (Lourencetti et al. 2012). Values for trihalomethanes (THMs) in pool water can be frequently found in the literature (Chu and Nieuwenhuijsen 2002; Erdinger et al. 2004; Fantuzzi et al. 2001). The various trihalomethanes are toxic and potentially carcinogenic to humans (IPCS 2000b). The bulk of information available on THM health issues focuses on chloroform. Chloroform is readily absorbed by the lungs, gastrointestinal tract and skin and is known to cause a range of symptoms including nausea, dizziness and irritation of skin, eyes and throat. High exposure levels can lead to heart failure. It has been classed as a category 2B carcinogen and is believed that long term exposure at acute levels could lead to liver and kidney
Water Quality Considerations for a Healthy Pool

damage (IPCS 2004). The Health Protection Agency (2007) has advised a long term exposure limit of 10 mg/m³ and a drinking-water limit of 0.2 mg/l in the UK. Similarly, bromodichloromethane (BDCM) is classed as a category 2B carcinogen and long term exposure may lead to liver and kidney damage and potentially cause male reproductive issues. A recent study by Hoffman et al. (2008) identified an association between THM exposure and adverse foetal growth at concentrations over the recommended levels. Bromoform and dibromochloromethane (DBCM) appear to be the least toxic of the THMs and, although they are expected to cause similar respiratory irritations as chloroform, have been classed as category 3 carcinogens (IPCS 2000b). Drinking-water guidelines for bromoform, DBCM and BDCM have been recommended as 0.1 mg/l, 0.1 mg/l and 0.06 mg/l respectively (WHO 2008).

Haloacetic Acids (HAAs)

Recent analysis by Weaver et al. (2009) of water samples taken from pools in the US has identified 10 common DBPs and published correlations between them and the free chlorine concentration. An attempt to identify the fate of free chlorine in swimming pools through the use of a simple mass balance on a pilot scale has been undertaken by Judd and Black (2000), however, it was reported that less than two thirds of the chlorine could be accounted for. The study only monitored for the presence of THMs and chloramines and it was suggested that the formation of HAAs could account for the shortfall. HAA exposure can potentially cause reproductive, carcinogenic and mutagenic effects including liver cancer and infant growth reduction. Human epidemiological studies have suggested that these effects may materialise following lifetime exposure to levels often found in drinking-water supplies (Hamidin et al. 2008). Other studies have found no evidence to associate HAAs in drinking-water with foetal growth defects (Hoffman et al. 2008).

Dichloroacetic acid (DCA) has been investigated in greatest detail because of its use in the treatment for a variety of metabolic diseases. DCA has been shown to affect male reproductive functionality and is known to be neurotoxic to humans when exposed to significant concentrations, >25 mg/kg/day, over long periods. Dermal contact to high concentrations of trichloroacetic acid (TCA) is known to cause burns whilst ingestion can damage internal tissue. Acute and chronic exposure to low concentrations of DCA and TCA are both considered to be relatively non-toxic (IPCS 2000b). Guideline values for drinking-water have been recommended at 0.05 mg/l and 0.2 mg/l respectively (WHO 2008).
Haloacetonitriles (HANs), Haloketones and Haloaldehydes

Other substances, including halogenated acetonitriles, aldehydes, and ketones, can also be formed in chlorinated pool water. These are often found in very low quantities and therefore have not been considered significant enough to be the focus of much research to date (WHO 2006). Limited information is available from work carried out in the drinking-water industry. The concentration of haloacetonitriles (HANs), haloketones and cyanogen halides formed in the presence of monochloramine in water has been found by Yang et al. (2007) to be dependent on chlorine dose and pH but relatively unaffected by temperature or the method of dosing. Kramer et al. (2009) believe that haloacetonitriles are likely to be more common in pools than in drinking-water because of the higher levels of nitrogenous compounds and elevated temperatures.

Hydrated trichloroacetaldehyde, also known as chloral hydrate, is irritating to the skin and mucus membranes and can cause nausea after ingestion. It is a commonly used sedative and hypnotic substance (IPCS 2000a). Acute doses of around 250 mg are sufficient to cause sedation whilst doses of 1-2 g will cause hypnotic effects in adults. Acute exposure at higher levels (>8g) is also known to trigger cardiac arrhythmias. Long-term exposure to chloral hydrate at low levels is thought to increase the risk of hyperbilirubinaemia amongst children. Ingestion of relatively high concentrations of chloral hydrate is reported to cause liver damage. It is suggested that the maximum daily intake that would not result in any side effects is 0.1 mg/l (IPCS 2000a). A drinking-water guideline value of 0.01 mg/l has therefore been suggested (WHO 2008).

Other haloaldehydes have not been extensively studied, however, they are generally considered irritants. Irritation to skin and eyes has been recorded from concentrations of chloroacetaldehyde of 0.02% and greater (IPCS 2000b). A maximum occupational short-term vapour exposure limit of 3.3 mg/m³ is advised for chloroacetaldehyde (HSE 2007). Halogenated aldehydes are considered to be more potent carcinogens than THMs or HAAs although data available is limited (IPCS 2000b). Limited data are available on the toxicity of haloketones and haloacetonitriles as these are not regulated at present. It is suggested, based on some animal testing, that they have some carcinogenic properties, however, the amount of information is insufficient to quantify the risk to human health (IPCS 2000b). A more recent study undertaken by Muellner et al. (2007) has shown that these are potentially more toxic than the currently regulated DBPs. The presence of nitrosamines in chlorinated water, known to be associated with causing bladder cancer, has also been identified (Karanfil et al. 2008).
Others

Aside from the commonly referenced DBPs discussed above, other chemicals can also be formed in the pool water. Chlorate is formed through the degradation of hypochlorite and is therefore a common DBP in swimming pools (Xie 2004). Chlorite has been identified as a DBP with significant health concerns, however, it is predominantly associated with chlorine dioxide disinfection processes that are rarely used in swimming pools (PWTAG 2009). Chlorite ingestion is known to cause methaemoglobinaemia, anuria, abdominal pain and renal failure. It is unlikely to be identified in the swimming pool water, as it readily reacts with free chlorine to produce chlorate (Health Canada 2008). It is suggested that chlorate ingestion also causes similar symptoms as chlorite (IPCS 2000b). Some research on animals has also indicated that chronic exposure may lead to adverse reproductive effects (Couri et al. 1982). The current limits on drinking-water concentration of 0.7 mg/l have been suggested with this in mind (WHO 2008).

Bromate is also a DBP that can form in the pool from the reaction between disinfectants and bromide in the water, although it is most common in pools using ozone as the primary treatment method (Xie 2004). It has been reported that hypochlorite solutions used as disinfectants can be a significant source of bromate in the water (Karanfil et al. 2008). Bromate is considered to be potentially carcinogenic and has been characterised as a class 2B carcinogen with a guideline limit of 0.01 mg/l in drinking-water is suggested (WHO 2008).

Nitrites are also involved in chlorination reactions. Nitrites present in the water will readily react with free chlorine to form nitrates. Nitrites are predominantly formed through the bacterial oxidation of ammonia (White 1986). Ingestion of nitrite is known to affect the haemoglobin in the blood preventing it from transporting oxygen around the body. Nitrate is also known to be reduced in the body to form additional nitrite. This is more prevalent in infants than in adults making them more susceptible to suffer from methaemoglobinaemia (Ward et al. 2005). Short-term guidelines for drinking-water concentrations are recommended as 50 mg/l and 3 mg/l for nitrate and nitrite respectively to prevent methaemoglobinaemia in infants. There is some evidence that chronic exposure to nitrite may cause adverse effects to the heart and lungs and that a long-term exposure limit of 0.2 mg/l should be adopted (WHO 2008). Ward et al. (2005) reported that inconsistent research outcomes have resulted in no clear understanding as to whether nitrate exposure is a causal factor for carcinogenic or reproductive abnormalities.
2.2.1.4 Exposure Routes

Erdinger et al. (2004) has shown that some DBPs can find their way into the blood of swimmers, lifeguards and spectators. There have been attempts to analyse the correlation between the concentration of the THMs in the pool water with various factors including organic content, temperature and number of users. Concentrations of some DBPs found in swimming pools have been published, however, it has been shown that a significant variation exists both within and between pools (Chu and Nieuwenhuijsen 2002). Uptake of DBPs by swimmers will be highly variable depending on the swimming environment. An assessment of chloroform uptake by swimmers and pool attendants was undertaken by Caro and Gallego (2007) and indicates that swimmers experience up to 8 times more exposure than non-swimmers. Although acute exposure to THMs at commonly found concentrations is considered to be unlikely to cause significant detrimental health effects, it has been modelled that lifetime exposure for frequent and competitive swimmers is likely to reach the doses associated with cancer (Bucchini and Prandi 2009).

It has been estimated by Erdinger et al. (2004) that no more than one third of the uptake of THMs by swimmers is via dermal adsorption, with the majority occurring via air inhalation. This finding puts additional emphasis on the importance of assessing the airborne concentration of DBPs. The rate at which different DBPs are absorbed by the skin is known to vary. The dermal permeability of haloketones has been found to be several orders of magnitude lower than that of chloroform, making the dermal route even less significant for these compounds (Xu and Weisel 2005).

Work by Caro and Gallego (2007) and Erdinger et al. (2004) suggests that there is a significant variability in the concentrations of DBPs in the air being inhaled. Hsu et al. (2009) have undertaken detailed research into the modelling of chloroform concentrations in the air at indoor swimming pools. Sampling undertaken as part of the study found the concentration of chloroform in the air to be in the range $10^1$ to $10^2$ µg/m$^3$ for still pools and $10^3$ to $10^4$ µg/m$^3$ for agitated pools. This research highlighted the importance of air flow rate and maximum recycle ratios on the accumulation of chloroform in the air (Hsu et al. 2009).

The third pathway of exposure, the ingestion of water, is considered to be much less significant. It is the primary pathway for some of the less volatile and skin-permeating DBPs, such as HAAs and chlorates. It has been estimated that the average swimmer will ingest less than 100ml of swimming pool water per visit (WHO 2006). Therefore, only highly toxic DBPs in fairly significant concentrations
are likely to be of any concern. It is also considered to be the reasoning behind lower recorded uptake levels of HAAs compared to THMs (Zwiener et al. 2007).

The various studies into DBP exposure have used different analysis techniques to attempt to quantify human uptake and response. These have included the onset of physical symptoms (Henry et al. 1995), breath analysis (Fantuzzi et al. 2001; Xu and Weisel 2005), blood analysis (Erdinger et al. 2004) and urine analysis (Caro and Gallegos 2007). All of these methods appeared to show good correlation with the environmental concentration.

2.2.2 Operational Consequences of Microbiological and Chemical Aspects

The health risks associated with water quality are only one aspect that needs to be considered in the case of swimming pools. Some characteristics of pool water may not present a health risk but still require careful consideration because of other potential impacts on the operation of a facility. This section summarises the key non-health-related aspects of water quality.

2.2.2.1 Microbiological Characteristics

Microbiological organisms in swimming pool water are associated with more than simply a direct health risk to bathers. The presence of organisms can lead to the formation of biofilms within the pool infrastructure. These biofilms can result in additional health risks such as making surfaces more slippery or protecting pathogens from disinfection. However, they can also affect the operation of pool equipment. The accumulation of a biofilm in filters can reduce their efficiency (WHO 2006). Similarly, biofilms can affect the ability of some treatment technologies to work efficiently (Goeres et al. 2004; Keuten et al. 2009). Biofilms can also result in the accumulation of suspended solids within the pool tank and therefore increase the opportunity for disinfection by-products to form (WHO 2006).

2.2.2.2 Chemical Characteristics

The presence of chemical substances in the water can have a range of impacts on the operation and maintenance of a swimming pool facility. Some impacts can be attributed to the presence of specific substances, such as chloride corrosion or sulphate attack, whilst other impacts are associated with a broad range of contributory substances, such as turbidity. The key chemical characteristics of swimming pool water are discussed in this section.

The acidity of the pool water is an important consideration not only for disinfection purposes but also because of the potential impact it may have on the fabric of the swimming pool. Water with a significantly low pH value can cause damage to metallic equipment and fittings in the treatment system, to grout and plaster within
the pool hall and to bathers swimming costumes. A high pH can cause scaling to become an issue within the pool equipment and pipework (PWTAG 2009). Many substances can affect the pH of the pool through either removing or adding hydrogen (H\(^+\)) or hydroxide (OH\(^-\)) ions. A relatively neutral pH of between 7.2 and 7.8 is generally accepted as suitable for swimming pool water (PWTAG 2009).

Alkalinity is a measure of the ability of water to neutralise acids. This is of operational significance as a very low alkalinity can lead to erratic pH variations to occur, an issue known as “pH bounce”. Conversely, a high alkalinity can result in the manipulation of pH to become very difficult, an issue known as “pH lock” (PWTAG 2009). The concentration of carbonate and bicarbonate ions in the water is largely responsible for the alkalinity of the swimming pool water. It is recommended that an alkalinity of between 80 and 200 mg/l CaCO\(_3\) is maintained to prevent pH bounce and pH lock. Similarly the hardness of the pool water is of interest to operators. Hard water, containing high concentrations of calcium or magnesium ions, can cause scaling inside pipework and restrict water flow. Soft water, however, can cause damage to metallic equipment and fittings (WHO 2011). The calcium hardness of water is therefore a key consideration for pool water. It is currently recommended for pool water to have calcium hardness between 75 and 150 mg/l CaCO\(_3\) (PWTAG 2009).

The clarity of the pool water is important for not only safety reasons but also for operational reasons. Cloudy water can prevent the bottom of the pool being visible presenting risks to bather safety. In addition, cloudy water can prevent some treatment options, such as UV, from working effectively (Saunus 1998). The turbidity of the water is a measure of the clarity of pool water. The presence of suspended and dissolved solids can both have an impact on the turbidity. Many of these solids are also precursors for harmful DBPs as discussed in the earlier section on health aspects (WHO 2006). It is currently recommended that a maximum turbidity of 0.5 Nephelometric Turbidity Units (NTU) is acceptable for swimming pool water (PWTAG 2009).

In addition to the parameters above that are dependent on the presence of multiple substances, there are also specific chemical substances that are associated with significant operational concern. The two most significant in the pool environment are chlorides and sulphates. Chlorides are introduced to pool water via a number of routes. These include through the sweat from bathers, the use of hydrochloric acid for pH amendment and as an impurity within sodium hypochlorite solutions (BSI 2007; Maughan \textit{et al.} 2009; White 1986). Once in the chloride form, the chlorine no longer has germicidal properties and will accumulate within the pool water. High chloride concentrations in water have the potential to cause
significant issues to the pool’s physical structure and associated equipment including the treatment plant (PWTAG 2009). At relatively low levels of chlorides, above 200 mg/l, the common form of stainless steel (304) becomes highly susceptible to corrosion (SSINA 2001). This is a well-known issue in other sectors (Gonzalez and Andrade 1982). For example, in coastal environments, where high chloride exposure is expected, more resistant marine steels (316) are required (Schumacher 1979). Even marine steel is susceptible to corrosion at high chloride concentrations and additional preventative measures, such as use of epoxy coatings, are sometimes required. Chlorides are stable in aqueous solutions and are also highly soluble meaning that it is possible for significant concentrations to accumulate over time. Similarly, sulphates can accumulate in the pool water and can cause damage to cement-based materials. The corrosion of these materials in this manner is an issue commonly termed “sulphate attack”. Current swimming pool guidance recommends a maximum limit of 360 mg/l SO\(_4\) (PWTAG 2009).

A final category of substances that are of interest are those that act as nutrients for organisms. These include phosphates, nitrogen and potassium. Algal growth is dependent on the presence of these substances and therefore effective management of their concentrations can prevent the need for algaecides to be added to the water (WHO 2006). There are currently no specific limits recommended for these substances.

2.2.2.3 Organoleptic Characteristics

In addition to the aspects of water quality that have the potential to impact the structure or equipment within the facility or have operational implications, the organoleptic characteristics are also important as they have significant influence on the aesthetics of a facility. Poor aesthetics can lead to users to perceive that the facility is poorly managed and can indicate real problems with operational procedures. The four key organoleptic characteristics of pool water are the colour, temperature, taste and odour (Sport England 2010). Pigmentation of the pool water can potentially reduce the visibility for lifeguards and bathers, reduce the effectiveness of UV treatments and affect the aesthetics of the facility. The taste and odour of the water can also negatively affect the comfort of bathers and staff. Although pool water is not ingested intentionally, accidental ingestion frequently takes place amongst swimmers. The temperature of the pool water has both safety and aesthetic implications. It is recommended that the pool water is maintained between 26°C and 30°C to ensure the pool is comfortable for most users however bather preference varies from individual to individual (PWTAG 2009). The variation also appears to be founded on a psychological basis rather than any physiological interactions (WHO 2006).
2.2.3 Current UK Standards

The current guidance for swimming pools published by PWTAG (2009) contains a summary of the key parameters that are recommended to be considered when managing water quality. The recommended limits for these parameters are shown in Table 2-1.

Table 2-1 - Summary of recommended parameter limits for swimming pool water

(PWTAG 2009)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PWTAG Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.2 to 7.4</td>
</tr>
<tr>
<td>Free Chlorine</td>
<td>0.5 to 2 mg/l</td>
</tr>
<tr>
<td>Combined Chlorine</td>
<td>&lt; 1 mg/l</td>
</tr>
<tr>
<td>Temperature</td>
<td>27°C to 30°C</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>80 to 200 mg CaCO₃/l</td>
</tr>
<tr>
<td>Hardness</td>
<td>75 to 150 mg CaCO₃/l</td>
</tr>
<tr>
<td>Turbidity</td>
<td>&lt; 0.5 NTU</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>&lt; 1000 mg/l above source water</td>
</tr>
<tr>
<td>Trihalomethanes</td>
<td>&lt; 100 µg/l</td>
</tr>
<tr>
<td>Sulphate</td>
<td>&lt; 360 mg SO₄/L</td>
</tr>
<tr>
<td>Bromate</td>
<td>&lt; 10 µg/l</td>
</tr>
<tr>
<td>Chlorate &amp; Chlorite</td>
<td>&lt; 3 mg/l</td>
</tr>
<tr>
<td>Nitrogen Trichloride</td>
<td>&lt; 0.2 µg/l</td>
</tr>
<tr>
<td>Monochloramine</td>
<td>&lt; 3 mg/l</td>
</tr>
<tr>
<td>Permanganate Value (PV)</td>
<td>&lt; 2 mg/l</td>
</tr>
<tr>
<td>Ammoniacal Nitrogen</td>
<td>&lt; 1 mg N/l</td>
</tr>
<tr>
<td>Albuminoid Nitrogen</td>
<td>&lt; 1 mg N/l</td>
</tr>
<tr>
<td>Total Organic Nitrogen</td>
<td>&lt; 1 mg N/l</td>
</tr>
<tr>
<td>Total Colony Count</td>
<td>&lt; 10 cfu/ml</td>
</tr>
<tr>
<td>Total Coliforms</td>
<td>&lt; 10 cfu/100ml</td>
</tr>
<tr>
<td>E. coli</td>
<td>&lt; 1 cfu/100ml</td>
</tr>
<tr>
<td>P. aeruginosa</td>
<td>&lt; 10 cfu/100ml</td>
</tr>
</tbody>
</table>
2.3 Surrey Sports Park Water Survey

2.3.1 Scope

The collaboration with Surrey Sports Park (SSP) enabled unprecedented access to an operational facility. A broad programme of water sampling was able to be carried out to assess the evolution of the pool water composition over a long time period. Water samples were taken from a variety of locations both within the pool tank and at specific points within the treatment plant in order for the water quality within the facility to be investigated in far greater depth than had been previously undertaken. The tank water samples were taken from multiple locations and at different depths within the pool tank to enable the uniformity of pool water composition to be investigated. Samples were taken from 30cm below the water surface at all pool tank locations in line with current best practice, whilst additional samples were taken from locations B, C, D and G at a depth of 180cm below the water surface to evaluate if any vertical variation existed. Samples were taken between each of the major stages in the treatment system to enable the cause of any changes in water composition to be determined. The locations used in this study are summarised in Figure 2-4.

Figure 2-4 Sampling locations (A-M) at the Surrey Sports Park pool

The water collected from each location was analysed for a broad spectrum of parameters in order to gain an understanding into the profile of properties found within pool water. The range of chemical analysis undertaken on the samples included parameters that are commonly monitored in the industry, such as pH and free chlorine concentrations, as well as substances that had historically been reported as having a link with pool-related health issues, such as chloroform. In addition, parameters that are considered important in the highly-regulated drinking-water industry, such as the dissolved metal concentrations, were included in order to get a broader understanding of the pool water composition. It was not possible to perform such a wide ranging analysis of the presence of microbiological pathogens. The scope of the microbiological analysis was therefore limited to the
Water Quality Considerations for a Healthy Pool

key indicators recommended in the guidance published by the WHO and PWTAG as listed in Table 2-2. The only commonly considered major substance of concern that was unable to be included in the suite of analysis was Cryptosporidium because of the cost of analysis. The full range of parameters that were considered is listed in Table 2-2 below.

**Table 2-2 - List of parameters included in the water analysis**

<table>
<thead>
<tr>
<th>General Chemistry</th>
<th>Physical Chemistry</th>
<th>Trihalomethanes (THMs)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammoniacal Nitrogen</td>
<td>Alkalinity</td>
<td>Benzene</td>
<td>Temperature</td>
</tr>
<tr>
<td>Ammonium as NH4</td>
<td>Colour</td>
<td>Bromodichloromethane</td>
<td></td>
</tr>
<tr>
<td>Bromate</td>
<td>Conductivity</td>
<td>Bromoform</td>
<td></td>
</tr>
<tr>
<td>Bromide</td>
<td>Hardness</td>
<td>Carbon Tetrachloride</td>
<td></td>
</tr>
<tr>
<td>Chlorine (free)</td>
<td>Langelier Index</td>
<td>Chloroform</td>
<td></td>
</tr>
<tr>
<td>Chlorine (combined)</td>
<td>pH</td>
<td>Dibromochloromethane</td>
<td></td>
</tr>
<tr>
<td>Chlorate</td>
<td>Turbidity</td>
<td>Dichloroethene</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>Total Dissolved Solids (TDS)</td>
<td>Tetrachloroethane</td>
<td></td>
</tr>
<tr>
<td>Nitrate as NO3</td>
<td></td>
<td>Trichloroethane</td>
<td></td>
</tr>
<tr>
<td>Nitrite as NO2</td>
<td></td>
<td>Trichloroethene</td>
<td></td>
</tr>
<tr>
<td>Sulphate as SO4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Oxidised Nitrogen (TON)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Organic Carbon (TOC)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microbiological Indicators</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Pseudomonas aeruginosa</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Coliforms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Viable Count - 24hr at 37°C (TVC)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An initial series of 15 sampling rounds were undertaken at increasing intervals over an initial 7-month period from April 2010 to October 2010. All the locations described in Figure 2-4 were sampled in each round. An additional series of 6 sampling rounds were also undertaken between March 2011 and September 2011 in order to look for seasonality in the sample analysis. Only two samples were able to be taken during these additional sampling rounds as a result of budget limitations. One shallow water sample was taken from location D, the usual water
sampling location used by the SSP staff, and one mains water sample was taken from location M. The repeated sampling undertaken enabled a far more detailed examination of temporal effects on the composition of water. The combination of the large number of sampling locations, the broad range of parameters analysed and the long-time window of the sampling window resulted in the most in-depth survey of swimming pool water quality undertaken to date. In total, over 250 samples were taken and analysed over the course of the water survey.

2.3.2 Sampling Methods

In order to ensure the collection and handling of water samples was consistent throughout the project, a sampling procedure was developed based on the regulatory methods set out in the Water Supply (Water Quality) Regulations 2001 (HMSO 2000). The sampling procedure can be broken down into 5 phases; General Preparation, Pre-sample Decontamination, Sampling, Field Parameter Measurement and Post-sample Routine.

2.3.2.1 General Preparation

Because of the wide range of analysis to be undertaken on the pool water, a suite of eight samples were required from each sample location. Each of these samples required a different sample bottle for the purposes of sample preservation and the requirements of the analysis equipment at the laboratories. The description of the eight samples are summarised in Table 2-3 together with the analysis undertaken on each. The bottles used for Sample 6 and 7 contained a solution of sodium thiosulphate in order to react out the residual free chlorine present in the pool water. This prevents any reduction in the microbiological indicators or any additional THMs from forming before the analysis is undertaken and is a common practice used for the sampling of chlorinated water (Connell 2002). In order to ensure minimal risk of cross-contamination between sampling rounds, sample bottles were only used once.
Prior to the collection of samples it was important to undertake appropriate decontamination steps to minimise inaccuracies in the sample analysis. The potential for microbiological biofilms and chemical residues to be present within the equipment used in the sampling process presents a risk of the water samples becoming contaminated. Three methods of decontaminating sampling equipment were used depending on the sample location, the type of sampling equipment being used and the type of sample being collected in line with the approved practice used by Thames Water for sampling drinking-water (Thames Water 2010).

The first method used was decontamination using isopropyl wipes. This process was used to remove any chemical residuals on the sampling equipment. The equipment was thoroughly rinsed with deionised water following being wiped with the isopropyl wipes to remove any residual alcohol. This method was used prior to the collection of any samples required for chemical analysis.

The other two methods, chlorine disinfection and flame sterilisation, were used to ensure the cross-contamination of microbiological pathogens were minimised. Chemical disinfection involved the use of a 1% chlorine solution that had been freshly prepared on the day of sampling. Two applications of the chlorine solution, each 1 minute in duration, were applied to the sampling equipment. The equipment

---

**Table 2-3 – Pool water survey sample descriptions**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bottle Type</th>
<th>Parameters Analysed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000ml Plastic Bottle (Blue Cap)</td>
<td>Alkalinity, Ammoniacal Nitrogen, Ammonium as NH4, Hardness, Nitrate, Nitrite, Sulphate, TON</td>
</tr>
<tr>
<td>2</td>
<td>500ml Plastic Bottle (Blue Cap)</td>
<td>Colour, Conductivity, Turbidity, pH</td>
</tr>
<tr>
<td>3</td>
<td>125ml HDPE Bottle</td>
<td>Metals</td>
</tr>
<tr>
<td>4</td>
<td>125ml Amber Plastic Bottle (Black Cap)</td>
<td>Bromate, Bromide, Chlorate, Chloride</td>
</tr>
<tr>
<td>5</td>
<td>125ml Amber Plastic Bottle (White Cap)</td>
<td>TOC</td>
</tr>
<tr>
<td>6</td>
<td>100ml Amber Glass Bottle with Na2S2O3</td>
<td>THMs</td>
</tr>
<tr>
<td>7</td>
<td>330ml Sterile Plastic Bottle with Na2S2O3</td>
<td>Microbiological Indicators</td>
</tr>
<tr>
<td>8</td>
<td>500ml Plastic Bottle</td>
<td>Field Parameters (Alkalinity, Hardness, pH, Chlorine (Free &amp; Combined), Temperature, Langelier Index, TDS)</td>
</tr>
</tbody>
</table>
was then thoroughly rinsed with the sample water prior to taking the final sample. This technique was used for the non-metallic sampling equipment. Most of the sample ports within the plant room were metallic which meant that flame sterilisation could be undertaken instead of chlorine disinfection. This involved heating the sample port pipework with a blowtorch following an initial rinse with water until steam from the pipe was visible. The use of flame sterilisation is preferred to chlorine disinfection as it does not introduce a risk of chemical interference with the sample.

2.3.2.3 Water Sampling

The various samples listed previously in Table 2-3 were taken from the locations shown previously in Figure 2-4. This involved collection of water samples from 3 types of location; shallow open water, deep open water and via sampling port. The method of collecting water samples from each of these locations was slightly different. The shallow water samples were collected using a standard pool water sampler as shown in Figure 2-5. This is a common piece of equipment used in the swimming industry for collecting shallow samples. The plunger is first depressed to close the sample opening and seal the empty sample bottle. The bottle is then submerged to the desired depth, 30cm in this study, and then the plunger is released to allow the sample bottle to fill. Once filled the plunger is depressed again to seal the sample bottle before the sampler is removed. The sample is then decanted into the required bottles on the surface.

![Figure 2-5 - Shallow water sampler used in the study](image)

The deep water samples were taken using an inertial pump sampling system. This system enables the manual collection of water from a specific depth of the water body. The smaller the range of vertical motion used the more accurate the sample location is. For the sample collection in this study the vertical range was kept below 10cm. The operation of the system is illustrated in Figure 2-6. This is a sampling methodology that is adopted widely in environmental sector to sample ground
Water Quality Considerations for a Healthy Pool

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes

water. The vertical motion of the foot valve causes water to rise up the pipe work which can then be pumped directly into the required sample bottles.

Figure 2-6 - Illustration of inertial pump operation (Solinst 2014)

The samples in the plant room were collected from dedicated sampling ports located in the pipework at specified points. These samples could be collected by simply opening the sample valve. An example of the plant room sample ports is shown in Figure 2-7.

Figure 2-7 - Sample port on sand filter inlet

2.3.2.4 Field Parameter Measurement

In addition to the analysis being undertaken by specialist analytical laboratories, a range of parameters, as listed in sample 8 of Table 2-3, were measured onsite
Water Quality Considerations for a Healthy Pool

during the sampling process. This onsite analysis was undertaken using equipment commonly available to pool operators. This included a Palintest Pooltest 25 Professional photometer, a total dissolved solids (TDS) meter and a temperature probe.

A balanced water is neither scale forming nor corrosive and is therefore preferred in swimming pool environments. The Langelier Saturation Index (LSI) is commonly recommended in current swimming pool guidance as a method of determining whether the water is in balance (PWTAG 2009). The LSI was calculated for each sample using the collected field data and Equation 2-1.

\[
LSI = TF + CF + AF + pH \text{ value} - TDSF
\]

In this equation TF is the Temperature Factor, CF is the Calcium Hardness Factor, AF is the Alkalinity Factor and TDSF is the Total Dissolved Solids Factor. The factors required for the calculation are selected by looking up the associated field measurement in Table 2-4.

Table 2-4 - Look up table for the Langelier Saturation Index factors (PWTAG 2009)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>TF</th>
<th>Calcium Hardness (mg/l CaCO\textsubscript{3})</th>
<th>CF</th>
<th>Alkalinity (mg/l CaCO\textsubscript{3})</th>
<th>AF</th>
<th>TDS (mg/l)</th>
<th>TDSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>50</td>
<td>1.3</td>
<td>5</td>
<td>0.7</td>
<td>1000</td>
<td>12.1</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>100</td>
<td>1.6</td>
<td>25</td>
<td>1.4</td>
<td>2000</td>
<td>12.2</td>
</tr>
<tr>
<td>18</td>
<td>0.5</td>
<td>150</td>
<td>1.8</td>
<td>50</td>
<td>1.7</td>
<td>3000</td>
<td>12.3</td>
</tr>
<tr>
<td>24</td>
<td>0.6</td>
<td>200</td>
<td>1.9</td>
<td>100</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>0.7</td>
<td>250</td>
<td>2.0</td>
<td>150</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>0.8</td>
<td>300</td>
<td>2.1</td>
<td>200</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>0.9</td>
<td>400</td>
<td>2.2</td>
<td>300</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3.2.5 Post-sample Routine

It is important that the microbiological, general chemistry and THM samples are kept cool between being taken and being analysed at the laboratory. Because of the environment present in the pool building, it is therefore necessary to place these samples in a refrigerator until the samples are ready to be delivered to the laboratories. A refrigerator was used to maintain the sample temperature between 5 °C and 8°C. After all the samples have been collected they were packaged into transport crates with icepacks to keep them cool during transit. The samples were successfully delivered to the laboratories for analysis within 24 hours of sampling taking place which conforms to recommendations made by UKAS (PWTAG 2014).

2.3.3 Analysis Methods

The samples were sent to external analytical laboratories operated by Thames Water and the Robens Centre for Public and Environmental Health (RCPEH) for
chemical and microbiological analysis respectively. In addition, onsite testing of some parameters were measured using the equipment available to the facility operators. A summary of the analysis methods used, including references specifying the source of the details of each method, is presented in Table 2-5.

Table 2-5 - List of methodologies and associated references used for water analysis

<table>
<thead>
<tr>
<th>Analyst</th>
<th>Methodology</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite</td>
<td>Colorimetry (Palintest 2010)</td>
<td>Free Chlorine, Combined Chlorine, pH, Alkalinity, Calcium Hardness</td>
</tr>
<tr>
<td></td>
<td>Digital Thermometer</td>
<td>Temperature</td>
</tr>
<tr>
<td>RCPEH</td>
<td>Membrane Filtration (HMSO 2009; HMSO 2010)</td>
<td>E. coli, Total Coliforms, <em>Pseudomonas aeruginosa</em></td>
</tr>
<tr>
<td></td>
<td>Pour Plate Technique (HMSO 2007)</td>
<td>Total Viable Counts</td>
</tr>
<tr>
<td></td>
<td>GCMS (HMSO 1984)</td>
<td>Benzene, Bromodichloromethane, Bromoform, Carbon Tetrachloride, Chloroform, Dibromochloromethane, Dichloroethane, Tetrachloroethane, Trichloroethane, Trichloroethene</td>
</tr>
<tr>
<td></td>
<td>Ion Chromatography (HMSO 1997)</td>
<td>Bromate, Bromide, Chlorate</td>
</tr>
<tr>
<td></td>
<td>Physchem Probe (HMSO 1978)</td>
<td>Conductivity, pH</td>
</tr>
<tr>
<td></td>
<td>Turbidity Meter (HMSO 1981b)</td>
<td>Turbidity</td>
</tr>
<tr>
<td></td>
<td>Infra-Red CO₂ Detection (HMSO 1979a)</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td></td>
<td>ICP-OES (HMSO 1996)</td>
<td>Aluminium, Calcium, Copper, Iron, Manganese, Zinc</td>
</tr>
<tr>
<td>ICP-MS (HMSO 1996)</td>
<td>Lead</td>
<td></td>
</tr>
</tbody>
</table>

2.3.3.1 Field Analysis

As shown by Table 2-5, the majority of field parameters were measured using a portable photometer. The method for each type of analysis was detailed in the associated user manual for the equipment. The free chlorine and total chlorine concentrations were measured using the diethyl-p-phenylenediamine (DPD) test method. Phenol Red test reagent was used for measuring pH whilst alkalinity and
Water Quality Considerations for a Healthy Pool

calcium hardness were measured using the Alkaphot and Calcicol test reagents respectively. All of these methods rely on determining the change in light transmission through the sample caused by the colouration of the water sample. A more detailed description of each method can be seen in the SSP Sampling Procedure contained in Appendix 4.

The measuring of pool water temperature and TDS concentration was undertaken using calibrated handheld meters. The TDS was therefore not calculated directly but was approximated using conversion factors that relate the measurement of the conductivity of the water to a TDS concentration in mg/l.

2.3.3.2 Microbiological Analysis

The microbiology testing of the water samples was undertaken by the UKAS accredited laboratory at the Robens Centre for Public and Environmental Health (RCPEH). The methods used by RCPEH for each of the microbiological parameters are detailed below.

Total Viable Counts at 30°C

Total Viable Counts were carried out using RCPEH Method No. MM08 which is based on the method described in “The Microbiology of drinking-water – Part 7-Methods for the enumeration of heterotrophic bacteria” published by the Environment Agency (HMSO 2007). The method is performed using the pour plate technique. A 1ml volume of the sample is mixed with molten Yeast Extract Agar (YEA) in a 90mm Petri dish and incubated at 37°C for 24 hours. Following incubation, all visible colonies are counted. The count is then expressed as colony forming units (cfu) per ml.

Enumeration of Total Coliforms and Escherichia coli:

Total coliform and *E. coli* counts were undertaken using RCPEH Method No. MM06 which involves using membrane filtration techniques based on “The Microbiology of drinking-water – Part 4 – Methods for the isolation and enumeration of coliform bacteria and *Escherichia coli* (including *E.coli* 0157:H7)” published by the Environment Agency (HMSO 2009). After filtration of 100ml of the sample the membrane is placed onto an absorbent pad saturated with Membrane Lauryl Sulphate Broth (MLSB). The plates are incubated at 30°C for 4 hours followed by 37°C for no more than 18 hours. After incubation all yellow colonies, which represent presumptive coliforms, are counted visually and reported in cfu per 100ml.

Subsequent confirmation of presumptive coliforms is carried out using Colilert, a reactive substrate medium manufactured by Idexx. Colonies demonstrating a yellow
colour are regarded as coliforms. In addition, colonies that exhibit a blue-white fluorescence under long wavelength ultra-violet light are regarded as *E. coli*.

*Enumeration of Pseudomonas aeruginosa*

*Pseudomonas aeruginosa* counts were undertaken using RCPEH Method No. MM09 which is based on the method described in “The Microbiology of drinking-water – Part 8 – Methods for the isolation and enumeration of *Aeromonas* and *Pseudomonas aeruginosa* by membrane filtration” published by the Environment Agency (HMSO 2010). The analysis is also performed using a membrane filtration method on 100ml of the sample. The membrane is placed on a solid medium containing magnesium chloride and potassium sulphate to enhance pigment production. The medium is made selective for *Pseudomonas aeruginosa* by the addition of cetyl trimethylammonium bromide and nalidixic acid. The plates are incubated at 37°C and examined twice to enable the count to be undertaken.

The first examination takes place after 22 hours incubation. The colonies exhibiting a green colouration that is associated with pycyanin production are confirmed as *Ps. aeruginosa*. The sample is then viewed under UV light and the presence of fluorescent, non-pyocyanin producing colonies is observed. The subculture is then added to milk agar and incubated at 37°C for a further 24 hours. The plate is examined again the number of fluorescent non-pyocyanin colonies that exhibit casein hydrolysis are confirmed as *Ps. aeruginosa*. The final count of *Ps. aeruginosa* is the sum of pyocyanin producing colonies plus fluorescent non-pyocyanin casein hydrolysis positive colonies and is expressed as cfu per 100ml.

**2.3.3.3 Chemical Analysis**

The analysis undertaken by Thames water involved the use of eight different analytical methods ranging from colorimetry to gas chromatography mass spectrometry (GCMS). The details of each of the analytical method was proprietary to Thames Water and was therefore not available for review, however in order for the laboratory to have UKAS accreditation the methods have to be in line with the various standards published by the Environment Agency, or its predecessor the Department of Environment. The relevant standards are referenced in the analysis summary in Table 2-5.
2.4 Water Survey Results

The results of the water sample analysis were collated by location and by date to enable both spatial and temporal fluctuations to be observed. The complete set of analytical results obtained during the water quality survey at Surrey Sports Park is contained within Appendix 5. A summary of the results is presented in this section.

2.4.1 Microbiological Analysis Results

There was no E. coli identified in any of the water samples taken from the swimming pool, its treatment plant or the source water. The presence of other coliforms was only identified in a single water sample throughout the entire survey. Although samples were found to be positive for P. aeruginosa more often, many were below the key action levels specified in current guidance. Swimming pool guidance recommends that counts above 10 per 100 ml should be considered to be of moderate concern and counts above 50 per 100 ml should be considered to be of serious concern. A colony of significance was identified within the automatic controller in the treatment system, sample location H, shortly after commissioning and was effectively removed.

Over a third of the water samples taken were found to have a positive total viable count, however most were below the recommended action levels. Swimming pool guidance recommends that counts above 10 cfu/ml should be considered to be of moderate concern and counts above 100 cfu/ml should be considered to be of serious concern. The sample of the water leaving the pool tank, location H, was found to have a higher proportion of positive samples than the other locations.

The total number of positive samples for each of the microbial indicators is shown in Table 2-6. The complete analytical results are included in Appendix 5.
Table 2-6 – Summary showing the number of positive microbiological results identified on each sampling date

<table>
<thead>
<tr>
<th>Date</th>
<th>E coli (no. of samples)</th>
<th>Total Coliforms (no. of samples)</th>
<th>P. aeruginosa (no. of samples)</th>
<th>TVC @ 37°C (no. of samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15/04/2010</td>
<td>0</td>
<td>0</td>
<td>1 (1 serious)</td>
<td>4</td>
</tr>
<tr>
<td>20/04/2010</td>
<td>0</td>
<td>0</td>
<td>2 (1 serious)</td>
<td>3 (1 moderate)</td>
</tr>
<tr>
<td>05/05/2010</td>
<td>0</td>
<td>0</td>
<td>1 (1 serious)</td>
<td>5 (1 moderate)</td>
</tr>
<tr>
<td>12/05/2010</td>
<td>0</td>
<td>1</td>
<td>1 (serious)</td>
<td>7 (1 serious, 1 moderate)</td>
</tr>
<tr>
<td>18/05/2010</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>25/05/2010</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6 (1 moderate)</td>
</tr>
<tr>
<td>02/06/2010</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8 (1 moderate)</td>
</tr>
<tr>
<td>15/06/2010</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8 (1 moderate)</td>
</tr>
<tr>
<td>29/06/2010</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4 (2 moderate)</td>
</tr>
<tr>
<td>14/07/2010</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>16 (3 moderate)</td>
</tr>
<tr>
<td>28/07/2010</td>
<td>0</td>
<td>0</td>
<td>5 (1 moderate)</td>
<td>6</td>
</tr>
<tr>
<td>10/08/2010</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>01/09/2010</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>27/09/2010</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1 (1 moderate)</td>
</tr>
<tr>
<td>02/11/2010</td>
<td>0</td>
<td>0</td>
<td>4 (1 moderate)</td>
<td>5</td>
</tr>
<tr>
<td>02/03/2011¹</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>31/05/2011¹</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>04/07/2011¹</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>09/08/2011¹</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>06/09/2011¹</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

1 – Only two samples collected (1 from Location D and 1 from Location M)

2.4.2 Chemical Analysis Results

The chemical analysis undertaken on the water samples generated a large amount of data. Initial data analysis undertaken on the results showed that the temporal variability was much more significant than the spatial variation for majority of the parameters monitored. The range of data values on each sampling date is shown via the use of error bars on the graphs included in this section. This section presents the average concentrations for the water in the pool tank together with the source water concentrations for each round of the water survey. The complete analytical results for the chemical analysis are presented in Appendix 5.

2.4.2.1 Trihalomethane Concentrations

The average total THM concentrations within the pool water are shown in Figure 2-8. The maximum and minimum concentrations recorded in the samples are represented by the vertical error bars. The source water concentration is also
Water Quality Considerations for a Healthy Pool

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes

Pool guidance recommends a maximum total THM concentration of 100 µg/l to minimise health hazards (PWTAG 2009).

Figure 2-8 - Total THM concentrations for pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011.

The presence of THMs in the pool water was further broken down into the 10 individual compounds. The average profile of the THMs identified in the water samples throughout the water survey is shown in Figure 2-9. Six of the THMs (benzene, carbon tetrachloride, dichloroethane, tetrachloroethane, trichloroethane and trichloroethene) were not found to be present within the water samples above the detection limits. The most significant THM present in the water samples was found to be chloroform with bromodichloromethane and dibromochloromethane contributing most of the remainder. A small proportion of bromoform was also identified in the source water.

Figure 2-9 - Average THM composition in A) the 231 pool water samples and B) the 21 source water samples taken during the water survey
2.4.2.2 Dissolved Metal Concentrations

The analysis identified that aluminium and calcium were the major metals present in all the water samples taken from the pool tank and the treatment system. The average pool water concentrations of aluminium and calcium are shown in Figure 2-10 and Figure 2-11 respectively. The current recommendation for the maximum calcium concentration in pool water is 75 mg/l (PWTAG 2009). The shallow pool samples were also found to contain trace amounts of iron. Iron was found above detection limits in the deep pool water samples and the treatment system samples. Figure 2-12 shows the average of the seven shallow water samples together with the source water iron concentrations. Occasional trace amounts of lead, copper and zinc were identified in some of the treatment system samples. These metals were identified more consistently in the source water samples. Figure 2-13 shows the concentrations of metals in the source water samples together with the average concentrations over the water survey. Manganese was not identified above the detection limit in any of the water samples.

![Figure 2-10](image)

**Figure 2-10 - aluminium concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011**
Water Quality Considerations for a Healthy Pool

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes

Figure 2-11 - Calcium concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011

Figure 2-12 - Iron concentration in shallow pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011

Figure 2-13 - Metal concentrations for source water samples taken on each sampling date during the study running from April 2010 to September 2011
2.4.2.3 Physical Chemistry

The alkalinity of the pool water and the source water is shown in Figure 2-14. Current guidance recommends that pool water is maintained with an alkalinity of between 80 and 200 mg/l CaCO₃ (PWTAG 2009). This range is also indicated in Figure 2-14 for comparison. Similarly the calcium hardness of the pool water and the source water is shown together with the recommended target range, 75 to 150 mg/l CaCO₃, in Figure 2-15 (PWTAG 2009).

Figure 2-14 - Alkalinity of pool water and source water samples taken on each sampling date during the study running from April 2010 to September 2011

Figure 2-15 – Calcium carbonate concentrations in pool and source water samples taken on each date in the study running from April 2010 to September 2011

The pH of the pool water and the source water is shown in Figure 2-16. There are two ranges shown in this figure. The first is the recommended target range for pool water, 7.2 to 7.4, whilst a secondary acceptable range, 7.4 to 7.8, is also shown (PWTAG 2009). Figure 2-17 shows the conductivity of the pool water and the source water.
water. The current guidance for pool water includes two different guides for a conductivity limit. It recommends a maximum conductivity of 4250µs/cm however it also recommends that pool water TDS should not be greater than 1000ppm above the source water value (PWTAG 2009). Calculating TDS directly through gravimetric methods are time consuming and therefore TDS is often calculated through the relationship in Equation 2-2, where \( F_c \) is the conductivity conversion factor (Lovibond 2010). A conversion factor of 0.7 is recommended for swimming pool applications.

TDS (ppm) = \( F_c \times \text{Conductivity (µs/cm)} \)  

**Equation 2-2**

Based on this relationship and the average source water conductivity of 450µs/cm, a maximum pool water conductivity of 1880 \( \mu \)s/cm would be recommended at Surrey Sports Park. This lower limit is shown in Figure 2-17. The turbidity of the samples was also measured. However, more than half of the samples fell below the detection limit of 0.09 NTU and less than 15% of samples exceeding 0.1 NTU. The maximum turbidity recorded was 0.38 NTU which is well below the advised limit of 0.5 NTU. Similarly, none of the samples were found to have any distinguishable colouration.

![Figure 2-16 - pH of pool water and source water samples taken on each sampling date during the study running from April 2010 to September 2011](image)
Water Quality Considerations for a Healthy Pool

2.4.2.4 Other Parameters

No bromide was found above the detection limit of 0.4 mg/l in any of the water samples taken from the swimming pool, its treatment plant or the source water in the first phase of sampling. Traces of bromide were identified in the source water in the second phase of sampling as the detection limit had reduced to 0.004 mg/l. No ammoniacal nitrogen, ammonium as NH₄ or nitrite was identified at concentrations above the detection limits in any of the water samples in the survey. The average bromate concentration of samples taken from the pool tank is shown together with the source water concentration in Figure 2-18. The pool water quality guidance currently recommends that the water should not have a bromate concentration greater than 10 µg/l because of its carcinogenic properties (PWTAG 2009). This is indicated on the figure for comparison.
The chlorate and chloride concentrations of the pool water and source water are shown in Figure 2-19 and Figure 2-20 respectively. The guidance recommends that pool water contains less than 3 mg/l to prevent children from becoming ill following the ingestion of pool water (PWTAG 2009). Unlike chlorate, chloride does not pose a health risk to the bathers and therefore currently no maximum limits are recommended in the pool guidance. Similarly, there are no recommendations in relation to the acceptable range of nitrate, shown in Figure 2-21. The maximum recommended sulphate concentration is 360 mg/l SO$_4$ (PWTAG 2009). The sulphate concentrations recorded in the water survey were significantly lower than this and are shown in Figure 2-22. The final two parameters measured in the water survey were the total oxidised nitrogen (TON) and the total organic carbon (TOC) content. These results are shown in Figure 2-23 and Figure 2-24 respectively. The current guidance recommends a maximum TON concentration of 1 mg/l (PWTAG 2009).
Water Quality Considerations for a Healthy Pool

Figure 2-21 - Nitrate concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011

Figure 2-22 - Sulphate concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011

Figure 2-23 - TON concentrations in pool and source water samples taken on each sampling date in the study running from April 2010 to September 2011
2.4.3 Field Measurement Results

A few parameters can only be measured accurately onsite because of their tendency to change during sample storage. These are the water temperature, the free chlorine concentration and the combined chlorine concentration. The temperature of the pool water and the source water is shown in Figure 2-25. The pool at Surrey Sports Park was operated at a target temperature of 28°C during the survey period.

The free chlorine concentration of the pool water is an important parameter to determine the effectiveness at which microbial pathogens can be deactivated. It is recommended that the free chlorine concentration should be greater than 0.5mg/l but less than 2mg/l to avoid swimmers experiencing skin and eye irritations (PWTAG 2009). The pool at Surrey Sports Park was operating at a target free
chlorine concentration of 1mg/l during the study period. The free chlorine concentrations are shown in Figure 2-26.

Figure 2-26 - Free chlorine concentrations in pool and source water measured on each sampling date in the study running from April 2010 to September 2011

The combined chlorine concentrations are shown in Figure 2-27. The current guidance recommends that the concentration of combined chlorine should be less than half the concentration of the free chlorine concentration (PWTAG 2009). Therefore for the Surrey Sports Park pool a maximum of 0.5mg/l is recommended during the survey period.

Figure 2-27 - Combined chlorine concentrations in pool and source water measured on each date in the study running from April 2010 to September 2011

The onsite measurements of pH, alkalinity and calcium hardness were also undertaken to provide comparison with the analysis undertaken by the Thames Water laboratory. The field measurements for pH, alkalinity and calcium hardness taken using the portable photometer are shown in Figure 2-28, Figure 2-29 and Figure 2-30 respectively. Unfortunately, as a result of a problem with the supply of
Water Quality Considerations for a Healthy Pool

reagents, the alkalinity and calcium hardness could not be measured onsite for the second half of the first survey period. Similarly, the measurement of conductivity onsite was not possible for the majority of the survey because of an irresolvable error with the equipment that caused it to lose calibration. The conductivity measurements that were collected are shown in Figure 2-31.

Figure 2-28 - Field measurements of pH measured on each sampling date during the study running from April 2010 to September 2011

Figure 2-29 - Field measurements of alkalinity measured on each sampling date during the study running from April 2010 to September 2011
2.4.4 Water Balance

The balance of water is an indication of the tendency of water to be corrosive or scale forming. The Langelier Saturation Index is a commonly used measure for the balance of water and is calculated using the alkalinity, pH, calcium hardness, conductivity and temperature of the water and the relationship shown previously in Equation 2-1. The Langelier Saturation Index for the water samples was calculated retrospectively using the results of the Thames Water analysis and is shown in Figure 2-32. It is recommended that the water should be as close to zero as possible (PWTAG 2009).
Figure 2-32 - Langelier saturation index for pool and source water calculated on each sampling date in the study running from April 2010 to September 2011.
2.5 Discussion

The ability to collect water samples at the commissioning stage prior to the opening of the facility to the public, together with access to the complete operational records, enable the transient properties of a pool environment to be studied in greater detail than had been possible in previously published studies such as Chu and Nieuwenhuijsen (2002), Fantuzzi et al. (2001) and Zwiener et al. (2007). The broad nature of the water survey undertaken enabled a number of the characteristics of swimming pool water to be examined. The following sections discuss the results presented in Section 2.4.

2.5.1 Microbiological Characteristics

The majority of samples taken were found to be under the limits recommended by PWTAG (2009) for the four microbiological indicators analysed in the study. The absence of coliforms in the majority of water samples agrees with the findings of the microbiological survey undertaken by Papadopolou et al. (2008).

During the early stages of the water survey, high concentrations of *Pseudomonas aeruginosa* were identified in the sample from the automated dosing controller, Location H in Figure 2-4. The presence of high concentrations of microbiological pathogens in the location of the sensors has the potential to affect the effectiveness of the automated control systems as the chlorine concentrations may be artificially reduced. The high concentrations did not return following the cleaning of the unit therefore it indicates that the initial colony was a commissioning issue rather than an operational one. Aside from this contamination issue, positive identification of *Pseudomonas aeruginosa* was only recorded within the shallow water samples. This supports the common assumption that the main source of *Pseudomonas aeruginosa* in pool water is through the shedding from the pool users as bathers rarely swim in the deep parts of the pool. The absence of *Pseudomonas aeruginosa* in the water samples taken from the plant room indicates that the disinfection methods used at the pool are working effectively. The range of *Pseudomonas aeruginosa* concentrations in the pool water samples of 0 to 24 cfu/100ml with a mean value of 0.5 cfu/100ml is similar to those published by Papadopolou et al. (2008) but is higher than those found by Martins et al. (1995). The surveys by Martins et al. (1995) and Papadopolou et al. (2008) both identified that *Staphylococcus aureus* was present in greater concentrations than *Pseudomonas aeruginosa* therefore it is suggested that future samples are also analysed for *Staphylococcus aureus*.

The TVC concentrations ranged from 0 to 42 cfu/ml and had a mean value of 1.6 cfu/ml. This is greater than the range identified by Papadopolou et al. (2008) but
Water Quality Considerations for a Healthy Pool

much less than the findings of Martins et al. (1995). The standard deviation of the TVC concentrations in each sampling round varied from as low as 0.5 cfu/ml to a maximum of 11.6 cfu/ml. This variability amongst samples taken from within the pool tank is significant when compared to the recommended limit of 10 cfu/ml. It also indicates that a single sample of pool water, as undertaken in the second phase of the water survey, may not give an accurate representation of the microbiological characteristics of the pool water.

2.5.2 Chemical Characteristics

The current industry focus in relation to pool water quality is on the presence of THMs and other DBPs. THM concentrations were seen to rise sharply soon after commissioning before returning to a relatively stable average concentration of 50 µg/l (standard deviation = 4.8 µg/l) after approximately 10 weeks of operation. This final concentration agrees with the study by Fantuzzi et. al (2001) and is at the lower end of the range identified in the water survey undertaken by Chu and Nieuwenhuijsen (2002). Chloroform accounted for 95.6% of the THM concentration in the pool water with the remainder being made up of bromodichloromethane (3.9%) and dibromochloromethane (0.5%). This is very similar breakdown to that published by Chu and Nieuwenhuijsen (2002). The peak value for THMs of 142 µg/l occurred 4 weeks after commissioning and is likely to be as a result of reactions between the disinfectant and residues in the pool remaining from the construction process.

A number of other DBPs were found to accumulate rapidly during the first phase of the water survey. The most significant increases between April and October 2010 were in relation to the concentration of bromate, chlorate and chlorides in the pool water. These parameters were found to increase by 620%, 775% and 319% respectively. A smaller, but still significant, increase was observed in the concentration of nitrates (70%) whilst the concentration of Sulphates was found to remain fairly constant throughout with an average of 62.7 mg/l (standard deviation = 1.1 mg/l). The presence of bromate above the incoming mains water level was not expected as the pool was not using any bromine based products. It is assumed that the source of the bromate is from contamination within the chemicals used at the facility however additional work is needed to confirm this. The accumulation of the other substances was more expected.

The TOC content of the swimming pool water appeared to follow a similar trend to that observed in the THM analysis with a sharp increase during the first couple of months after commissioning before declining to a stable average concentration of 1.6 mg/l (standard deviation = 0.11 mg/l). The Spearman’s Rank Correlation and the
Pearson’s Product-moment Correlation were used to evaluate the relationship between the two parameters and values of 0.84 and 0.92 were calculated respectively. This confirms that there is a strong positive and linear correlation between the TOC concentration and the THM concentration of the pool water. This supports recent research by Beleza et al. (2011) and Keuten et al. (2011a) that has also suggested that managing the concentration of TOC in the pool water could assist in ensuring healthy swimming environments are achieved.

The concentrations of aluminium in the pool water were observed to be very volatile during the initial water survey. This is considered to be associated with issues with the coagulant dosing system that were recorded by the facility operators during this period. The calcium concentrations were observed to increase in line with the hardness of the water, with the parameters increasing by 28% and 32% respectively during the first phase of the water survey. The pH of the water, although always within acceptable limits, was found to be erratic. The low average alkalinity levels of 34.6 mg/l CaCO$_3$ (standard deviation = 9.2 mg/l CaCO$_3$) indicates that a lack of buffering capacity in the pool water could be the basis for the observed fluctuation in pH. In addition to the fluctuations in pH, a difference was observed between the onsite and laboratory analysed values. The pH measured onsite was 0.12 lower on average (standard deviation = 0.09) than that measured at the Thames Water laboratory. Similarly, the onsite hardness measurements were lower than the laboratory measurements.

The results for the parameters measured onsite, with the exception of temperature, also exhibited large variation within each sampling round. This is in stark contrast to the samples that were sent to the Thames Water laboratory, which showed less variation. The difference is likely to be associated with inaccuracies in the undertaking of the field measurements. These inaccuracies are discussed in more detail within Chapter 4 which focuses on the operational aspects of the research project. The variation in the field measurements means that it is not possible to draw strong conclusions about the concentration of chloramine in the pool water. An average chloramine concentration of 0.17 mg/l was recorded however the variation was fairly large (standard deviation = 0.12 mg/l).

The analysis undertaken by Thames Water showed that the water quality parameters, with the exception of iron concentrations, varied more between sampling rounds than between sampling locations, represented by the error bars in the figures in Section 2.4. This observation was the basis for reducing the number of samples taken during the second sampling phase. In general, the parameters were observed to be more stable during the second phase of the water survey. A summary of the analysis of the sample data from the second phase is presented in
Aside from examining spatial and temporal variations in the water quality parameters within the pool tank, the samples before and after each unit operation were analysed to see if any of the major treatment stages had a measurable effect on the water quality. Following the initial period of operation, the THM concentration following the UV unit was found to be 6.2 µg/l lower on average than in the water entering the process. However, the low number of samples and the occurrence of some samples showing an increase in THM concentration mean it is not possible to draw firm conclusions on whether UV is effective at removing THMs from pool water based on these results alone. A similar uncertainty was presented by Kristensen et al. (2009). Similarly, the very small average reduction of 0.7 µg/l observed in the bromate concentration across the UV unit may not be as a result of the UV irradiation, however, the degradation of bromate in this way has been reported by Bensalah et al. (2013). An increase in the aluminium concentration was
identified between the water leaving the pool and the water entering the sand filters. This was as expected as the facility uses poly-aluminium chloride as a coagulant and this is injected between these two sampling locations. No other identifiable effects of the various treatment processes were observable in the results of the water survey.

2.5.3 Source Water

The analysis of the source water samples was more straightforward than for the pool water samples. The source water parameters were found to be fairly constant throughout the whole of the water survey, as can be seen in the figures in Section 2.4. The only exceptions to this are the copper concentration and the temperature of the source water. The copper concentration was found to range from 0 to 97 µg/l with an average of 20.9 µg/l (standard deviation = 22.2 µg/l). The temperature of the incoming water was observed to fluctuate by as much as 10°C during the water survey. The water temperature is seasonal with the lowest temperature, 8.8°C, recorded in March 2011 and the highest temperature, 18.8°C, recorded in August 2011. Rapid changes in the mains water temperature are unlikely, however, as a result of the limited number of samples and the absence of samples from November through to February, the temperature fluctuations could potentially be greater than observed in this study.

A summary of the recorded water quality parameters for the source water is shown in Table 2-8. Only parameters measured above the detection limits of the analytical methods are shown.
### Table 2-8 - Summary of water quality parameters for the source water between April 2010 and September 2011

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Concentration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.0 µg/l</td>
<td>7.0 µg/l</td>
</tr>
<tr>
<td>Bromide</td>
<td>8.3 µg/l</td>
<td>2.5 µg/l</td>
</tr>
<tr>
<td>Bromodichloromethane</td>
<td>8.8 µg/l</td>
<td>2.2 µg/l</td>
</tr>
<tr>
<td>Bromoform</td>
<td>2.3 µg/l</td>
<td>0.6 µg/l</td>
</tr>
<tr>
<td>Calcium</td>
<td>78.5 mg/l</td>
<td>5.8 mg/l</td>
</tr>
<tr>
<td>Chlorate</td>
<td>0.13 mg/l</td>
<td>0.06 mg/l</td>
</tr>
<tr>
<td>Chloride</td>
<td>36.9 mg/l</td>
<td>2.5 mg/l</td>
</tr>
<tr>
<td>Chloroform</td>
<td>13.7 µg/l</td>
<td>3.1 µg/l</td>
</tr>
<tr>
<td>Copper</td>
<td>20.9 µg/l</td>
<td>22.2 µg/l</td>
</tr>
<tr>
<td>Dibromochloromethane</td>
<td>7.2 µg/l</td>
<td>1.3 µg/l</td>
</tr>
<tr>
<td>Iron</td>
<td>8.0 µg/l</td>
<td>9.5 µg/l</td>
</tr>
<tr>
<td>Lead</td>
<td>1.7 µg/l</td>
<td>3.1 µg/l</td>
</tr>
<tr>
<td>Nitrate</td>
<td>21.4 mg/l</td>
<td>1.2 mg/l</td>
</tr>
<tr>
<td>Sulphate</td>
<td>29.8 mg/l</td>
<td>3.1 mg/l</td>
</tr>
<tr>
<td>THMs</td>
<td>31.9 µg/l</td>
<td>6.3 µg/l</td>
</tr>
<tr>
<td>TOC</td>
<td>1.2 mg/l</td>
<td>0.3 mg/l</td>
</tr>
<tr>
<td>TON</td>
<td>4.8 mg/l</td>
<td>0.3 mg/l</td>
</tr>
<tr>
<td>Zinc</td>
<td>9.4 µg/l</td>
<td>14.4 µg/l</td>
</tr>
<tr>
<td>TVC</td>
<td>1.25 cfu/ml</td>
<td>2.5 cfu/ml</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>143.6 mg/l CaCO₃</td>
<td>12.9 mg/l CaCO₃</td>
</tr>
<tr>
<td>Hardness</td>
<td>449.2 mg/l CaCO₃</td>
<td>18.1 mg/l CaCO₃</td>
</tr>
<tr>
<td>pH</td>
<td>7.56</td>
<td>0.17</td>
</tr>
<tr>
<td>Temperature</td>
<td>15.2 °C</td>
<td>2.8 °C</td>
</tr>
<tr>
<td>Langelier Index</td>
<td>-0.04</td>
<td>0.2</td>
</tr>
</tbody>
</table>
2.6 Conclusions

The water survey undertaken as part of this research project provided a broad assessment of the water quality of a fully operational pool for the first 20 months following commissioning. The study identified that there is a period of time before the pool water at a facility stabilises. In the case of the Surrey Sports Park, the pool water quality did not stabilise for approximately 10 months following commissioning. The subsequent stable results provide baseline pool water quality which can enable the effects of technical or managerial changes at the facility to be assessed.

The concentration of THMs, the DBP which is the subject of industry focus at present, was found to be approximately one third of the concentration of chloramine in the pool water. The survey identified that chloroform was the most prevalent THM in the swimming pool water which is in agreement with the previous studies undertaken on chlorinated swimming pools. THM levels recorded in the present survey were at the bottom end of the range identified in previous studies. This indicates that the inclusion of UV within the treatment process may help to reduce THM concentrations in swimming pool water, however, the survey did not provide any strong evidence to show this. The concentration of THMs was found to be strongly correlated to the concentration of TOC in the pool water and therefore suggests that control of TOC is vital to minimising the risks associated with THMs. This is in agreement with the recommendations made recently by Beleza et al. (2011) and Keuten et al. (2011a).

It was also shown that the variation in the chemical water quality parameters was greater between sample date than between sample location. This indicates that there are no substantial hydraulic issues with the facility in this study and that the pool tank is essentially well mixed and uniform. The monitoring of these parameters with a single sample location is therefore appropriate. The examination of microbiological indicators, however, contradicts this as the variation between samples taken on the same date was significant. This survey highlighted the difficulty in obtaining a representative sample for microbiological analysis.

The water survey highlighted that the majority of parameters associated with health risks are currently within the limits indicated in current swimming pool guidance. The exceptions to this were bromate and chlorate which are both present at concentrations far exceeding the recommended maximum limit. Further investigation into the source of these substances and the potential remedial options needs to be investigated further. In addition, a number of parameters associated with potential operational risks have been observed to fall outside of currently
recommended ranges. These include the alkalinity, hardness and chloride concentration in the pool water. The current status of these parameters indicates that there is potential for damage to the equipment at the facility to occur. Further investigation into the reasons for the parameters falling outside of the acceptable range and potential remedial options also needs to be investigated further.

The source water at the Surrey Sports Park was found to be fairly stable in terms of composition. However, noteworthy variations in temperature were identified. The implications of composition and temperature on the current operations at Surrey Sports Park, including the requirement for pre-treatment options, can now be examined.

Water surveys published since the undertaking of this study have shown that even broader surveys may be required to capture all of the risks associated with the treatment of pool water. Richardson et al. (2010), Santos (2012) and Silva et al. (2011) have all identified the presence of DBPs that were not included in the scope of this project. It is recommended that future water surveys broaden the scope to include haloacetal acids, haloacetonitriles, haloketones and haloaldehydes.
Water Quality Considerations for a Healthy Pool

2.7 References


Water Quality Considerations for a Healthy Pool


Water Quality Considerations for a Healthy Pool


Water Quality Considerations for a Healthy Pool


Water Quality Considerations for a Healthy Pool


Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes


Water Quality Considerations for a Healthy Pool


Water Quality Considerations for a Healthy Pool


SSINA (2001) *Designer handbook: Stainless steel in water handling and delivery systems*, The Specialty Steel Industry of North America, USA

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes 2-58
Water Quality Considerations for a Healthy Pool

Thames Water (2010) Approved procedure for drinking water sampling, Thames Water


Water Quality Considerations for a Healthy Pool


Chapter 3 – An Assessment of the Impacts of Different Types of Activity on Swimming Pool Water Quality

3.1 Introduction

The design of swimming facilities, water treatment plants and management procedures is dependent on the nature of the contaminants that are present in the water. A large number of these substances are introduced to the pool water by the users as discussed in Chapter 2. The recent drive to increase the participation in swimming-related activities within the UK has the potential to exacerbate any issues regarding user-related contamination and therefore it is becoming increasingly important that this topic is well understood. A review of published literature was undertaken to identify the current knowledge base available in relation to the impacts of user behaviour and introduction of bather-derived contaminants on the swimming pool environment. The review is presented in Section 3.2.

To date, UK swimming pool guidance has not explicitly differentiated between the types of pool users and therefore operators have tended to apply generic water management procedures for all activities that take place in the pool. The current guidance does imply that different user groups may present different water quality challenges by recommending that learner pools are operated with a shorter turn-over period to adult pools (PWTAG 2009). Modern pools are being used by an increasingly diverse range of users for many different types of activity. It is therefore important to assess whether the largely activity-independent recommendations within existing UK guidance is appropriate for modern pool use. This research project examined the link between user groups and pool water quality through undertaking an activity-based water survey at the Surrey Sports Park. The results of the activity survey are presented in Section 3.3.

A discussion of the results of the activity survey is presented in Section 3.4. The findings of the surveys are subsequently used to generate recommendations for the swimming pool industry in relation to user education requirements, operator responsibilities and further research needs.
3.2 Literature Review

The most effective way to manage the concentration of disinfection by-products (DBP) in swimming pool water is to prevent them from being formed in the first place. The only way to do this is to remove one of the reacting species, in most cases either the disinfectant or the precursors. The use of disinfectants is essential to maintain the microbiological safety of the pool water, however, the addition of alternative technologies, such as UV, can enable the concentration of disinfectant required to be reduced (PWTAG 2009). This would in turn reduce the rate of DBP formation. Karanfil et al. (2008) reported that the use of technologies such as UV still presents the potential for the formation of complex and potentially toxic DBPs. It is therefore more effective to reduce the concentration of DBP precursors in the water.

3.2.1 Disinfection By-Product Precursor Prevention

Encouraging good pre-swim hygiene routines and using clean source water have been recommended by Liviac et al. (2010) as effective methods to prevent contaminants from being introduced to the pool water. Lakind et al. (2010) showed that taking a short shower prior to entering the pool can reduce the amount of precursors added by the bather by up to 60%. Judd and Bullock (2003) estimated that 50ml of urine and 200ml of sweat is introduced to the water on average by a bather during a single visit to a swimming pool. A more in-depth study of bather-derived contaminants was undertaken by Keuten et al. (2011). In contrast to the studies by Lakind et al. (2010) and Liviac et al. (2010) which grouped all contaminants together, the study by Keuten et al. (2011, 2012) defined three types of bather-derived DBP precursors: Initial, Continuous and Incidental. The initial precursors were defined as the substances that are introduced to the water when the bather first enters the pool water. The continuous precursors were defined as the substances that cannot be prevented from being introduced into the pool as a direct result of the activity. Incidental precursors were defined as the substances introduced to the water following the intentional or accidental occurrence of preventable actions of the bather. The research by Keuten et al. (2011, 2012) indicated that less than half of the contaminant loading from a bather was associated with exercise-related continuous precursors such as sweat. It also observed that a 30-second shower could reduce the amount of initial precursors by up to 80% with a maximum reduction of 90% achievable after approximately 60 seconds.

The incidental precursors are associated with a wide range of bather actions including urination, faecal releases, vomiting and excretion of saliva (Keuten et al. ...
2011). These actions may take place accidentally or intentionally. It is advised that bathers go to the toilet prior to swimming and avoid swimming when ill to reduce the risk of accidental incidents from taking place (PWTAG 2009). The occurrence of intentional excretions is hard to prevent as it is reliant on the behaviours of the pool users. Conversations with the Surrey Sports Park pool manager revealed a belief that the behaviours exhibited by users vary and are influenced by culture within the group of users (Mansi 2010). For example, the practice of spitting into the overflow channels is fairly common among competitive athletes that are training for long periods of time. Although the use of pre-swim showers can reduce the amount of initial precursors entering the pool and good behaviours can reduce the amount of incidental precursors entering the pool, the existence of continuous precursors means that there is a limit to which DBP formation can be prevented.

3.2.2 Relationship between Pool Use and Water Quality

The variability in the number of bathers using a facility, known as the Bather Load, means that there is the potential for impacts on the water quality to also vary. UK guidance currently addresses this issue by recommending that water exchange rates are linked to bather numbers (PWTAG 2009). However, this assumes that the initial precursors are the dominant type and that activity type and duration are insignificant. Although a number of studies have been undertaken to evaluate the presence of DBPs within pool water and the potential for precursors to generate DBPs (Li and Blatchley 2007; Kim et al. 2002), there has been little research undertaken to attempt to relate the presence of precursors or DBPs to the number or type of bathers using the pool. Poor access to operational records has been presumed as the reason for this gap in knowledge (PWTAG 2010). Chu and Nieuwenhuijsen (2002) and Thacker and Nitnaware (2003) reported a positive correlation between the amount of organic carbon present in the water and the number of bathers. Similarly Zwiener et al. (2007) showed a positive correlation between the concentration of THMs in the water and the number of bathers using a facility. A real-time study by Kristensen et al. (2009) showed that THM concentrations in the water decreased whilst the pool was open to users and then increased again during the closed hours overnight. Kristensen et al. (2009) proposed that this could be as a result of increased volatilisation of THMs linked to increased water agitation during use. This study highlighted the importance for short-term variations to be considered in addition to the longer-term trends identified within swimming pool surveys like the one discussed in the previous chapter.
3.3 Surrey Sports Park Activity Survey

3.3.1 Scope

The study by Kristensen et al. (2009) showed the importance of evaluating water quality on a short timescale. The purpose of the Surrey Sports Park Activity Survey was to assess short-term variation in water quality within an operational pool and to examine the relationships between bather numbers, activity type and water quality. Fourteen different activities take place in a typical week at the Surrey Sports Park. Of these, four activities, including Sub Aqua and Adult Learn to Swim sessions, were not assessed because of either very low expected bather loads (<5 people in the pool) or equipment availability issues. The ten activities that were examined are listed in Table 3-1 together with their durations. In addition to the scheduled activities, it was considered that the periods when sections of the pool were closed should also be examined to establish the effects of rest periods. The canoe club session on the 16th November 2010 was used to trial the set-up of the equipment as preparation for the main study on 18th November 2010.

Table 3-1 - List of activities included in the Surrey Sports Park activity survey

<table>
<thead>
<tr>
<th>Day of Assessment</th>
<th>Activity</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuesday</td>
<td>Canoe Club</td>
<td>1.5 hours</td>
</tr>
<tr>
<td>Thursday</td>
<td>50m Lane Swimming – Public</td>
<td>4 hours</td>
</tr>
<tr>
<td></td>
<td>50m Lane Swimming – Competitive</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td>25m Lane Swimming – Public</td>
<td>8.5 hours</td>
</tr>
<tr>
<td></td>
<td>25m Lane Swimming – Competitive</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td>Aqua Fitness – Zumba</td>
<td>0.75 hours</td>
</tr>
<tr>
<td></td>
<td>Aqua Fitness – Power Workout</td>
<td>0.75 hours</td>
</tr>
<tr>
<td></td>
<td>School Swimming</td>
<td>0.5 hours</td>
</tr>
<tr>
<td></td>
<td>Junior Learn to Swim</td>
<td>2.5 hours</td>
</tr>
<tr>
<td></td>
<td>Water Polo</td>
<td>1.5 hours</td>
</tr>
<tr>
<td></td>
<td>Rest Period</td>
<td>2 hours</td>
</tr>
</tbody>
</table>

The main study was conducted on a Thursday as the majority of activities took place on this day. In order to facilitate such a wide range of activities, the pool configuration was changed throughout the day by moving the traversable boom as well as the movable floor. Activities took place in different sections of the pool and therefore the water quality was monitored at locations A and D from the longitudinal water survey, shown in Figure 2-4. Table 3-2 shows the pool schedule for the day of the study and indicates which sample location was used to represent the various activities.
PWTAG (2009) suggest that an increase in bather load will increase the concentration of precursors in the water and therefore result in a reduction in the free chlorine available for disinfection and an increase in DBP concentrations, the combination of which would increase the health risks to bathers. This study consisted of monitoring pool water quality parameters before, during and after each of the activities. The water was monitored for the parameters used in the longitudinal water survey described in Chapter 2. In addition, observations of user behaviour were made during the study including a detailed record of the number of people in the pool during each activity and the number of people entering the pool without using the showers. In order to undertake the behavioural observations, the amount of time available for onsite sample analysis was limited. The field measurements on grab samples were therefore limited to free chlorine and combined chlorine measurements.

3.3.2 Methodology

Pool water grab samples were taken before, during and after each activity from the associated sampling point shown in Table 3-2. Samples were analysed for the parameters included in the longitudinal water survey. Microbiological and chemical analysis was undertaken by RCPEH and Thames Water analytical laboratories respectively. Both laboratories are accredited by UKAS. Onsite analysis of free and combined chlorine concentration was also undertaken using grab samples. The water samples were collected and analysed for the activity survey using the sampling and analytical methodologies used in the longitudinal water survey detailed in Chapter 2.

3.3.2.1 Real-time Water Monitoring

In addition to the grab samples, in-situ water monitoring was carried out using a pair of 6920DW sondes manufactured by YSI, shown in Figure 3-1. The sondes have been specifically developed for the monitoring of key parameters of drinking-water systems. They are capable of measuring and recording values for pH, conductivity, temperature and free chlorine. Each of the parameters is measured using dedicated
probes located within the sonde housing. They are powered using an internal power supply and the sampling rate is fully customisable. This allows them to be configured in advance and then deployed and left to monitor the water unattended. For this study, a sonde was placed in each of the sampling locations and was set to record measurements every 60 seconds during the study period. Prior to placing the sondes in the pool water each sensor was calibrated.

The free chlorine was measured using an amperometric free chlorine sensor. The probe was calibrated by measuring the current in a solution of known free chlorine concentration and adjusting the output accordingly. This was achieved by taking a grab sample and measuring the free chlorine concentration using a Palintest Pooltest 25 photometer and the DPD No.1 test reagent. The pH probe is a combination electrode consisting of a proton selective glass reservoir filled with buffer at approximately pH 7 and a reference electrode with a gelled electrolyte. The pH probe was calibrated using a 3-point procedure with solutions of known pH as recommended by the manufacturer. The pH measurement is affected by temperature and therefore the probe incorporates a thermistor to allow automatic adjustment. The thermistor exhibits a known variation in resistance with temperature changes and is factory set. The conductivity probe consists of four nickel electrodes that measures the voltage drop and converts it into a conductance value. The exact value of the conversion factor is automatically identified by the sonde during the calibration process using solutions of known conductivity.

![YSI Sonde](image)

**Figure 3-1 - YSI Sonde used for in-situ monitoring of pH, conductivity, temperature and free chlorine**
3.4 Results

3.4.1 Bather Loading

Bather load is considered to be a potentially significant factor on the quality of the water (Keuten 2012; PWTAG 2009). An increase in bather load is likely to result in the increased amount of unwanted material entering the pool. The instantaneous bather load for the pool varied greatly, ranging from a minimum of 2 to a peak of 63. The instantaneous and cumulative bather loads for each activity are shown in Table 3-3. An average value for the instantaneous bather load is given for those activities that either took place multiple times or on a continuous basis during the survey.

Table 3-3 - Cumulative and average instantaneous bather loads for each pool activity

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cumulative Bather Load</th>
<th>Instantaneous Bather Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canoe Club</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>50m Lane Swimming – Public</td>
<td>68</td>
<td>10 (σ = 3.9)</td>
</tr>
<tr>
<td>50m Lane Swimming – Competitive</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>25m Lane Swimming – Public</td>
<td>148</td>
<td>7 (σ = 3.4)</td>
</tr>
<tr>
<td>25m Lane Swimming – Competitive</td>
<td>49</td>
<td>24</td>
</tr>
<tr>
<td>Aqua Classes</td>
<td>24</td>
<td>12 (σ = 3)</td>
</tr>
<tr>
<td>School Swimming</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>Learn to Swim</td>
<td>85</td>
<td>17 (σ = 4.8)</td>
</tr>
<tr>
<td>Water Polo</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

Unlike the other activities, public swimming sessions are subject to varying demand throughout the day. The average instantaneous bather load quoted above does not present the complete picture. When the bather loading is plotted on a timeline it is possible to identify periods of low and high demand. The variability of public swim sessions can be seen in the location D data in Figure 3-2 between 6am and 7pm. The number of public swimmers peaked at three times during the day: 08:00 to 09:30, 12:00 to 13:00 and 17:00 to 19:00. The bather load in each of the monitoring locations is shown in Figure 3-2 together with the cumulative bather load.
3.4.2 Bather Behaviours

During the study, observations of bather habits were also documented as poor. Pre-swim hygiene is frequently quoted as a potential issue in the UK (PWTAG 2010). Each bather was monitored as they entered the pool hall and their use of the pre-swim showers was recorded. Table 3-4 shows a breakdown of the types of user that visited the pool during the study and the proportion of them that used the shower before entry.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cumulative Load</th>
<th>Bather Load</th>
<th>% Showered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canoe Club</td>
<td>20</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>Public Swimming</td>
<td>216</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>Swimming Club</td>
<td>60</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td>Aqua Classes</td>
<td>24</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>School Swimming</td>
<td>59</td>
<td>76%</td>
<td></td>
</tr>
<tr>
<td>Learn to Swim</td>
<td>85</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>Water Polo</td>
<td>24</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>488</td>
<td>54%</td>
<td></td>
</tr>
</tbody>
</table>

In addition to the monitoring of shower use, other general observations were recorded. The use of swimming hats and swimming costumes reserved for use in swimming pools appeared to vary with user group. They were very common amongst the swimming club, learn-to-swim and water polo club user groups, however, they were far less common amongst the other groups.

Other potential sources of contaminants were observed during some activities. Many of the activities involve the use of equipment such as swimming aids and canoes. These can potentially introduce contaminants into the water if they are not stored and cleaned appropriately. The canoe club at Surrey Sports Park are required to use different canoes in the pool from the ones they use for outdoor activities, however, the storage location and cleaning procedures followed was unknown.

A number of parents were observed escorting their children to poolside for the swimming lessons. Many of these did not remove their shoes resulting in the transfer of dirt through the showers and onto poolside. Similarly, the members of staff rotate roles during the day resulting in frequent movement between poolside and the rest of the facility including external court areas. Finally, the swimming instructors were observed to enter the pool without showering. As the instructors wear clothing during the lessons there is potential for these items to introduce contaminants to the water.
3.4.3 Chemical Analysis Results

The pool water parameters reported in Chapter 2 that did not exceed the detection limits in the longitudinal water survey were also not identified in this study. The remaining parameters were plotted on a timeline to enable any significant peaks to be identified.

3.4.3.1 Pollutant Indicators

Three of the parameters measured during the survey have been suggested as potential indicators for the level of pollutants present in the pool water (Keuten et al. 2012, Kim et al. 2002). The total organic carbon (TOC) and total oxidised nitrogen (TON) concentrations can indicate the presence of substances that commonly act as precursors. Similarly, chloride is a major constituent of sweat which is the predominant activity-related contaminant. The concentrations measured at locations A and D are shown in Figure 3-3 and Figure 3-4 respectively.

![Figure 3-3](image1.png)

*Figure 3-3 - Chloride, total organic carbon and total oxidised nitrogen concentrations in pool water at location A during the activity survey*

![Figure 3-4](image2.png)

*Figure 3-4 - Chloride, total organic carbon and total oxidised nitrogen concentrations in pool water at location D during the activity survey*
3.4.3.2 Disinfection By-Products

THMs are the primary disinfection by-products with health concerns found within chlorinated swimming pool water. Chloroform, bromodichloromethane (BDCM) and dibromochloromethane (DBCM) were identified in the pool water samples in order of decreasing concentration. The chloroform concentrations were found to fluctuate more than the other THMs throughout the study as can be seen in Figure 3-5 and Figure 3-6.

In addition to THMs, the concentrations of other DBPs of interest were also recorded. As detailed in Chapter 2, bromate and chlorate exposure is known to have health implications whilst sulphate can affect cement-based materials. The results of these parameters are shown in Figure 3-7 and Figure 3-8.
3.4.3.3 Dissolved Metals

The presence of dissolved metals in the pool water can influence the operational parameters of the water. The concentrations of the three metals identified above the detection limits of the analytical methods used, aluminium, calcium and iron, are shown in Figure 3-9 and Figure 3-10.
3.4.3.4 Operational Parameters

Alkalinity, calcium hardness and conductivity were identified in Chapter 2 as three of the key water quality parameters associated with swimming pool operation. The results of the Thames Water analysis of these parameters are shown in Figure 3-11 and Figure 3-12. The alkalinity and calcium hardness were fairly consistent throughout the study whilst an overall increase of 10 µS/cm was observed in the conductivity throughout the day.
3.4.4 Microbiological Analysis Results

A summary of the microbiological analysis results is shown in Table 3-5. The presence of coliforms was not observed in any of the water samples taken from the pool. This is in line with the current water quality recommendations and indicates that the treatment plant and facility staff are effectively managing any faecal contamination of the pool water that may have occurred. The results of *Ps. aeruginosa* and total viable count (TVC) for location A and location D are shown in Figure 3-13 and Figure 3-14 respectively.

**Table 3-5 - Summary of microbiological results of samples taken during the activity survey**

<table>
<thead>
<tr>
<th>Microbiological Indicator</th>
<th>Total Number of Samples</th>
<th>Number of Positive Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ps. aeruginosa</em></td>
<td>33</td>
<td>10</td>
</tr>
<tr>
<td><em>E. coli</em></td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>Total Coliforms</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>Total Viable Count</td>
<td>33</td>
<td>14</td>
</tr>
</tbody>
</table>

*Ps. aeruginosa* was identified in approximately one third of the water samples taken during the investigation. Only one sample was found to have a concentration above
the current recommended threshold value of 10 cfu/100ml (PWTAG 2009). This sample had been taken from location A shortly after the floor had been repositioned for the morning aqua class. The most significant increases were identified following the aqua class, school swimming and 25m swimming club sessions. As expected, a slightly higher proportion of samples were found to give a positive result for TVC than for *Ps. aeruginosa*. Increases in TVC were identified following many of the activities. The greatest increases were identified after the aqua class and 25m swimming club sessions. Smaller increases were identified following the school swimming and learn to swim sessions. Only one sample, following the first aqua fitness class, was found to have a concentration exceeding the recommended threshold value of 10 cfu/ml (PWTAG 2009).

3.4.5 Onsite Measurements

The results of the onsite measurements collected via both grab samples and in-situ sonde measurements are presented in this section.
3.4.5.1 Free and Combined Chlorine

The free chlorine concentrations collected using the amperometric sensor in the sonde is shown together with the photometric results of the grab samples from location A in Figure 3-15. The chlorine probe within the sonde installed at location D malfunctioned during the study and therefore only the grab sample results are shown in Figure 3-16. Although the frequency of the oscillations makes it impossible to identify any small scale effects of the activities, an increase in free chlorine concentration is visible from around 5pm in the location A sonde data. The combined chlorine results for location A and D are also shown on Figure 3-15 and Figure 3-16 respectively.

Figure 3-15 – Amperometric and photometric results of free and combined chlorine concentrations in the pool water during activities taking place in location A

Figure 3-16 - Photometric results of free and combined chlorine concentrations in the pool water during activities taking place in location D

3.4.5.2 pH

The pH of the pool water did not vary greatly during the activity survey however a slight increase was observed at both sampling locations during the day. The slight
elevation in pH can be seen in Figure 3-17 below. The pH fell back to the initial level after around 8pm.

![Figure 3-17 - In-situ pH measurements of the pool water during activities taking place in locations A and D during the survey](image)

**Figure 3-17** - In-situ pH measurements of the pool water during activities taking place in locations A and D during the survey

### 3.4.5.3 Conductivity

The specific conductivity at both locations is shown in Figure 3-18. An unknown issue occurred between 9:30am and 1:30pm resulting in large oscillations in the recorded values on both sondes. Following this period of oscillations, the conductivity appeared to be much steadier. The data suggests that an overall increase in the conductivity of between 10 µS/cm and 15 µS/cm. A rate of increase of this order is in line with the monthly increases in conductivity recorded during the longitudinal survey.

![Figure 3-18 – In-situ conductivity measurements of the pool water during activities taking place in locations A and D during the survey](image)

**Figure 3-18** – In-situ conductivity measurements of the pool water during activities taking place in locations A and D during the survey
3.4.5.4 Temperature

The water temperature at both locations during the study is shown in Figure 3-19. The water temperature appears to decrease at an average rate of 0.02 °C/hr throughout the day, however, a number of step changes can be seen in the data.

![Figure 3-19 – Pool water temperature measured at locations A and D during different activities at the Surrey Sports Park](image-url)
3.5 Discussion

3.5.1 Comparison of Grab Sample Results and In-situ Results

Two parameters, free chlorine and conductivity, were measured both in-situ and through grab sample analysis. The comparison of the data collected by the sonde with the results of grab sample analysis was undertaken. For conductivity, both methods highlighted an overall increase of 10 µS/cm across the day, however, differences were observed in the absolute values recorded by the two methods. The difference in absolute conductivity measurements, and the period of high oscillations in the sonde data, shows that there may be issues with the accuracy of calibrating the sondes used in this study compared to the equipment used within the UKAS accredited laboratory.

A similar calibration issue was observed with the small handheld conductivity probe used during the longitudinal survey. Similarly, the complexity of the calibration process for the free chlorine sensor used in the sonde could be responsible for the differences observed between the photometric and amperometric free chlorine measurements. The free chlorine sensor was found to easily lose calibration and resulted in the failure to accurately record the chlorine concentration at location D during the study. Discussions with the operators at Surrey Sports Park discovered that similar calibration issues had also occurred with the automated monitoring unit used to control the chemical dosing pumps during the commissioning of the facility.

Although the straightforward nature of photometric methods is less likely to be associated with complex calibration errors, the increased frequency of sampling achievable through the use of in-situ devices enables the water quality to be potentially analysed in greater detail and therefore generate opportunities for the more efficient application of water treatment processes. The use of automated controllers containing amperometric sensors is becoming more common in pool water treatment systems and this study shows that the calibration and continual validation of these units is essential to ensure they function correctly.

3.5.2 Effect of Bather Numbers on Water Quality

At present, guidance by PWTAG (2009) recommends that water management is adjusted with respect to the number of bathers using the facility. Two different bather loads are mentioned in the guidance (PWTAG 2009). The first is the total bather load which is the total number of people using the facility in a day. The second is the instantaneous bather load which is the number of people using the facility at a given time. It is assumed that each bather impacts the water equally and that a positive correlation exists between instantaneous bather number and the
Impact of Activities on Pool Water Quality

centration of contaminants in the water (PWTAG 2009). The concentration of combined chlorine at the end of each activity is plotted against the bather load in Figure 3-20. In addition, a linear trendline is shown for the activities taking place when the pool is in the 2x25m configuration. Reviewing the data in this way enabled the following observations to be made.

The data indicated that, in many cases, the amount of chloramine in the pool water is dependent on the number of bathers taking part in the activity. The 50m swimming sessions did not appear to impact the chloramine concentration of the water as greatly as the 25m activities. The canoe session also took place in the 50m pool configuration and showed a relatively high concentration of chloramine compared to the other 50m sessions. The combined chlorine concentration actually fell during the canoe session, however, the initial concentration was very high as the session followed a very busy 25m swimming club session. This high initial concentration may have influenced the concentration during the canoe session.

A few activities can be seen to deviate significantly from the overall trendline. These include the 25m swimming club sessions, the aqua fitness session and the water polo session. In each of these cases, the concentration of chloramine was far greater than the trend indicates would be expected for the associated bather load. This shows that these activities have a greater impact on the water quality than other activities and suggests that other factors aside from the number of bathers may be influencing the water quality.

![Figure 3-20 - Combined chlorine concentration at the end of each indicated activity plotted against the total activity bather load](image-url)
The positive trend between bather numbers and concentration was not observed in the measurements of the other monitored pollutant indicators. This could be partly as a result of the composite nature of these indicators and therefore their concentration is dependent on a wide range of substances that could include those from non-bather-related sources. Small increases in TON and TOC (<5%) were observed between the sample collected at the start of the session and the sample collected 30 minutes into the session for many activities. However, in the majority of cases the increase was not found to persist to the end of the session resulting in no clear correlation between total bather load and the concentration of TOC or TON. This indicates that the changes in TOC and TON concentrations are most likely associated precursors introduced by the bathers as they enter the pool, known as initial precursors (Keuten et al. 2011). Similarly, no clear correlation can be identified between the total bather load and the THM concentration as shown in Figure 3-21. This is in agreement with the findings of Erdinger and Mashcer (2011).

Figure 3-21 – Total THM concentration at the end of each indicated activity plotted against the total activity bather load

There were also large variations throughout the day with THM concentrations ranging from 36.6 µg/l to 69.5 µg/l. A potential reason for the fluctuation is the high volatility of the chloroform making the accumulation of chloroform in the pool water less likely than for monochloramine (Stottmeister and Voigt 2006). The amount of water agitation could be an important factor associated with the volatilisation of THMs from the water. The amount of agitation is likely to be closely
related to the number of bathers in the pool and therefore the effect of instantaneous bather load on THMs was investigated.

The instantaneous bather load was fairly consistent during the activities with the exception of the public swimming sessions which had clear peak periods which coincided with demand for pre-work, lunchtime and post-work swimming. The instantaneous bather loads shown in Table 3-3 were used in the analysis. The fairly similar instantaneous bather loads of many of the activities meant that only a semi-quantitative assessment could be undertaken. All of the activities had a relatively low instantaneous bather load, from 2 to 63 bathers, compared to the designed maximum instantaneous bather load for the facility of 303 bathers (SSP 2010).

The data collected during the survey did not exhibit any strong evidence for a correlation between the instantaneous bather load and the THM concentration, however, it was observed that samples exceeding 50 µg/l only occurred during periods with very low (<10) instantaneous bather loads. The peak concentration was identified at 6:30am shortly after the facility had opened. The instantaneous bather load up to this point had not exceeded 2 bathers and followed a long rest period overnight in which the water circulation is also reduced. Higher concentrations were also identified during both of the other rest periods during the day. During these periods there is minimal surface agitation except as a result of overflow at the deck-level drains. This supports the hypothesis that the rate of THM removal from the water is dependent on the turbulence within the pool tank.

The review of literature in relation to recreational water quality that was presented in Chapter 2 also identified that bathers are the primary source of microbial pathogens. It is therefore logical to expect the concentration of pathogens to be positively correlated with the number of bathers using the pool. Review of the results of microbiological analysis showed that peaks in *Ps. aeruginosa* concentrations were associated with the two activities with higher instantaneous bather loads, 25m swimming club and school swimming (Figure 3-13 and Figure 3-14). Peaks were also identified around both of the aqua fitness classes which were attended by lower numbers of bathers. This indicates that the consideration of other factors is also potentially important when assessing the impact of users on the water quality.

3.5.3 Effect of User Behaviour on Water Quality

In addition to the water sample results, the behaviour of the bathers was also observed and recorded. This included recording whether the bathers used the shower before entering the pool as well as general observations with respect to swimming attire, use of accessories and participant age. The data was gathered...
using visual observations only as there was insufficient time to conduct an interactive participant survey. These observations provide additional information that can be used to assess the impact of bathers on the water quality.

3.5.3.1 Uptake of Pre-swim Showering

There was variation between the different user groups with the learn-to-swim and aqua classes having the lowest proportion of people using the showers. In both cases, the users tended to arrive early for the session and wait on poolside until the activity is ready to start. The activity deliverers did not control the entry of the users and no request was made for the users to shower before taking part in the activity. The highest pre-swim shower rates were observed with the water polo and school groups. The school group was actively controlled at the point of entry to the pool hall by the group organiser. However, when the organiser had moved from the shower area to the poolside with the initial group of children there was no one encouraging the remainder to shower. It was also observed that a large number of people who did use the shower only did so for a matter of seconds and failed to wet their hair, which is believed to be a significant source of pollutants (Kim et al. 2002).

The aqua fitness sessions were observed to have the highest proportion of attendees not-showering before entering the pool. Only two of the attendees (8%) used the shower before taking part in the activity. The assessment of bather load dependency on water quality presented above identified that the aqua fitness sessions were associated with higher than expected concentrations of monochloramine as well as peaks in TVC and *Ps. aeruginosa*. Increases in TON concentration during the aqua fitness classes were also identified and shows that the attendees are introducing contaminants to the water. In addition to the analytical results, it was also observed that an oil-like sheen was identifiable on the pool water surface following the aqua class. This phenomenon was not identified during any of the other activities and is likely to be as a result of cosmetics washing off into the pool water. This indicates that the pre-swim habits of the users could be a significant contributor to the impact on water quality and supports the recommendation that bathers should be encouraged to shower before entering the pool.

Learn to swim attendees were the next most common participants to avoid showering before their session with 87%. However, the peaks in DBP and precursor concentrations observed during the aqua fitness classes were not replicated in the learn to swim results. Large differences between the two activities were observed including in participant age, swimming attire and pool configuration. The learn to swim attendees were significantly younger than those taking part in the aqua
fitness class. Young children tend to not to use as many cosmetics such as perfume, make-up and hair products compared to adults. This means there is likely to be fewer substances present with the potential to wash off in the pool water. In addition, the learn to swim group all wore swimming caps whilst none of the aqua fitness class attendees wore swimming caps. Swimming caps prevent the hair from being in contact with the pool water and therefore reduces the opportunity for DPBs to form or any residual hair products to enter the pool water. Finally the water depth for the learn to swim activity was much shallower than for the aqua fitness classes (0.75m vs 1.25m). As the circulation rate of water is maintained, reducing the water depth can potentially increase the water turnover rate. These differences could explain the reason why water quality appears to be less affected by the low uptake of pre-swim showers in the learn to swim session.

During the survey, a number of bathers, both those who had showered before entry and those who had not, were spoken to in order to give an indication to the reasons behind the observed actions. This ad-hoc questioning generated a range of responses from the bathers. Reasons for not showering beforehand included the following:

- They had showered in the morning
- Not wanting to get cold as they waited for the activity
- Showers were for washing the chlorine off
- They were late for the activity

Reasons for showering also ranged and included the following:

- Prevent dirt from entering pool water
- Makes getting into the pool less of a shock to the body
- Aids putting on equipment

This brief survey indicates that there is a wide range of awareness amongst the users of the pool. It supports the need for a more in-depth survey of user perception to enable the issues that need to be addressed to be identified and therefore determine appropriate strategies for improving the proportion of users using pre-swim showers. By doing this, the unnecessary initial loading bathers introduced to the pool water would be reduced and therefore the efficiency of the water treatment system would be increased.

3.5.3.2 Use of Accessories

The range of accessories used by each group was also observed during the study in order to develop an understanding of potential sources of contaminants. The
Impact of Activities on Pool Water Quality

accessories could be broadly categorised into three groups: Swimwear, Swimming Aids and Activity Equipment.

The swimwear used by the public swimmers, learn to swim participants and the school group varied widely. Both traditional style and modern style, tight fitting swimming costumes were used by some participants, however, a large number of participants were seen to wear leisure swimwear including bikinis and loose fitting shorts. The occasional participant was observed to wear a t-shirt whilst swimming for religious reasons. It was unknown whether the bathers used their swimwear for other activities such as open water swimming, sun-bathing or visiting the beach. Using the swimwear for these types of activities increases the risk of dirt and other contaminants being carried into the pool water. In addition, the use of swimming caps and goggles varied in each group with the exception of the learn to swim group in which all participants were required to wear swimming caps in order to differentiate between swimming ability. Some bathers were observed to use swimming aids including floats and resistance devices. These swimming aids were often taken straight from a bag before use and then put back in the bag immediately after use. No washing of the items either before or after was observed during this study. These swimming aids are potential sources of microbiological pathogens or other unwanted substances. The risk of contamination is likely to depend on how the items are stored and whether any regular cleaning is undertaken.

A similar variety of swimwear was worn by the aqua fitness session attendees. As mentioned previously none of the participants wore swimming caps for the activity during this survey. The activity also often involved the use of swimming aids such as foam floats. These floats were supplied by Surrey Sports Park and were stored in a pool side store when not in use. Once again no washing of these items was undertaken at any point meaning there is potential for microbiological pathogens and other debris to accumulate on them and transfer to the pool water.

The participants in the swimming club and water polo sessions all wore tight fitting dedicated swimming costumes to aid their performance. All participants wore swimming caps, however the ones used by the water polo participants were special caps designed for the sport and not made of rubber like the standard caps used for swimming. The equipment used by each group differed with the swimming club using a wide range of floats and resistance aids whilst the water polo session only used a pair of floating goals and a handful of balls. As was the case with equipment used in the other session no cleaning beforehand was observed.
The group using the most significantly different equipment during the survey was the canoe participants. Not only did the activity require the use of the kayaks and paddles but also the participants were observed to wear a range of clothing not specifically designed for swimming including neoprene wetsuits, t-shirts and board shorts. It was not known whether the participants used this equipment and clothing when participating in outdoor activities. The use of the kayaks on natural waters would present a risk of introducing a broad range of microbiological pathogens into the pool water if they are not cleaned effectively. The kayaks and paddles are also exposed during the transportation to the facility and therefore have the potential for introducing dirt and oils thrown up from the road. No cleaning of equipment was observed during the survey, however it is not known if cleaning was undertaken prior to bringing the equipment into the pool hall.

3.5.3.3 In-pool Actions
The actions of the bathers were also observed to vary depending on the activity being undertaken. The different actions could be seen to result in visible differences in the surface disturbances and the overflow of water from the pool tank. The high intensity of the swimmers in the swimming club sessions resulted in greater surface rippling than during public swimming sessions. The school and learn to swim sessions also were seen to be associated with large amounts of surface agitation. The presence of the lane ropes for all of these activities, however, meant that the lateral waves across the pool are restricted. This was not the case for the aqua fitness, water polo and canoe sessions. In these activities, the motion of the bathers was observed to generate large waves across the pool resulting in surges of water overflowing the pool tank. A large amount of surface water displacement was also observed during the canoe session. This large overflow of water may contribute to the substantial fluctuations in the THM and combined chlorine that were observed for these activities during this study.

3.5.4 Effect of Pool Configuration on Water Quality
The effect of pool configuration on the pool water is another key consideration that was investigated during this study. Throughout the study the pool was reconfigured on a number of occasions to enable activities to take place. This included moving the traversable boom to adjust the pool from being a single 50m pool to two 25m pools as well as moving the floor to change the depth of the pool at Location A. The movement of these structures was observed to cause substantial disturbance to the water in the pool tank as they passed through. The time and nature of configuration changes was assessed to evaluate whether configuration changes could be potentially responsible for the changes observed the in water quality parameters.
The first parameter that was assessed in relation to configuration changes was the pool water temperature. The pool water temperature was observed to fall consistently at a rate of 0.02°C/hr during the study, however, a large step change in the temperature was observed at three occasions. The loss of temperature is expected as the heat will be continually lost to the surroundings via evaporation from the surface. The water temperature is maintained through an automated heat exchanger in the plant room with a set point of 28°C. The step changes potentially could be as a result of the automated heating system, however, if this was the case it would be expected that the temperature would return close to the initial temperature rather than stopping short. Therefore further investigation of potential causes was undertaken.

When the floor movements are plotted on the temperature profile, shown in Figure 3-22, it can be seen that each of the increases in pool water temperature coincided with the floor being lowered.

![Figure 3-22 – Overlay of floor and boom movements onto pool water temperature data collected by automated sondes at location A and location D](image)

The process of lowering the floor forces water that had been largely contained under the floor to mix with the water above the floor. The floor insulates the water below it from the cooling water above and therefore when the water forced above the floor during the lowering is at a higher temperature it results in an increase in the water temperature at the sampling locations. The evidence of a link between the floor movement and the temperature increases is further strengthened by the observation that the temperature increases are sharper and larger at Location A than at Location D. This would be expected as the presence of the boom would limit
the rate at which the heat can transfer to the water in Location D. There were no changes in water temperature observed when the floor was raised. This is as expected as the process is taking place in reverse with water being sucked beneath the floor from the main pool water body. Similarly, no noteworthy changes in water temperature were observed when the boom was moved. This is logical as the longitudinal study had identified that the water temperature was fairly uniform along the length of the pool. In addition to the changes in temperature, the movement of the floor and boom was also found to coincide with observations of changes in the concentration of other parameters.

The largest concentration of *Ps. aeruginosa* was observed at Location A shortly after the first, and largest, reconfiguration of the pool. The boom had been moved from 50m to 25m and the floor had been raised from 2m to 1.25m. Internal structures such as these have been quoted as being potential sites for microbiological pathogens to accumulate in biofilms (PWTAG 2009). The boom movement pushed water towards Location A whilst the raising of the floor also caused substantial movement of water in Location A. The absence of *Ps. aeruginosa* in the samples at Location D, which was also affected by the boom move, indicates that the floor is the more likely of the two structures to be the source, however, as microbiological sampling of the structure surfaces or the water within them was not undertaken during the study no conclusions can be made.

The movement of the internal structures may also be the cause of the large reductions in THM concentration identified following the 50m swimming activities. The process of moving the boom involves inflating an air bag within the structure and pushing it through the water. The process causes agitation throughout the entire depth of the water body and forces a large amount of water to overflow through the deck-level drains. Air bubbles caused by seepage from either the pipework or the air bag were also observed in the water during the process. This bubbling of air through the water column could enhance the removal of volatile compounds in the water in a similar way to an air-stripper.

The results in this study provides evidence that internal structures can influence the water quality found within swimming pools, however, further investigation of the flows around these structures and within the tank is required in order to make more specific conclusions about their effects.
3.6 Conclusions

The results of the activity-focused water survey undertaken at the Surrey Sports Park show that there are many aspects related to pool use that can have an effect on the pool water quality. The key contributors included the number of bathers using the facility, the use of pre-swim showers, the extent of surface disturbance, the use of additional equipment and accessories, and the setup of the pool tank.

The distribution of the bathers across activities can have a significant impact on some aspects of water quality, especially THM and microbial pathogen concentrations. This study provides evidence that the current guidance needs to be developed to make clearer reference to the instantaneous bather load and its importance beyond matters of physical safety. The continuous and variable nature of the pool treatment plant provides operators with the opportunity to investigate the potential for reducing operating costs through turning down the system during periods of lower instantaneous bather loading. Further operational data is required to understand the extent to which this can be achieved and therefore an operational review of the facility is recommended as an essential next step.

There were large discrepancies observed between activity types in the proportion of bathers using the showers prior to entry to the pool. A simple adhoc survey of bathers using the facility during the study indicated that the level of understanding of swimming related issues varies amongst the public. The benefits of pre-swim hygiene and the risks to health of swimmers depend on the individual perceptions of the bathers. The actions of the bathers are shown in this study to have significant impact on the water quality, therefore it is important for an accurate assessment of public awareness to be undertaken. A parallel project has recently been undertaken at the University of Surrey to begin to address this issue by surveying the perceptions of parents in relation to the risk and benefits of children swimming, however, a much broader assessment of public perception is required to substantially improve the targeting of bather education. The study highlights the importance of a change in bather behaviour as a fundamental requirement in the move towards more sustainable pool facilities. The broad range of users involved means that the facilities themselves are likely to be the best placed organisations to deliver a program of bather education. It is therefore recommended that facility operators are engaged in a process to identify the support needed to enable them to do so.

The internal structures were found to have some noticeable effects on the water body. The manoeuvring of the floor and boom causes large volumes of water to be displaced and the observed impacts on water quality show that further information
Impact of Activities on Pool Water Quality

about the effects of these structures on the water circulation in the tank is required. The temperature effects of floor positioning observed in this study indicates that there is potential for these structures to be used to help reduce unwanted heat loss during periods when the pool is unoccupied.

The survey highlighted the broad range of clothing, accessories and equipment used by bathers in the pool. These items present various risks in relation to impacting the pool water and therefore it is recommended that further investigation into the management requirements of these items is undertaken.

This study has provided evidence that activity type and associated bather behaviours impact the pool water to differing extents with some activities presenting a higher risk to bather health, specifically aqua classes and the swimming club sessions. Therefore, it is important that the nature of the activity should be considered when creating pool schedules or designing pool treatment systems. The study showed that the water treatment system installed at the Surrey Sports Park was successfully maintaining the water quality within recommended limits even during the heaviest periods of use. This means that there is potential for savings to be made through system optimisation. The results have a broader implication for the swimming pool industry as it supports the recommendation that multi-use facilities should be designed to enable the treatment system to be easily adapted to suit the activities taking place within it.
3.7 References


Karanfil, T., Krasner, S.W., Westerhoff, P., Xie, Y. (2008) Recent advances in disinfection by-product formation, occurrence, control, health effects and regulations, *Disinfection By-Products in Drinking Water*, Washington, American Chemical Society


Lakind, J.S., Richardson, S.D., Blount, B.C. (2010) The good, the bad, and the volatile: Can we have both healthy pools and healthy people, *Environmental Science and Technology* 44, 3205-3210


Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes


Chapter 4 – An Assessment of the Impacts of Operational Aspects and Utility Consumption on the Sustainability of Swimming Pools

4.1 Introduction

The energy and water consumption aspects of swimming pool operation are becoming increasingly important (Carbon Trust 2008). Whether for private or public use, swimming pools represent a significant consumer of water and energy resources (Carbon Trust 2006, Forrest and Williams 2010). The cost of energy and water has increased significantly in the UK in recent years causing facility operating costs to rise dramatically (DECC 2011, Ofwat 2009). The introduction and development of the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme in the UK has also significantly increased the interest in the use of energy in these facilities as they are required to publicly display the emissions associated with operating the building (DECC 2012).

The development of new treatment technologies presents an opportunity to reduce the energy and water burden of swimming pools whilst maintaining the required air and water quality (Sun et al. 2011). In addition, many aspects of a swimming pool facility can be affected by the actions of the facility operators. An understanding of the energy and water use associated with design options and operator decisions is fundamental to enabling future guidance for sustainable swimming pool design and operation to be developed.

This chapter presents a review of current knowledge in relation to the operation of swimming pool facilities and the actual operational practices at the Surrey Sports Park. Three operational studies were undertaken during the research project to provide qualitative data for use in the analysis of the operational aspects of swimming pools. The first study focused on the water consumption of the facility whilst the second looked at the energy consumption of the facility. The third study reviewed the potential seasonality of demand for swimming and therefore potential variability in the necessary management procedures. The results of the studies are presented and the implications on the sustainability of swimming pools are discussed. Recommendations for the improved management of swimming pools, based on the study results, are made both specifically for the Surrey Sports Park as well as more generally for the industry.
4.2 Literature Review

There has been significantly less academic interest in the operational aspects of swimming environments than there has been in the health-related aspects that were discussed in earlier chapters. In general, the research that has been undertaken has focused on reducing the energy consumption of swimming pools, however, limited studies have focused on the water burden associated with swimming pools.

4.2.1 Energy Consumption

The Carbon Trust (2006) reported that there are a large number of significant energy-consuming activities associated with swimming pools including the heating, circulation and treatment of both air and water. Pool facilities therefore often have a large demand for energy, usually in the form of gas and electricity. The heating of pool water has been the most common energy concern to date as it has been traditionally achieved through the use of onsite boilers running on gas or heating oil (Carbon Trust 2006). Heating is required to maintain the pool water at a comfortable temperature for swimming. Heat is lost from the pool through the evaporation of pool water, through the pool tank to the environment and through the discharge of heated pool water to sewer (PWTAG 2009).

Smith et al. (1994) reported that evaporation accounts for the majority of heat loss from a pool. In addition, the replacement water will require heating as it is often sourced from the mains network in the UK (Devin 2010). The dependency of evaporation rate on water temperature, air temperature and air humidity is well-known. It has also been widely claimed that other parameters of the swimming pool facility can have a significant impact on the rate of evaporation. Asdrubali (2009) and Smith et al. (1998) reported that evaporation rates from pools can be up to 70% greater during occupied periods than unoccupied periods because of increased surface agitation. Moghimam and Jodat (2007) suggested that the design and operation of air handling systems also needs to be considered as the air velocity across the pool surface will also have an effect on the evaporation rate. It is therefore important for operational parameters to be well managed in order to minimise energy wastage through this route. The evaporation of water is associated with an additional energy demand relating to the requirement for the humidity of the pool hall to be carefully controlled. Air handling systems are significant consumers of electricity and therefore reducing the requirement for humidity control can have a significant impact on energy demand.

The use of pool covers during periods when the pool is not in use has been widely suggested as a necessity for addressing the energy consumption of swimming pools.
Impacts of Operation on Facility Sustainability

(Carbon Trust 2006, Forrest and Williams 2010, US Department of Energy 2009). Traditionally solid barriers have been used on small pools, however, the operational issues relating to covering large recreational or competition pools has prevented them from being commonly used on these types of pool (Devin 2010). Recently the use of monolayer liquid covers has been suggested (Brenntag 2009). McLannet et al. (2008) reported that evaporation rates from large water bodies could be reduced by 40% through the use of liquid covers. Although this is a lower reduction than achievable with solid covers, the reduction is achieved throughout most of the day not just during the periods when the pool is closed. The use of liquid covers, however, is associated with potential disadvantages. Barnes (2008) reported that the presence of the monolayer can encourage the growth of microbiological pathogens such as Pseudomonas aeruginosa. McLannet et al. (2008) also highlighted that the use of liquid covers is associated with an ongoing cost of re-application, especially in the case of a deck-level pool. There is also currently limited research into the potential for these monolayer substances to cause operational issues in the water treatment plant or form additional undesirable disinfection by-products (DBP).

Aside from reducing the amount of evaporation taking place, it is also possible to reduce the energy demand through the use of more efficient air handling systems. Shah (2003) identified inaccuracies with the existing evaporation correlations developed by Biasin and Krumme (1974) and Carrier (1918) and subsequently proposed modified methods of calculation in order to improve the design of air handling equipment in swimming pool environments. Shah (2011) has developed evaporation equations for occupied and unoccupied swimming pools. An improved prediction in evaporation could enable opportunities to develop energy efficient systems. The addition of new technologies within the air handling systems have been reported to offer significant energy savings (Carbon Trust 2007b). The study conducted by Johansson and Westerlund (2001) showed that the addition of a mechanical heat pump in the air handling system could result in a reduction in air side energy consumption of 14% compared to traditional air recycling systems. Sun et al. (2011) suggest that further improvements could be made through adding external air heat exchangers. The use of an open absorption system, as an alternative method for air quality management, was suggested by Lazzarin and Longo (1996) and Westerlund and Dahl (1994). The study by Johansson and Westerlund (2001) indicated this option could yield energy savings of 20% as a result of a reduction in the amount of useful heat expelled to the environment.

The pumping of water around a swimming facility is also a major consumer of electricity. The ability to reduce the pumping speed when the pool is not in use can
significantly reduce the energy demand (Forrest and Williams 2010). The use of variable speed drives to control the circulation pumps has become a more common occurrence in recent years in line with the recommendations by the Carbon Trust (2007b) (Devin 2010). Similarly the application of variable speed drives on the air handling plant can also generate energy savings. The balance between reducing circulation and maintaining air and water quality has not been investigated in much depth to date and therefore there is a risk that chasing energy targets could result in unintended quality issues.

The lighting levels required within the pool hall can vary from 300 lux to 600 lux depending on the activity taking place (Sport England 2008). The Carbon Trust (2008) reported that pool lighting can account for up to 16% of swimming pool energy consumption. Developments in energy efficient lighting in recent years present operators with opportunities to make significant reductions in the lighting energy demand. The use of automatic motion sensors and variable lighting settings can also help to reduce the demand further (Devin 2010). In addition to technological solutions, it is recommended that opportunities to maximise the use of natural lighting are considered during building design (Sport England 2008), although this can cause additional issues with associated with varying lighting conditions.

The development and uptake of alternative treatment systems, driven by the desire to reduce the risk to health, has also had an impact on the energy consumption of swimming pools. The use of UV or ozone treatments, for example, will see an increase in the direct electricity demand compared with traditional chlorination, however, the cost of this additional energy use was found by Anderson and Kaas (2009) to be less than the savings the technologies delivered elsewhere.

The variety of energy-related aspects mentioned above shows the importance of maintaining a broad approach to sustainable design. The common shortcoming of the studies mentioned in the above review is that they did not put the energy consumption into the wider context of facility consumption. There is currently very limited information on the overall energy consumption of operational facilities available in literature. A recent publication by Kampel et al. (2013) presented a basic survey of energy consumption of swimming pools in Norway. A subsequent paper by the same authors provided some additional analysis which identified some common characteristics of the more efficient facilities included in the study (Kampel et al. 2014). A similar study looking at the characteristics of open-air swimming pools in Greece has also been recently published by Mousia and Dimoudi (2015). A breakdown of the contributors to the overall consumption of a facility, however,
was not included in any of these studies. More detailed information on facility energy use is needed to enable this to be possible.

4.2.2 Water Consumption

The operation of a swimming pool is also associated with a significant consumption of water. There are both direct and indirect contributors to the water burden. Water is consumed through direct processes such as backwashing and evaporation as well as indirectly as part of the chemical or power production process (Forrest and Williams 2010). Prevention of evaporation through the use of pool covers was observed to result in a 50% reduction in pool water consumption in a study reported by the US Department of Energy (2009). Systematic addition of fresh water to reduce the concentrations of DBPs accumulating in the pool can have a high cost associated with it (Forrest and Williams 2010).

Optimising the frequency of backwashing and installing equipment that enables the reuse of backwash water can significantly reduce the water consumption of a facility (Carbon Trust 2006). The reuse of swimming pool backwash water will require varying levels of treatment depending on its final use. Skibinski et al. (2009) showed that simply using granular activated carbon (GAC) filters can effectively remove free chlorine and DBPs from the water to enable its use in low level applications such as toilet flushing. Additional treatments would be required for other applications such as irrigation or reuse in swimming pools (PWTAG 2010b). McCormick et al. (2010) and Walsh et al. (2008) highlighted that there is a risk of increased DBP generation during the backwash water treatment process than in pool water treatment. Reißmann et al. (2005) undertook a study to evaluate the potential benefits of using a combination of ultra-filtration (UF) and reverse osmosis (RO) to enable backwash water to be reused within the swimming pool itself. The study showed that significant water savings could be achieved through this methodology. Similarly to the case of backwash water, the use of harvested rainwater in swimming pool applications is not straightforward (PWTAG 2010a). PWTAG (2010a) suggest that rainwater is used in grey water applications such as in toilets rather than in pool use. For large multi-use facilities this is an option as they often have a large water demand for sanitation.

Andersen and Kaas (2009) reported that significant water savings could be achieved through the adoption of new treatment technologies such as UV and ozone. The reduction in water consumption is as a result of the reduction in the accumulation of dissolved chemical substances associated with traditional chlorine disinfection methodologies. Similarly, Keuten et al. (2012) indicated that controlling bather pre-
swim routines better could enable operators to also reduce their water burden by reducing the chemicals introduced by bathers.

4.2.3 Carbon Emissions

Building-related carbon emissions have become an increasing concern with the adoption of the CRC Energy Efficiency Scheme for public buildings in the UK. The CRC scheme has promoted the consideration of energy aspects in the design, refurbishment and operation of aquatic facilities in a similar way as utility price rises have done (Trianti-Stourna et al. 1998). Swimming pool facilities are associated with a wide range of carbon emissions. These can be categorised into scope 1, scope 2 and scope 3 emissions as defined in the Greenhouse Gas Protocol by the World Business Council for Sustainable Development (WBCSD 2004). In the case of a typical swimming pool, the Scope 1 emissions are associated with the fuel used for providing heat in the facility as well as for any ancillary onsite activity such as catering. Scope 2 emissions relate to the electrical consumption of the facility, including but not limited to lighting, water treatment and air handling equipment. Scope 3 emissions are associated with aspects that are outside the control of the operator such as waste disposal, off-site water treatment, transport and the supply chain of purchased goods. The ability to significantly impact scope 3 emissions is relatively limited and therefore most focus is placed on Scope 1 and Scope 2 emissions.

Examples of significant emission reductions achieved through the use of biomass as an alternative fuel for meeting the heat loading for a swimming pool have been published by a number of organisations including the Carbon Trust (2007a). Alternatives to fuel-based heating systems have also been investigated. The Carbon Trust (2008) have suggested that solar heating is a viable alternative to provide the low level heating required by swimming pools. Medved et al. (2003) showed that incorporating solar thermal heating at the design stage can significantly reduce the payback period compared to typical retrofit scenarios. This study was undertaken in a hot climate and therefore the findings may not be applicable in the cooler climate of the UK. Another alternative to fuel-based heating is the use of ground source heat pumps. The uptake of this technology has been low because of a combination of the significant installation costs and the short payback periods often desired by developers, however, Omer (2008) also reported that they are economically viable in the long-term.
4.3 Operational Review of Surrey Sports Park Facility

4.3.1 Facility Overview
The Surrey Sports Park (SSP) is a multi-sport venue that consists of a main building that contains a number of sports arenas, well-being rooms, offices and catering facilities in addition to the swimming pool which is the focus of this research project. The facility also has a number of external grass and artificial sports areas as well as a large carpark. The facility is open 7 days a week and is regularly used by professional sports teams, amateur clubs, schools and the general public as well as the students of the University of Surrey.

4.3.2 Facility Management
The facility’s management procedures are based on the guidance published by Pool Water Treatment Advisory Group (PWTAG 2009), Institute of Sport and Recreational Management (ISRM 2010) and the Health and Safety Executive (HSE 2007). The responsibilities are, however, split between two separate groups of people. The customer facing aspects related to day to day operations at the facility are undertaken by the SSP staff. The pool-related tasks that are undertaken by SSP staff include cleaning of the pool and ancillary areas, setting up the pool for activities, controlling access to the pool and lifeguarding. The infrastructure-related aspects of the facility management are undertaken by the Estates and Facilities Management (E&FM) department of the University of Surrey. The E&FM team are responsible managing the pool water conditions, operating and maintaining the air and water treatment systems and managing the mechanical and electrical building services. This is a common practice within the swimming pool industry (Mansi 2010). Copies of the normal operating procedures (NOP) for the swimming pool and the pool plant are included in Appendix 3 along with other operational documents relating to the facility.

The facility is fitted with a Building Management System (BMS) that automatically controls many of the energy-related activities in SSP. This includes the air conditioning, water heating and water circulation in the swimming pool hall. In addition the BMS system records the consumption of electricity in the facility. Additional controllers have been installed to assist with the automated operation of the pool water treatment system. These controllers manage the addition of the pool chemicals including disinfectants, coagulants and pH regulators. The settings for these automated controllers are the responsibility of the E&FM staff. Other aspects of the pool operation can be adjusted manually using various control panels. These include the pump speeds and the dosage of the UV treatment unit.
The discharge of water is also a manual process, although, a level controller ensures that the addition of fresh water is managed automatically.

Regular onsite water testing for key disinfection parameters is undertaken by SSP staff. The measurements of free chlorine, combined chlorine and pH are recorded on daily record sheets, together with observed bather numbers. Any anomalies in the water quality data are reported to the E&FM team, however, the SSP staff have no ability to make any changes directly. The E&FM team also undertake regular water quality sampling and record the measurements for these parameters on separate daily record sheets. In addition, the E&FM team record measurements for calcium hardness, alkalinity and total dissolved solids along with the daily water consumption.

Much of the operational data for the swimming pool facility is therefore collected by the E&FM team, however, the extent to which this data is communicated to the SSP management is unclear. This is of significance as decisions made at the management level in relation to operational aspects of the facility may be being made without consideration of this information.

4.3.2.1 Corporate Social and Environmental Responsibility

The nature of the services being provided by the Surrey Sports Park results in a wide range of social and environmental impacts on the local community. It is important that these impacts are assessed to ensure that the benefits are maximised and detrimental aspects are minimised or avoided all together. The Surrey Sports Park, however, did not have a defined corporate social and environmental responsibility (CSER) policy in place at opening. An initial CSER review of operations at Surrey Sports Park was undertaken as part of the scoping works of this research project and is presented in Appendix 4. Aspects from the CSER review are expanded upon in the discussion sections of this chapter.

4.3.2.2 Bather Control and Management

The control of access to the pool hall is achieved through the use of a coded and locked door at the entry to the pool-side changing rooms. As the pool facility is open to both SSP members and the general public there are two options for users to access the pool. SSP members can swipe themselves into the changing rooms using their membership card whilst the general public are given an access code when purchasing swim time at the main reception. Access to the spectator area of pool side is less controlled with no restriction on access during pool opening hours.

Bather numbers in the pool are manually controlled by the on-duty lifeguards. Temporary barriers are available for them to use should they be required to prevent
additional bathers entering the pool hall for any reason. The lifeguards are also responsible for monitoring and managing the behaviour of the bathers including encouraging bathers to shower before getting in and ensuring correct equipment and attire is used.

A few issues were observed with the above systems. Firstly, the same door is used for both entry and exit from the pool-side changing rooms. During busy periods, the constant turnover of swimmers meant that the door rarely closed meaning bathers could easily access the changing rooms without needing to swipe their membership card or enter the access code. Therefore, the facility is open to opportunists gaining unauthorised access to the pool. Another issue identified was that placing the responsibility of ensuring bathers showered before swimming with the on-duty lifeguards presented an opportunity for confrontation. Many of the lifeguards are young temporary workers who can often feel intimidated by older bathers. This is also a distraction from their primary duty of ensuring bather safety and therefore should a bather ignore their initial request they do not have the time to follow up further. The lifeguards have been trained and assessed for their competency at responding to water-based emergencies but not in the details of pool water treatment and the reasons for bather showering. This often means they are inadequately informed to provide accurate explanations to bathers who query the request to shower.

The final issue identified in relation to bather control and management was surrounding young swimmers. Whether attending as part of a school group or for the learn-to-swim classes, the young swimmers are accompanied by non-swimming adults. It was observed that often the adults accompany their children through the showers and onto pool-side. This presents an opportunity for dirt to be brought pool side especially if they have not removed their footwear. Another frequent occurrence was that the adults brought the children into the spectator area whilst waiting for the session to start. In these cases, the children have been observed to frequently join the session directly from the spectator area, bypassing the showers completely.

4.3.2.3 Performance Monitoring

The manual paper-based system used by SSP for monitoring and recording the bather numbers and pool water sampling results means that performance monitoring is not straightforward. The collation and review of data in this fashion is time consuming and is therefore not undertaken regularly. An example of how analysis of this data could generate potential benefits to the operation of the pool is presented in Section 4.6. Although membership numbers and financial flows for the
overall facility are assessed and used to generate key performance indicators (KPI), the organisation does not have any pool specific KPIs. The generation of meaningful KPIs for the swimming pool would require information regarding not only basic water quality and bather numbers data but also information about water use, energy use and chemical use. As mentioned above, these aspects are the responsibility of the E&FM team and the information was not regularly recorded and communicated to the SSP team. It is therefore not possible for SSP to monitor the performance of the pool activities in detail. Unfortunately, it was also not possible to acquire information with regards to any performance monitoring that may have been undertaken by the E&FM team. Limited access to the water and energy consumption data of the swimming pool was possible during this research project and analysis of this data is presented in Sections 4.4 and 4.5 respectively.

4.3.3 Operational Case Studies

During the facility review, two case studies were undertaken to provide information to the operational management teams at the facility. Although not initially considered within the original scope of the research project, these studies generated information that could subsequently be drawn on in the core research objectives. A summary of the two case studies has therefore been presented in this section.

4.3.3.1 Equipment Corrosion Issue

Shortly after the opening of the SSP swimming pool, the operators observed signs of corrosion on some of the metallic equipment in the pool hall, namely the lifeguard chairs, the lane rope holders and some of the bolts on the traversable boom. Six months after opening there were widespread signs of corrosion on the metallic surfaces including on the handrails and the surrounds of the traversable boom. Review of the swimming pool air and water parameters by Devin Consulting did not reveal anything outside of normal operational conditions. Therefore no explanation for the corrosion was provided. The research being undertaken at SSP involved the in-depth monitoring of the pool water for additional parameters not normally monitored in the swimming pool industry. This included the analysis for chloride concentrations in the pool water.

Chloride can be introduced to pool water via a number of routes such as sweat from bathers, the addition of hydrochloric acid for pH correction and as an impurity in sodium hypochlorite solutions and other treatment chemicals (BSI 2007; Maughan et al. 2009; White 1986). Chloride, unlike chlorine, exhibits no germicidal properties and is very stable meaning it will accumulate in the pool water. High chloride concentrations in water have the potential to corrode a pool’s physical structure.
and fittings and also components of the treatment plant, therefore current standards specify the use of stainless steels for pool applications (BSI 2008). As a result of the stable nature of chloride, it must be physically removed from the pool water via the disposal of water as part of the backwash procedure.

Initial chloride concentrations in the SSP pool water were found to be close to the recommended maximum for the common grade (304) of stainless steel, 200 mg/l (SSINA 2001). The trend in chloride concentrations over the first 6 months of operation indicated that, if left unchecked, it would exceed the recommended operational range for the more resistant marine grade (316) of stainless Steel, 1000 mg/l (SSINA 2001), see Figure 4-1.

![Figure 4-1 Pool water and mains water chloride concentrations for A) April to November 2010 and B) March to September 2011](image)

Upon investigation of the equipment in the pool hall it became apparent that there was inconsistency in the type of steel used by manufacturers. The lifeguard chair and lane rope holders were made from a mixture of stainless steel 304 and chrome-plated carbon steel. These items were therefore highly susceptible to chloride corrosion. The handrails and the traversable boom were constructed of stainless steel 316, which could explain the comparative delay in showing signs of corrosion. Similarly, the bolts used on the top of the boom were made from stainless steel 304, whilst those on the submerged section were made from stainless steel 316.

Modifications that were introduced to the pool operations in November 2010 as a result of the results of this study were found to stabilise the chloride concentrations and prevent concentrations exceeding the limit for 316 stainless steel, see Figure 4-1. The modifications resulted in an increase in the mean daily water exchange volume from a fairly steady 5 m³/day during period A to a rate as high as 17 m³/day.
Impacts of Operation on Facility Sustainability
during period B. Figure 4-2 shows the change in chloride concentration plotted against the daily water exchange rate. The data shows that when daily water additions were above 13 m$^3$/day the chloride concentration stabilised whilst exchange rates exceeding 15 m$^3$/day resulted in declining chloride concentrations in the pool water.

![Figure 4-2 – The change in pool water chloride concentrations plotted against the mean daily water exchange rate](image)

The study suggests that a minimum water exchange rate of 13 m$^3$/day should be adopted by SSP in order to ensure that the corrosion issue does not return. Current guidance makes recommendations that the water exchange rate should be linked to bather numbers (PWTAG 2009). The comparison of the existing and suggested water exchange rates with the PWTAG recommended exchange rate of 30 litres per bather per day would provide a basis to assess the suitability of current pool guidance. A further discussion on the impacts of water exchange rate is included as part of the longitudinal water survey work presented in section 4.4.

4.3.3.2 Backwashing

Backwashing of the sand-filters provides two key functions for the SSP pool. The first is the removal of particulate matter that has accumulated in the sand filter. This accumulation of solids causes the pressure drop across the sand filters to increase reducing the water circulation rate and putting additional load on the circulation pumps. It is therefore good practice to regularly backwash the filters to prevent damage to the pumps and maintain the efficiency of the treatment system (PWTAG 2009). The second function that the backwashing process has is in the
removal of dissolved compounds from the pool water, such as chloride, as discussed previously.

The process of backwashing the filters, however, interrupts the normal operation of the swimming pool. It is very rare for a separate system to be installed to enable pool circulation to be maintained during backwashing and therefore this is a common occurrence across the industry (Devin 2010). The procedure for backwashing is fairly uniform for pools using medium-rate sand filtration, although air scouring is omitted from the process in some facilities. The interruption of the water circulation during the backwashing process means that both the dispersion of disinfectants and the removal of water from the pool tank are no longer taking place. This increases the risk of bathers being exposed to microbiological pathogens should this take place during periods of use. Current best practice recommends that the backwashing of filters takes place while the pool is closed for this reason (PWTAG 2009).

The backwashing of the filters at SSP is undertaken by the E&FM team. It was observed that the backwashing often took place during the operational hours of the pool. Upon questioning, it became apparent that the E&FM team were unable to perform the backwash after the pool was closed or before the pool opened because of the timings of the shifts they were employed to work. Undertaking the backwashing process out of hours would require the E&FM shifts to start either 30 minutes earlier or finish 30 minutes later because of the manual elements of the process. This would require changes in policy within the wider University of Surrey as the E&FM shifts are centrally organised. To minimise the risk to bathers the E&FM team scheduled the backwashing to take place during times when the pool was being reconfigured. Although this meant that no bathers were present in the pool while the circulation was switched off, it meant that the circulation system was only just starting as bathers re-entered the pool.

The time required for the pool circulation and chemical dispersion to reach normal operational conditions following the suspension of pumping has not been investigated to date, however, design guidance suggests that this should be approximately 15 minutes (PWTAG 2009). Some modern facilities, such as the Aquatic Centre for the London 2012 Olympics, have removed the issue of out of hours staffing by installing an automated backwashing system (Devin 2010). These systems can be activated either manually by pressing a button when the pool is closing or automatically via scheduled timers. This is a relatively low-cost modification that has been widely used in other industries such as groundwater treatment and drinking-water treatment processes.
The final area of discussion around the backwashing process is regarding the length of time the filter should discharge to drain following backwashing prior to being placed fully back online. Current best practice recommends a rule of thumb of 30 seconds, however, no relation to the vessel size or flow rate is involved in this recommendation. The basis for the concern is that it is known that sand filters require a period of time, known as the ripening time, before they return to their maximum efficiency (AwwaRF 2002). During this time there is the potential for small particles, such as *cryptosporidium* oocysts, that have been dislodged during backwashing to pass through the filter and enter the pool circulation system. Short studies undertaken in parallel to this research project did not identify any clear evidence for either redefining or supporting the current recommendations (Nikoleris 2013, Papathanasiou 2011).
4.4 Water Consumption Survey

4.4.1 Scope

Disposing of pool water is costly on many accounts. Firstly, there is the cost of discharge to sewer, secondly, there is the cost of purchasing fresh mains water and thirdly, there is the cost of heating the fresh make up water to the desired pool temperature. These costs have been increasing recently as a result of the rise in the number of people taking part in swimming and the bill for running large facilities is now of the order of thousands of pounds per year (Leisure Database Company 2009). In the UK, pools are becoming increasingly more expensive to operate because of the rising cost of both water and energy. Additionally, pressure for facilities to be sustainable with a reduced environmental footprint, is challenging facility operators to optimise their pool operations to minimise impact on natural resources whilst ensuring bather safety is not compromised (Carbon Trust 2006)

In order to maintain the quality of the pool water, fresh water is required to be added at regular intervals. This prevents the accumulation of dissolved substances in the pool water. It is currently advised that 30 litres of fresh water is added to the system for each bather that uses the pool (PWTAG 2009) although this has not been reviewed since it was included in the first swimming pool guidance in 1999. As the pool water treatment system is a closed loop, during operation the addition of fresh water requires the discharge of existing pool water. The process of backwashing provides an ideal opportunity to discharge the required water volume to allow addition of fresh water (PWTAG 2009). This is the extent to which current UK guidance covers water consumption expectations for swimming pools and is wholly inadequate for ensuring efficient water management practices.

This survey collated and analysed the water consumption data for the Surrey Sports Park to enable water saving opportunities to be identified. This study aimed to review the overall water consumption of the Surrey Sports Park and use the collated data to identify opportunities for efficiency improvements in relation to the swimming pool through modifications to existing practices. The data gathered during the study and subsequent analysis is presented in this section and proposals are made in relation to a new relationship that can be used to predict the impact of operational parameters on the water consumption of a swimming pool.

4.4.2 Methodology

The water used within the facility is currently sourced completely from the mains system. Although the facility was initially designed to enable grey water use for sanitation the system was removed during construction. The consumption of water
is recorded by a number of inline water meters. The flow meter on the mains inlet for the building records the total consumption of water by the facility. Three further flow meters within the facility record the volumes of water used for sanitation, the swimming pool and irrigation. The difference between the mains water meter and the sum of the segregated meters was assigned to general applications. The general applications include the use of water for cleaning, showers, drinks fountains, hand basins, the bar, the kitchen and the coffee shop.

The water meters are not directly connected to the BMS system and therefore they required manual logging in order to track trends in use. This was undertaken by the E&FM team for the pool water flow meter in order to record the amount of water discharged during the backwash process. These manual recordings were collated and analysed in this study.

4.4.2.1 Prediction of Pool Water Evaporation

The study also used theoretical relationships published by Shah (2011) for evaporation from occupied and unoccupied pools to calculate expected volumes of water to be lost at the facility. These values were then compared to the actual consumptions recorded at the facility. For unoccupied pools Shah (2011) defines the evaporation rate \( E_0 \) as the larger of the results of Equation 4-1 and 4-2.

\[
E_0 = 290D_w x (D_r - D_w)^{1/3} x (W_w - W_r) \quad \text{Equation 4-1}
\]

\[
E_0 = 0.0346 x (p_w - p_r) \quad \text{Equation 4-2}
\]

For occupied pools Shah (2011) defines the evaporation rate \( E \) using Equation 4-3.

\[
E = 0.023 - (0.0000162/U) + (0.041 x (p_w - p_r)) \quad \text{Equation 4-3}
\]

Where,
\[
D_w = \text{density of air saturated at water temperature (lb/ft}^3\text{ dry air)}
\]
\[
D_r = \text{density of air at room condition (lb/ft}^3\text{ dry air)}
\]
\[
W_w = \text{humidity ratio, air saturated at water temperature (lb/lb)}
\]
\[
W_r = \text{humidity ratio, air at room condition (lb/lb)}
\]
\[
p_w = \text{water-vapour pressure in air, air saturated at water temperature (in Hg)}
\]
\[
p_r = \text{water-vapor pressure in air, air at room condition (in Hg)}
\]
\[
U = \text{utilization factor (number of people in pool area multiplied by 48.4 divided by pool area)}
\]
For ease of use, Shah (2011) has generated look-up tables in SI units based on the above equations for a wide range of common pool water and air conditions. The evaporation rate look-up tables for unoccupied and occupied swimming pools are shown in Table 4-1 and Table 4-2 respectively.

Table 4-1 – Evaporation rate (kg/hr/m²) look-up table for unoccupied pools based on the formulas proposed by Shah (2011)

<table>
<thead>
<tr>
<th>Space air temperature, degrees Celsius</th>
<th>25°C</th>
<th>30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.1085</td>
<td>0.0918</td>
</tr>
<tr>
<td>60%</td>
<td>0.0636</td>
<td>0.0693</td>
</tr>
<tr>
<td>50%</td>
<td>0.0515</td>
<td>0.0547</td>
</tr>
<tr>
<td>60%</td>
<td>0.0450</td>
<td>0.0479</td>
</tr>
<tr>
<td>50%</td>
<td>0.0382</td>
<td>0.0479</td>
</tr>
<tr>
<td>60%</td>
<td>0.0311</td>
<td>0.0417</td>
</tr>
</tbody>
</table>

Table 4-2 – Evaporation rate (kg/hr/m²) look-up table for occupied pools based on the formulas proposed by Shah (2011)

<table>
<thead>
<tr>
<th>Space air temperature, degrees Celsius</th>
<th>25°C</th>
<th>30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.2174</td>
<td>0.2136</td>
</tr>
<tr>
<td>60%</td>
<td>0.1661</td>
<td>0.1667</td>
</tr>
<tr>
<td>50%</td>
<td>0.1477</td>
<td>0.1500</td>
</tr>
<tr>
<td>60%</td>
<td>0.1287</td>
<td>0.1300</td>
</tr>
<tr>
<td>50%</td>
<td>0.1092</td>
<td>0.1117</td>
</tr>
<tr>
<td>60%</td>
<td>0.0906</td>
<td>0.0918</td>
</tr>
</tbody>
</table>

4.4.3 Results

4.4.3.1 Facility Water Consumption Overview

The total consumption of water by each of the four categories of application was recorded in October 2011 in order to assess the water footprint of the facility after 18 months of operation. The distribution of water consumption over this period is shown in Figure 4-3.
The pool water consumption accounted for 22% of the total water consumption during this period compared to 15% for sanitation and 38% for irrigation. The remaining water consumption of the facility was largely associated with applications requiring potable water such as in the kitchen, bar and coffee shop. The amount of water used for irrigation is believed to be inflated because of an international sports tournament that took place during the summer of 2010 and required very heavy water use to maintain the quality of numerous grass pitches.

4.4.3.2 Carbon Dioxide Emissions and Cost of Water at Surrey Sports Park

At present all of the water demands for the facility are met through the use of mains water. The water used in all applications with the exception of irrigation is liable to both supply and sewerage charges. The pricing and CO₂ emissions associated with supply of mains water and treatment of disposed water is shown in Table 4-3 (Defra 2014, University of Surrey 2011).

<table>
<thead>
<tr>
<th>Utility Type</th>
<th>Utility Pricing¹</th>
<th>CO₂ Intensity²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains Water</td>
<td>75.05 p/m³</td>
<td>0.3441 kg/m³</td>
</tr>
<tr>
<td>Sewerage</td>
<td>47.19 p/m³</td>
<td>0.7085 kg/m³</td>
</tr>
</tbody>
</table>

¹ – Utility pricing as provided by University of Surrey (2011)
² – CO₂ intensity for 2010 taken from Defra guidance (2014)

Using the consumption data shown in Figure 4-3 and the above pricing information the cost of the water consumption during the 18 month study period is approximately £41,700. The carbon emissions associated with this water consumption is approximately 31,300 kg CO₂. This would equate to a monthly
average of approximately £2,300/month and 1,700 kg CO$_2$/month. At present the carbon emissions associated with the off-site supply and disposal of water are not included in the scope of the facility’s carbon footprint for carbon reduction commitment (CRC) reporting purposes and therefore only the financial implications are currently of concern to a facility (DECC 2012).

4.4.3.3 Swimming Pool Water Consumption

The water consumption of the pool ($W_p$) was subsequently analysed in greater detail. As mentioned previously, the swimming pool water consumption is made up of three different elements: the disposal of water to maintain water quality and filter efficiency ($W_{wex}$), the evaporation of water from the pool tank ($W_{ev}$) and carry-out via bathers’ clothing. The bather carry-out is considered to be very small and has therefore not been included in this study.

The most significant cause of water consumption is the disposal of water as part of the water exchange required to maintain the pool water quality. Figure 4-4 below relates the amount of fresh water added to the swimming pool with the number of bathers using the pool during the day for the first 6 months of the study period. The water exchange rate ($W_{b}$) required to meet the PTWAG recommendations, 30 litres per bather per day, is also shown for comparison (PWTAG 2009). As can be clearly seen in the figure, the actual daily refresh rate in litres per bather was highly variable. This was as a result of a combination of the manual process of exchanging water and the variable daily bather load.

![Figure 4-4](image)

**Figure 4-4** – Actual and recommended volumes of fresh water added to the pool for various daily bather loads.
In the 6 month period following the opening of the facility, the amount of fresh water added to the pool was significantly less than the recommended volume on 77% of the days. This lack of water exchange was because of a combination of infrequent backwashing being required as a result of the low amount of solids present in the water as well as incorrect conversions from litres to m$^3$ by the estates and facility staff responsible for the water exchange. Inadequate water exchange was the probable cause of the corrosion issues discussed previously. The issues were addressed in November 2010 and the maintenance schedules updated. Large volumes of water were exchanged subsequently to attempt to bring the water concentrations back in line with recommendations.

A monthly-averaged daily water refresh rate was also considered to be a more suitable measure to use than an actual daily water refresh rate as the pool water composition was observed to change fairly slowly, as discussed in Chapter 2, and it enabled some of the variability to be moderated. The monthly-averaged daily refresh rate for the swimming pool is shown in Figure 4-5. Although substantially more water was exchanged following the operational changes in November 2010, the average daily refresh rate fell below recommended values soon afterwards because of the E&FM team not being aware of large increases in recorded bather numbers. This highlights the importance of a robust communication procedure between operational and maintenance teams.

![Monthly-averaged actual and recommended daily refresh rates based on actual monthly bather numbers for Surrey Sports Park.](image)

**Figure 4-5 – Monthly-averaged actual and recommended daily refresh rates based on actual monthly bather numbers for Surrey Sports Park.**

4.4.3.4 Water Exchange Deficit

The consistent inadequate exchange of water can cause operational issues in a pool facility. A new performance indicator was created to enable the E&FM team to
monitor long-term trends in the rate of water exchange. The Water Exchange Deficit (WED) was defined as the difference between cumulative actual water consumption and cumulative recommended water consumption. An increase in the WED is likely to be the cause for the recorded increases in the concentrations in stable dissolved compounds such as chloride, as these are only removed through the water exchange process. Observations of equipment corrosion that were recorded between September and November 2010 also provided evidence of the increase in chloride concentrations.

The WED for the facility from May 2010 to March 2011 is shown in Figure 4-6 together with the actual cumulative water consumption and the recommended cumulative water consumption based on recorded bather numbers. The data shows that the WED rapidly increased from May 2010 to November 2011. The WED was then significantly reduced following the adjustments made to the operational procedures at this time. The WED was then seen to increase again between March 2011 and July 2011 before remaining fairly stable until September 2011. Further increases in the WED were observed from October 2011 to March 2012. This was as a result of the E&FM team not adequately adjusting the water exchange rate with respect to bather numbers.

![Figure 4-6 – Actual and recommended cumulative water consumption and water deficit for Surrey Sports Park swimming pool between April 2010 and March 2012](image)

Unfortunately there was no water analysis data available for the period between November 2011 and March 2012, however, there were no further observations of the corrosion issues that had been present in 2010 despite the WED being higher. This indicated that the corrosive nature of the pool water may not be as strongly
dependent on bather numbers as suggested by current guidance. This prompted further investigation into the water exchange requirements to be undertaken.

4.4.3.5 Impact of Inaccurate Bather Loads on the Recommended Water Consumption Values

In November 2010, a user group study was undertaken at the facility as discussed in Chapter 3. During this study, the number of bathers was recorded in real time. When the total number of bathers was compared to the number of bathers documented by the facility staff, there was a discrepancy of over 20%. Following this discrepancy, the method of bather counting used by the facility staff was investigated. The facility staff calculated the bather load through the summation of headcounts taken every 30 minutes during pool opening hours, a common method used by facilities in the UK (PWTAG 2011). Many of the activities that take place in the pool last for an hour or longer, therefore, some bathers could be double counted. At some times, for example during swimming club sessions, the recorded bather count can be up to four times higher than the actual number of bathers.

This overestimate of bather numbers means that the amount of water recommended to be exchanged is also overestimated. Assuming that the user group study was undertaken on a representative day for the facility, it suggests that the bather count, as calculated by the facility staff could be reduced by 20% when calculating the amount of water that should be exchanged daily. The effect of this modification to the cumulative water consumption data for the facility is shown in Figure 4-7.

![Graph](image-url)
After taking account of the overestimates in bather numbers, the amount of water
that was added to the pool between May 2010 and November 2010 can be seen to
remain significantly less than the recommended volume. However, the WED for the
period following the operational changes is observed to remain close to zero. This
provides a potential explanation for why the corrosion issues were not observed in
2011 onwards even though the raw data suggests the WED was higher than in 2010.
It is recommended that for the water exchange requirement ($W_{ex}$) a correction
factor ($F_b$) is applied to the bather number ($N$) calculated using the half-hour
observation method as shown in Equation 4-4. Additional surveys would be
required to verify that the appropriate correction factor was used for the facility.

$$W_{ex} = F_b \times N \times W_b$$  \hspace{1cm} \text{Equation 4-4}

In this equation, $W_b$ would remain at the PWTAG guidance value of 30 litres per
bather per day.

4.4.3.6 Pool Water Evaporation

The pool water at the facility is maintained at 28°C with the air temperature
maintained at 29°C. The humidity of the air in the pool hall is set to 60% and the
pool is in use between 13 and 17 hours each day. Using the look-up tables published
by Shah (2011), the above settings and a pool surface area of 1000m², the
theoretical volume of water expected to evaporate daily is between 3.42 m³/day
and 3.87 m³/day. This is in close agreement with losses observed at the facility
during this study and acts as validation of the equations proposed by Shah (2011).

This addition of water to compensate for evaporation does not affect the
concentrations of the dissolved compounds in the pool water as many of them are
non-volatile. This means that an additional volume of water ($W_{ev}$) based on pool
surface area and hours of use should be added to the water exchange requirement
($W_{ex}$), as shown in Equation 4-5, to account for the evaporative losses when
calculating expected pool water consumption.

$$W_p = W_{ex} + W_{ev}$$  \hspace{1cm} \text{Equation 4-5}
4.5 Energy Consumption Survey

4.5.1 Scope

A major driver behind the desire to optimise swimming pool operations is the significant cost associated with its energy consumption. In order to identify potential opportunities for reducing the energy consumption of the facility, a survey of current energy use was undertaken. The energy survey undertaken as part of this project aimed to quantify the significance of swimming pool operations within the overall facility energy consumption. In addition, the survey reviewed the energy consumption of the pool facility in more detail to provide a baseline against which the implications of modifications to the operating practices could be assessed.

4.5.2 Methodology

The Surrey Sports Park is fitted with a building management system (BMS) that monitors the energy consumption of the facility in predefined zones. The system displays real-time energy data and can also be setup to record data at user-specified intervals. The system was initially setup to record energy consumption data in 15 minute intervals. Limited access to the BMS data was granted by the E&FM team between June and August 2010 to enable the detailed survey to be undertaken. The setup of the BMS system enabled the energy consumption of the swimming pool to be broken down into 4 categories; Water Heating, Air Handling, Lighting and Water Treatment.

In addition, cumulative energy consumption data based on utility bills was provided by the E&FM team for the 18 month study period. CO₂ conversion factors were taken from the DEFRA guidance for 2010 (Defra 2014) and utility pricing information was supplied by the facility, as shown in Table 4-4. In the case of electricity, the facility was on a dual rate tariff meaning that lower charges were applicable to consumption between 00:00 and 07:00. The night time electrical consumption for the facility was found to account for approximately 18% of the total electrical consumption. This data enabled a broad overview of energy consumption to be compiled and a carbon footprint of the facility to be calculated.

**Table 4-4 – 2010/11 pricing and CO₂ emissions factors for the consumption of energy at Surrey Sports Park**

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Fuel Price¹</th>
<th>CO₂ Intensity²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (Day Rate)</td>
<td>8.02 p/kwh</td>
<td>0.590 kg/kwh</td>
</tr>
<tr>
<td>Electricity (Night Rate)</td>
<td>5.37 p/kwh</td>
<td>0.590 kg/kwh</td>
</tr>
<tr>
<td>Gas (inc. CCL)</td>
<td>0.178 p/kwh</td>
<td>0.204 kg/kwh</td>
</tr>
<tr>
<td>Biomass (wood chips)</td>
<td>3.017 p/kwh</td>
<td>0.016 kg/kwh</td>
</tr>
</tbody>
</table>

¹ – Utility pricing from University of Surrey (2011)
² – CO₂ intensity for 2010 from Defra guidance (2014)
4.5.2.1 Weather Information

The weather is known to greatly affect the amount of energy consumed by buildings to provide heating (Carbon Trust 2007b). Heating Degree Days (HDD) are a useful measure for enabling energy data to be corrected to account for the effects of temperature variations. The data included in this paper is non-weather corrected as comparative assessments are not made however the HDD data calculated using a 15.5°C baseline temperature measured at the regional weather station during the study period is provided in Table 4-5 for reference (Vesma 2014).

<table>
<thead>
<tr>
<th>Month</th>
<th>HDD</th>
<th>20-Year Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2010</td>
<td>180</td>
<td>165</td>
</tr>
<tr>
<td>May 2010</td>
<td>146</td>
<td>98</td>
</tr>
<tr>
<td>June 2010</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>July 2010</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>August 2010</td>
<td>34</td>
<td>19</td>
</tr>
<tr>
<td>September 2010</td>
<td>74</td>
<td>42</td>
</tr>
<tr>
<td>October 2010</td>
<td>154</td>
<td>106</td>
</tr>
<tr>
<td>November 2010</td>
<td>298</td>
<td>215</td>
</tr>
<tr>
<td>December 2010</td>
<td>442</td>
<td>313</td>
</tr>
<tr>
<td>January 2011</td>
<td>334</td>
<td>311</td>
</tr>
<tr>
<td>February 2011</td>
<td>232</td>
<td>271</td>
</tr>
<tr>
<td>March 2011</td>
<td>243</td>
<td>243</td>
</tr>
<tr>
<td>April 2011</td>
<td>90</td>
<td>165</td>
</tr>
<tr>
<td>May 2011</td>
<td>80</td>
<td>98</td>
</tr>
<tr>
<td>June 2011</td>
<td>83</td>
<td>42</td>
</tr>
<tr>
<td>July 2011</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>August 2011</td>
<td>41</td>
<td>19</td>
</tr>
<tr>
<td>September 2011</td>
<td>48</td>
<td>42</td>
</tr>
</tbody>
</table>

4.5.3 Results

4.5.3.1 Overall Fuel Consumption of Surrey Sports Park

The Surrey Sports Park uses energy through consumption of three fuels; electricity, gas and biomass wood chips. The energy consumption of each of these fuels by the facility over the first 18 months of operation is shown in Figure 4-8.
The biomass boiler at the Surrey Sports Park provides the energy required by the facility’s central heating circuit and uses locally sourced wood chips as the fuel. This provides most of the heating requirements of the building including heating the pool water. The system is supported by gas boilers which are used only when demand exceeds the capacity of the biomass boiler or when the system is offline for maintenance. Some gas is also used within the facility for catering purposes. The cold weather between November 2010 and March 2011 meant that the heat load exceeded the capacity of the biomass boiler and additional gas consumption was required. In addition, issues with the biomass boiler between October 2010 and December 2010 meant that the gas use was significantly higher than expected.

The consumption of electricity by the facility was seen to be fairly consistent throughout the 18 month study window. Unlike the gas and biomass consumption, the electrical consumption is associated with a broad range of uses. Using the data collected by the BMS system between April and September 2010 it was possible to calculate the distribution of electrical consumption as shown in Figure 4-9. The swimming pool was observed to account for 25% of the facilities overall electrical consumption. This was second only to the air conditioning systems in the facility which accounted for 29% of the electrical consumption. Catering facilities were also identified as a significant consumer of electricity contributing 8% of the total consumption. A large percentage, 19%, of the electrical consumption was unable to have its use clearly defined through review of the BMS data and is shown in the miscellaneous category. This category includes aspects such as external floodlighting which are expected to be significant consumers of electricity. Unfortunately access to the BMS data was not granted during the remainder of the
study window and therefore it was not possible to analyse consumption for seasonal changes.

Figure 4-9 – Distribution of electrical consumption at Surrey Sports Park between April 2010 and September 2010

4.5.3.2 Carbon Dioxide Emissions and Cost of Energy at Surrey Sports Park

Using the fuel consumption data shown in Figure 4-8, together with the utility pricing and CO₂ intensity data for each fuel shown in Table 4-4, it was possible to calculate the financial cost and the carbon dioxide emissions associated with the facility for each month.

Figure 4-10 – Monthly carbon emissions and cost for energy consumption at Surrey Sports Park from April 2010 to September 2011

The carbon emissions and cost associated with the fuel consumption of SSP is shown in Figure 4-10. A peak in CO₂ emissions was observed in December 2010.
which coincides with when the gas boilers were extensively used to provide heating to the facility. The average monthly energy related CO₂ emissions of 155,400 kg CO₂ is over 90 times greater than the emissions associated with water consumption at the facility presented in Section 4.4.

The biomass boiler installed at SSP has reduced the overall CO₂ emissions associated with the heat requirements of the facility by approximately 327,400 kg CO₂ over the study period compared to a solely gas fuelled system. This equates to approximately a 10.5% reduction in the overall CO₂ emissions for the facility, however, it has also resulted in an additional cost of almost £50,000.

The use of electricity at the facility is the greatest contributor to the CO₂ emissions as shown in Table 4-6. Mains supplied electricity has the highest CO₂ intensity of the three fuels used at SSP with an average emission of 0.590 kg CO₂ emitted per kWh consumed. This is 2.9 and 39 times the carbon intensity of gas and biomass wood chip consumption respectively. In addition, electricity accounted for over 50% of the total energy consumption during the study period. As a result electricity consumption was found to contribute 85% of the CO₂ emissions and 84% of the utility cost for the facility during the study period.

Table 4-6 – Average monthly energy consumption, CO₂ emissions and cost for fuels used at Surrey Sports Park based on data from April 2010 to September 2011

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Energy Consumption (kWh/mth)</th>
<th>% of Total</th>
<th>CO₂ Emissions (kg CO₂/mth)</th>
<th>% of Total</th>
<th>Cost (£/mth)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>222,900</td>
<td>52%</td>
<td>131,500</td>
<td>85%</td>
<td>£16,800</td>
<td>84%</td>
</tr>
<tr>
<td>Gas</td>
<td>109,600</td>
<td>26%</td>
<td>22,400</td>
<td>14%</td>
<td>£200</td>
<td>1%</td>
</tr>
<tr>
<td>Biomass</td>
<td>96,500</td>
<td>22%</td>
<td>1,500</td>
<td>1%</td>
<td>£2,900</td>
<td>15%</td>
</tr>
<tr>
<td>Total</td>
<td>429,000</td>
<td>-</td>
<td>155,400</td>
<td>-</td>
<td>19,900</td>
<td>-</td>
</tr>
</tbody>
</table>

A summary of the average monthly energy consumption, CO₂ emissions and financial cost for each fuel type is shown in Table 4-6. Based on this data it can be concluded that there is greater potential for significant benefits to be achieved through electrical energy savings compared to reducing the consumption of gas or biomass. The total carbon emissions submitted for CRC reporting for the first year of operation resulted in a display energy certificate (DEC) rating of 78, which classifies the facility as performing marginally better than a typical building of this type defined as having a rating of 100.
4.5.3.3 Swimming Pool Energy Consumption for Water Heating

The energy consumption of the swimming pool at SSP was examined in greater detail using data gathered by the BMS system between June 2010 and August 2010. The system recorded the delivered heat load to the pool water every 15 minutes. The heating requirement of the pool water at SSP is met using a centralised heating circuit powered by the biomass and natural gas boilers.

The daily pool water heat load raw data for June and August 2010 is shown in Figure 4-11. Upon review of the data, a sudden drop in the daily heat load was observed after the 20th June 2010. Further investigation discovered that there was an error in the BMS recording of the cumulative pool water heat load. The error was caused by a limitation in the number of digits the system was able to store. As the system could only handle 6 digits, the cumulative meter had incorrectly recorded the heat load after it exceeded 999,999 kWh. This resulted in the recorded energy consumption being 10 times lower than the actual energy consumption.

Attempts to remedy the system meant that no data was recorded during July 2010. Unfortunately, no fix was found for the issue and therefore a manual modification to the data was required. The modified daily heating energy consumption data is also shown in Figure 4-11. A malfunction with the BMS system also occurred on the 24th August 2010 resulting in no heat data being recorded until the 28th August 2010. An average daily heat load of 3,900 kWh was calculated using the data collected during the survey period. The large spike on the 10th August 2010 coincides with major maintenance works on the pool including the exchange of a large volume of water.

![Figure 4-11 – Raw and modified BMS output data for the daily pool water heating load in June and August 2010](image)

There are multiple contributing factors that affect the energy demand for water heating. Heat is lost from the pool water in a variety of ways including conduction,
Impacts of Operation on Facility Sustainability

Convection and radiation from the water body and evaporation of water from the pool surface. The addition of fresh water also adds to the heating demand as the mains water is anything from 10 to 15°C lower than the desired pool water temperature as observed in the longitudinal water quality survey presented in Chapter 2. An estimation of the heating requirement was calculated using data collected during the water quality survey, the user group survey and the water consumption survey in order to provide comparison with the recorded average daily energy consumption.

The evaporation of water from the pool surface is considered to be the most significant route of energy loss (Carbon Trust 2006). An evaporation study for the facility showed that up to 4 m³ was expected to evaporate from the pool each day. The energy associated with this volume of evaporation was calculated to be approximately 2,500 kWh based on a latent heat of evaporation for water of 2260 kJ/kg. It is widely claimed that the evaporation of water accounts for 70% of the energy lost from a swimming pool (Carbon Trust 2008, US Department of Energy 2009). Applying this assumption to the calculation made for evaporative losses results in an expected daily energy loss through the other routes to be approximately 1,000 kWh.

The daily addition of fresh water during the study period ranged from 5 m³ to 25 m³ with an average temperature difference of 13°C. The associated daily energy requirement for heating the fresh water was therefore calculated to range from 75 kWh to 380 kWh using a specific heat capacity for water of 4.18 kJ/kg/°C.

Combining these three energy demands generates an estimated total daily heating demand of up to approximately 3,880 kWh. This is very close to the daily average energy demand that was calculated from the BMS system data. This provides confidence that the BMS system data is correctly accounting for the heat loading of the swimming pool.

4.5.3.4 Swimming Pool Energy Consumption for Water Handling Equipment

The pool water is pumped around the facility using three parallel centrifugal pumps. The pumps are operated at full speed during opening hours but are turned down overnight. Initially the pumps were operated at 50% during the overnight period, however, this was changed by the E&FM team to 75% from July 2010 because of complications with flow control sensors. The power demand for the water pumping system is shown in Figure 4-12. The data shows that the power consumption of the pumps at full speed is 48kW. A reduced power consumption of approximately 30 kW and 18 kW were recorded when the pump speeds were lowered to 75% and 50% respectively.
Impacts of Operation on Facility Sustainability

Figure 4-12 – Power demand profile for the swimming pool water treatment pumps using 15-minute measurements for three weeks selected during the survey period

The BMS also records the cumulative energy consumption of the pool water transfer pumps. An average of 18.7 kWh/day was reported by the system, however, this was significantly lower than the expected energy consumption. During a typical day, the pumping system operates at 100% for 16.5 hours a day with the remaining 7.5 hours operating at the reduced rate. Based on the reported power consumption and the hours of operation it is expected that the daily power consumption should be approximately 1,000 kWh, around 50 times greater than the consumption recorded by the BMS. This indicates that the BMS has not been correctly configured and that the recorded value for the cumulative energy consumption is not correct. The daily energy consumption was therefore calculated using the power demand data shown in Figure 4-12. The daily energy consumption associated with water pumping is shown in Figure 4-13. An average daily energy consumption of 933 kWh (standard deviation = 102) was calculated for the study period.
Reducing the pump speed to 75% overnight has resulted in an annual saving in energy consumption of 54,300 kWh. This energy saving is also associated with a reduction in potential carbon emissions of 32,000 kg CO₂ per year. Addressing the flow control issues to enable the pump speed to be reduced to 50%, as had initially been possible, would result in additional energy reductions of 36,200 kWh per year. This equates to a potential reduction in carbon emissions of 21,400 kg CO₂ per year, approximately 1.1% of the total scope 1 and 2 emissions of SSP.

4.5.3.5 Swimming Pool Energy Consumption for Air Handling Equipment

The air in the pool hall is maintained at 29°C and a relative humidity of 60% by two large air handling units. The electrical power consumption of these air handling units was recorded by the BMS and is shown in Figure 4-14. An unexpected and significant reduction in power consumption was observed during the middle of the day. This was as a result of incorrect specification of the operational period causing the system to reduce the turnover volume by 2/3 between 10:30 and 15:00. In addition the evening unoccupied setting was incorrectly set as between 18:00 and 05:00. The power demand for the air handling units was observed to be more volatile than for water system. This is because the demand on the air handling system is affected by a number of factors including the external weather conditions and the activity levels in the pool. During normal operation, the power consumption was recorded to be between 40 and 65 kW. This was observed to reduce to between 15 and 30 kW when operating using the unoccupied pool settings.
Figure 4-14 - Power demand profile for the swimming pool air handling units using 15-minute measurements for three weeks selected during the survey period

The cumulative energy consumption for the air handling systems was calculated in the same way as the energy consumption for the water pumps using the 15 minute power demand data. The daily energy consumption for the study period is shown in Figure 4-15. An average daily consumption of 800 kWh (standard deviation = 124 kWh) was calculated for the air handling system during the study period. This is likely to increase to approximately 900 kWh/day once the correct timings for reduced-rate operation are loaded into the BMS.

Figure 4-15 – Daily electrical energy consumption for the swimming pool air handling units from June 2010 to August 2010 based on 15-minute power consumption data

The variable nature of power consumption for the normal and reduced-rate operation meant that calculation of the energy saving associated with reduced-rate operation was less accurate. Average power consumption values for full-rate and low-rate operation was calculated as 51 kW and 22 kW respectively. Using these
Impacts of Operation on Facility Sustainability

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes

average values and the correct periods for unoccupied operation an annual energy saving of 87,500 kWh is potentially possible compared to operating at full-rate all day. The addition of a pool cover and an increase in pool air temperature could dramatically reduce the evaporation of water taking place in the pool hall and could potentially result in the ability to turn off the air handling units overnight. If possible this could yield a reduction in energy consumption of 66,400 kWh per year. This would equate to potential carbon emission reductions of 39,000 kg CO2 per year, approximately 2.1% of the total scope 1 and 2 carbon emissions for SSP.

4.5.3.6 Swimming Pool Energy Consumption for Lighting

The final aspect of the swimming pool that can be analysed for its energy consumption is the lighting. The power demand for the swimming pool lighting is shown in Figure 4-16. At night the main pool lights are switched off and only security lighting is left on. In addition, the lighting in the corridors and changing rooms are controlled by passive infrared sensors. This enables the lights to turn off automatically in areas that are unoccupied. As a result the power demand for lighting is observed to fluctuate more significantly during opening hours. The average power demand for lighting in normal operation was calculated to be 6kW during the study period. The overnight settings reduced the power consumption to 0.8kW, a reduction of 87%.

![Power demand profile for the swimming pool lighting using 15-minute measurements for three weeks selected during the survey period](image)

The daily energy consumption associated with the pool lighting for the study period is shown in Figure 4-17. An average daily power consumption of 110 kWh was calculated for the entire study period, however, improved management of lighting resulted in a reduced energy usage towards the end of the study. This is most noticeable in the data for Saturdays where the shorter opening hours means a
lower daily energy consumption of approximately 80 kWh is possible. Analysis of the power demand data indicated that the automated PIR controlled lighting reduces the annual energy consumption by 11,000 kWh. The low energy consumption associated with pool lighting, compared to the other aspects of the pool operation, means that there is less scope for significant savings.

![Figure 4-17 – Daily electrical energy consumption for the swimming pool lighting from June 2010 to August 2010 based on 15-minute power consumption data](image)
4.6 Bather Load Seasonality Survey

4.6.1 Scope

As mentioned previously, it is currently recommended that the amount of water required to be exchanged each day is dependent on the number of people using the pool (PWTAG 2009). The collection of bather numbers at Surrey Sports Park is the responsibility of the SSP staff whilst the exchange of water is the responsibility of the E&FM staff. This can introduce communication challenges to the process. In addition, the manual nature of the process means it is not easy to control the daily exchange volume accurately.

Although it is possible to calculate the discharge time required to exchange a particular volume of water using the discharge pump flow rate, potential errors in calculating the required time by the E&FM staff meant that it was preferable for the a simple standardised procedure to be used. An average bather load was used to determine the discharge time required to ensure adequate water exchange was taking place at the facility. It is therefore important for any trends in facility usage to be evaluated to ensure the optimal water exchange volume is used.

In addition, the successful scheduling and management of pool activities is dependent on understanding the user demands on the facility. These demands can fluctuate from day to day as well as from year to year. Opportunities for optimising the management of the swimming pool facility is therefore only possible if both short term and long term trends are understood. This survey aimed to evaluate the trends in bather numbers at the Surrey Sports Park for the first 2 years after opening in 2010.

4.6.2 Methodology

This survey utilised bather numbers recorded by the SSP team as part of their daily management procedures. Bather numbers were collected by conducting an anonymous head count of people in the pool every 30 minutes during pool opening hours. Total daily bather loads were then calculated by summing the individual head counts throughout the day. The daily record sheets were then filed in the SSP operational office for future reference.

In order to observe trends in overall bather load, cumulative data was generated from the discrete head count data and subsequently analysed using a fortnightly moving average. The use of a fortnightly moving average on the daily bather load data enabled the short-term variation to be moderated and sustained increases and decreases to be observed. Although the use of a fortnightly moving average of cumulative bather numbers presents an effective way for long-term trends to be
identified, the instantaneous bather load is also an important parameter for pool management for two reasons. Firstly, the number of bathers permitted in the pool at any one time must be limited to ensure a safe and manageable environment. The second reason is the introduction of DBP precursors, such as sweat, and other substances into the pool water by bathers that consumes the available disinfectant (Keuten et al. 2012). Two 10-week periods during times of high use were selected for the study; October to December 2011 and January to March 2012. Average daily profiles using the discrete bather head count data were then generated for each period to enable variations in instantaneous bather load to be analysed.

4.6.3 Results

4.6.3.1 Total Bather Load Observations

Figure 4-18 shows the fortnightly moving average of the total bather numbers for the SSP pool, as calculated from the cumulative value of the half-hourly head count data, from the opening of the facility in 2010 for a period of 2 years. There are two significant long-term observations that can be made based on this data. Firstly it is clear that there has been a continual increase in the number of bathers using the facility. Secondly, the data shows that there is large seasonality with regards to the number of bathers using the pool facility.

![Fourtiethly moving average of daily bather numbers at the Surrey Sports Park swimming pool for May 2010 to April 2012](image)

The bather numbers were expected to increase following the initial opening of the facility as public awareness of the facility developed. The continued increase well into the second year of operation indicates that the facility was still in its growth phase and that continued monitoring and adjustment of the operational procedures is necessary to ensure they are fit for purpose.
Daily bather numbers were also observed to be between 38% and 45% lower in the months of April, July, August, November and December than during the rest of the year. This coincides with non-term time periods for the local schools and university. During these periods, the number of school and learn to swim activities taking place at the facility reduces significantly. Similarly, as the facility is linked with the University of Surrey, the staff and students of the university make up approximately one third of the facility’s membership. The combined effect of these factors is likely to account for the majority of the reduction in bather numbers that is observed.

4.6.3.2 Instantaneous Bather Load Observations

The average instantaneous bather load profiles for Monday through to Sunday are shown in Figure 4-19 to Figure 4-25. The range of bather head counts at each monitoring time for each day during the study period is indicated on the figures by the vertical bars.

![Figure 4-19](image1)

**Figure 4-19** – Averaged instantaneous bather loads on Mondays at Surrey Sports Park during two selected periods from the 2011 and 2012 records

![Figure 4-20](image2)

**Figure 4-20** – Averaged instantaneous bather loads on Tuesdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records
Impacts of Operation on Facility Sustainability

Figure 4-21 – Averaged instantaneous bather loads on Wednesdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records

Figure 4-22 – Averaged instantaneous bather loads on Thursdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records

Figure 4-23 – Averaged instantaneous bather loads on Fridays at Surrey Sports Park during two selected periods from the 2011 and 2012 records
Impacts of Operation on Facility Sustainability

Optimising Sustainability, Performance and Public Health Protection in the 4-40 Design and Operational Life Cycle of Sports and Leisure Pool Complexes

Figure 4-24 – Averaged instantaneous bather loads on Saturdays at Surrey Sports Park during two selected periods from the 2011 and 2012 records

Figure 4-25 – Averaged instantaneous bather loads on Sundays at Surrey Sports Park during two selected periods from the 2011 and 2012 records

From this analysis of the data it can be seen that the instantaneous bather profile for each day was significantly different, however, there was good similarity between the profiles generated for the two study periods. Although the times, sizes and durations or the peaks in instantaneous bather load vary from day to day a few general trends can be observed. During weekdays the peak in bather loading occurs in the late afternoon and early evening. In addition, the number of early morning swimmers is fairly consistent for the weekdays with an instantaneous bather load of between 20 and 30. Finally, the data shows that during the weekdays the bather numbers are highly volatile and directly associated with the scheduling of activities in the pool.

The weekend profiles exhibit a couple of significant differences from the weekday profiles. The peak bather load was predominantly in the morning with the number of bathers declining over the day. The instantaneous bather load was also far less
volatile on the weekends. This reinforces the evidence that pool activity scheduling is a very significant factor influencing the loading on a pool.

The final observation with significant relevance to the operator is in relation to pool capacity. Current guidance recommends that, for a facility the size of the SSP pool, the maximum instantaneous bather load is 250 bathers. The actual peak instantaneous bather load observed at the SSP facility did not exceed 80 bathers which is significantly lower than this limit.
4.7 Discussion

Following the assessment of the impacts associated with the current Surrey Sports Park operations, as described in Section 4.3, a series of improvement proposals were developed supported by the findings of the three operational surveys, presented in Section 4.4 to 4.6. These proposals could be broadly grouped into three categories: Infrastructural Changes, Operational Changes and Behavioural Changes. These proposals are discussed here together with the potential benefits that could result.

4.7.1 Potential Improvements through Changes to Surrey Sports Park Infrastructure

Many of the simple and mainstream efficiency saving options, such as the installation of variable speed drives on the water pumps, have already been implemented during the construction of the facility as part of planning requirements. This has the effect of more substantial changes in the infrastructure being required in order to make additional improvements. The improvement strategy proposed within this section focuses on two clear objectives: to reduce the impact of water use and to reduce the impact of energy use.

4.7.1.1 Reducing the Impact of Water Use

As shown in the water consumption survey, water is a resource that the facility currently consumes in significant quantities. There are two approaches that can be used to reduce the impact of water consumption by the facility. The first is to find alternative, non-mains sources of water and the second is to reduce the overall water demand of the facility. Some potential options for each approach are presented below.

*Installing a Rainwater Harvesting System*

The facility has a grey water storage system installed, however, it is not connected at present as it was removed from the plans during construction. Completing the installation would enable rainwater harvesting to take place and provide additional water for either irrigation or sanitation. The south-east receives around 650mm of rainfall annually (Met Office 2011). The footprint of the building is approximately 10,000 m² therefore the potential volume of water that could be provided by rainwater harvesting is 6,500 m³. This equates to 45% of the annual water consumption associated with irrigation and sanitation. Water run-off from the hard standing areas could also potentially be recovered and used although additional treatment systems may be required to prevent oil and silt from impacting the final...
use. The use of hard standing water harvesting has the potential to double the volume of water that could be collected for use at the facility.

The demand for water at the facility is a key factor in assessing the benefits of rain water harvesting. The demand for sanitation is fairly consistent throughout the year and is estimated to be around 11 m$^3$ per day. The current storage facility is capable of holding approximately 9 m$^3$. Unfortunately, storage becomes a significant issue when considering re-using water run-off for irrigation. The demand for irrigation is highest when rain has been at its most infrequent. The inclusion of large adaptable water features in the future Manor Park development would enable significant storage of storm water to be achieved making it available for irrigation during dry weather.

*Reusing Backwash Water*

An alternative potential source of water is associated directly with the swimming pool operations. Large volumes of water, currently between 15 m$^3$ and 20 m$^3$, are discharged daily as part of the water management process for the swimming pool. This water is discharged directly to sewer at present. It is proposed that SSP should invest in a system that can enable the reuse of the discharged water from the pool. There are three potential reuse options at SSP, each of which will require a different level of investment in order to be implemented:

- Reuse in the pool
- Reuse in the grey water system
- Reuse for pitch irrigation

For backwash water to be used in the pool, an extensive treatment system would be required including additional filtration, chlorine removal and reverse osmosis equipment. After allowing for efficiency losses, this would reduce the amount of mains water required and pool water discharged by an estimated 4,400 m$^3$ per year. This system would not require additional storage facilities as the treated water would be instantly reused as makeup water in the pool. Although this would realise a saving of approximately £5,400 per year in water utility costs, the capital cost of the installation and the operational costs of the additional energy required to run the treatment plant is likely to impact the payback period significantly. This system is currently operating at a number of facilities, such as the Tottenham Green Leisure Centre, and therefore it would be advised to review a fully operational system as part of a more general feasibility study.

Irrigation activities are the largest consumer of water at SSP. Treating the backwash water and reusing it for this purpose could greatly reduce operational costs. The level of treatment required is significantly lower than that required for use in the
Impacts of Operation on Facility Sustainability

pool as health risks associated with its use are lower. The main requirements would be the removal of solid debris and the residual chlorine. This can be achieved using the combination of a filter and granular activated carbon. Some water would be still be required to be discharged in order to clean the additional filters, however, up to an estimated 5,600 m$^3$ per year could be reused based on a 95% recovery. As mentioned in relation to rainwater harvesting, the uneven demand for irrigation would result in a seasonal ability for water to be reused and would also present storage issues. The significant difference is that the supply of backwash water is not seasonal therefore large-scale long-term storage is not required. Potentially an additional UV unit may be required downstream depending on the final microbiological quality required for the water. This would have a potential impact on the operational savings that could be achieved although it is expected to be relatively small compared to the estimated £7,000 per year in water savings.

The use of backwash water to the flush the toilets in the facility would require minimal treatment as only suspended solids would have to be removed. A simple cartridge filter could be used for this. The amount of water discharged by the pool daily, currently 16 m$^3$/day on average, is greater than the amount of water used for sanitation purposes, currently 11 m$^3$/day on average. This strategy would have the lowest upfront cost as the facility already has a grey water storage tank connected to the sanitation system and could also realise savings of approximately £7,000 per year. This is likely to be the most beneficial option for the facility at present. Should the following proposals for reducing water demand in the facility also be implemented there may be significantly more water available than the sanitation requires. In this case it could be more beneficial to implement the changes required to use the water for irrigation purposes as well in order to maximise the water reuse potential.

Reducing Overall Water Demand

The use of water efficient equipment and fittings within the facility can also help reduce the impact associated with water use. At present the urinals are on a single automated low-flow flush system. This means that all urinals in a zone are flushed regularly regardless of whether they have been used. Waterless urinals are an option, however, the conversion and maintenance costs offset the financial savings from reduced water use. This type of urinal also often requires the use of specialist chemicals which may have a greater environmental impact on a life cycle basis. Reducing the amount of water used for each flush and ensuring that flushes happen only when necessary are therefore considered more beneficial. The use of Infra-Red (IR) sensors on the urinals would prevent unnecessary flushing from occurring. Preventing the urinals from flushing overnight would also reduce water
consumption by approximately one third. Similarly, the use of water efficient dual flush toilets could reduce the water demand for sanitation in the facility.

Most of the sink taps in the facility are low-flow plunger operated ones meaning that they continue to run for a short period after the user has finished using it. IR sensors would prevent this from occurring and therefore could reduce wasted water. Similarly, IR sensors could be fitted to the low-flow showers in the facility to prevent the running of showers when unoccupied. With over 14,000 members and an even greater numbers of occasional visitors using the facility, significant water savings could be achieved. For example, reducing the wasted run time of showers in the swimming pool alone by just 15 seconds for each of the 250,000 visits that take place in a year could result in a saving of 450 m$^3$ per year, approximately 1.7% of the annual water consumption of the entire facility.

As highlighted in Section 4.4, approximately 82 litres of water evaporates from the unoccupied SSP pool each hour. The use of a pool cover during the hours when the pool is unoccupied would significantly reduce the amount of evaporation. Placing a cover over the pool overnight could therefore reduce the water consumption by approximately 250 m$^3$ per year resulting in a saving of £300 per year. Raising the moveable floor to the surface when the top end of the pool is not in use would also help to reduce the evaporative losses. Although the cover would help to reduce the water demand for the facility, the main benefits are in relation to energy savings as discussed below.

4.7.1.2 Reducing the Impact of Energy Use

The facility uses a significant amount of energy at present. Opportunities to directly reduce the electricity and gas consumption have been considered in the design of the facility. These include the use of variable speed drives on the pool circulation pumps, energy efficient and PIR controlled lighting and a biomass powered heating circuit. The main impacts in relation to energy use were associated with the electrical consumption of the facility. This section therefore focuses on potential improvements that could result in a reduction in the electricity demand for the facility, however, some methods of achieving potential heating savings are also mentioned.

*Installing a Pool Cover*

Installing a swimming pool cover would prevent evaporation of pool water during times when the pool is not in use as mentioned in the previous section. The overnight evaporation of 250 m$^3$ of water each year is associated with the direct loss of approximately 157,000 kWh of heat energy from the pool. In addition,
installing a pool cover could enable the ventilation system to be turned off altogether during the unoccupied periods, reducing the annual electrical consumption of the pool by a further 66,400 kWh. The combination of these energy savings could result in financial savings of up to £8,300 per year and a reduction in CO$_2$ emissions of 41,700 kg CO$_2$ per year.

*Installing Pool Side Controls for Air and Water Plant*

The bather load survey showed that the number of people using the pool can vary significantly during the day. Smith *et al.* (1998) and Shah (2011) have shown that the evaporation rates of swimming pools are significantly affected by the number of people using the pool. The instantaneous bather load of the pool at SSP was observed to vary from as low as 10 bathers to upwards of 80 bathers. At the low end of the range the evaporation rate may not be much greater than for an unoccupied pool whereas at the higher end evaporation could be more than double that of an unoccupied pool. Similarly, Keuten *et al.* (2012) showed that the impact on water quality is dependent on the instantaneous bather load. The bather load survey highlighted that the facility is operating far below the designed capacity and therefore a reduction in the water treatment intensity could be possible.

The significant variation in bather numbers presents an opportunity for potential energy savings to be made through the implementation of bather-load-related controls on the water and air handling systems. Installing poolside controls would enable the operator to reduce the turnover rates when the bather count is low, for example less than 10% of occupant capacity. On average, the instantaneous bather load is below 10% of designed capacity for approximately 40% of the opening hours. The ability to operate the facility at the reduced rate during low use periods could potentially reduce the electrical consumption of the swimming pool by up to 108,000 kWh per year. This equates to a financial saving of £8,600 per year and a CO$_2$ emissions reduction of 63,700 kg CO$_2$. The impact on air and water quality of making these changes is unknown and therefore an in-depth monitoring program would be needed following these changes.

*Installing Energy Recovery Systems*

At present the air and water discharged from the pool facility do not pass through any form of energy recovery. The outgoing air and water is usually significantly warmer than the incoming fresh supplies. The energy used in raising the air and water to the desired temperature is therefore lost during discharge. The use of energy recovery systems could enable the heat energy in the discharge to be used to offset some of the heating requirement for the facility. Similarly the heat output from the buildings air conditioning systems could be harnessed to provide heating.
elsewhere in the facility. Further work would be required to determine the potential energy savings that would be achievable through the implementation of these techniques as feasibility studies were not within the scope of this research project.

**Installation of Renewable Energy Generation Systems**

The impact of the energy consumption of the facility could also be reduced through the use of onsite renewable energy generation systems. There are a wide range of renewable energy sources that may be suitable for use. These include electricity generating technologies such as wind turbines, photo-voltaic panels and combined heat and energy systems as well as thermal energy systems such as ground source heat pumps and solar thermal panels. Conducting feasibility studies on these major infrastructural changes falls outside the scope of this research project, however, a basic strategic review of the options was undertaken.

The swimming pool presents a significant opportunity to maximise the benefits of a renewable heating system as it requires a fairly constant low level of heating. The presence of a large unobstructed roof and a large amount of land surrounding the facility means that both solar thermal collectors and ground source heat pumps are potentially feasible. As the facility has already invested in a biomass boiler system to provide the bulk of the heating requirements of the facility, however, the benefits of installing these systems now is greatly reduced.

The large unobstructed roof of the facility also makes the installation of a large scale photo-voltaic system possible. The average electrical power consumption of approximately 300 kW means that it is unlikely that any of the electricity would be exported to the grid unless a very large solar array was constructed. The potential annual solar power generation in the south-east of England is approximately 850 kWh per kW_{peak} of the installed system per year (PVGIS 2012). Therefore, assuming a 250 kWp system was installed, the total annual electrical generation could be up to 212 MWh, which is approximately 8% of the total electrical consumption of the facility. The financial benefit for any installed system is likely to be dependent on the feed-in-tariff achieved for the installation, however, assuming a feed-in-tariff rate of 10 p/kWh, the installation of such a system could result in financial savings of up to £38,200 per year and reduce CO₂ emissions by up to 125,000 kg CO₂ per year. The cost of photovoltaic installations has come down sharply in recent years and a recent installation of this size was built for £250,000 (Choudhury 2013). At this cost the payback period would be less than 7 years.
4.7.2 Potential Improvements through Changes to Surrey Sports Park Operations

In addition to the infrastructural changes mentioned in the previous section, there are a few opportunities to improve the sustainability of the Surrey Sports Park through the modification of operational practices. The following proposals can be undertaken without the need for changing the existing equipment.

4.7.2.1 Modification of Pool Air Conditions

The temperature and humidity of the pool air has a direct impact on the rate of evaporation from the pool water surface. As mentioned in the previous section, evaporation is associated with significant energy use at SSP. At present the air temperature is maintained at 1°C above the water temperature and at a maximum humidity ratio of 60%. Increasing the temperature differential between the air and water to 2°C would reduce the occupied and unoccupied evaporation rate by 4.3% and 24.4% respectively. This would result in a reduction in water evaporation of approximately 110 m$^3$ per year and therefore a reduction in the water heating requirements of 69,000 kWh per year. Unfortunately no data on the air side heating requirements was collected during the energy survey so it is not possible to compare this with the potential additional energy demand for air side heating. Similarly, it is not possible to calculate the savings the reduced evaporation would have on the air handling unit energy consumption. It is therefore recommended that the pool air temperature is increased to 30°C and a period of energy monitoring is undertaken. Although further increases in temperature would reduce the evaporation further, this could create an uncomfortable environment for the bathers.

The current guidance by PWTAG (2009) also recommends a minimum of 30% fresh air to be used in order to prevent the accumulation of airborne contaminants. A reduction in the amount of evaporation taking place will reduce the benefits of adding fresh air. The monitoring of air quality in the pool hall falls outside the scope of this research project and is required to make further analysis possible. An in-depth quality and energy study on the air-side of the pool environment, similar to that undertaken on the water side, would enable better quantitative analysis of operational changes to be undertaken.

4.7.2.2 Modification of Pool Water Refresh Rate Formula

The control of water quality through dilution is a necessary aspect of pool operation. At present a very simple method is recommended by PWTAG (2009) for the calculation of the required volume of water to be added, 30 litres per bather
per day based on bather numbers calculated using half-hourly head count data. The work undertaken in this project identified some issues with this simple approach. The first is that, at very low bather numbers, the method may result in inadequate water exchange. The method also has the potential to greatly overestimate the amount of water required to maintain a clean and safe swimming environment in a well-designed pool. Finally, the methodology for assessing bather numbers can be very inaccurate.

A main source of dissolved contaminants in the pool water is through the use of pool chemicals. The volume of chemicals added to the pool at the facility in the study is controlled automatically. The activity study, presented in Chapter 3, showed that although the type and number of users affected the rate at which disinfectant was consumed, chemical dosing was found to still occur during unoccupied periods as well. Accordingly there is a base load of chemical addition that means an amount of water ($W_c$) is required to be exchanged regardless of bather load in order to prevent accumulation of impurities, such as chlorides, in the pool water.

The study by Keuten et al. (2012) reported that a large proportion of bather-related contaminants (60%) are usually introduced upon initial entry to the pool or through preventable releases that can be significantly reduced through good pre-swim hygiene practices. The amount of water required to meet the bather load demand will therefore depend on the bather management of the facility. Including the proportion of bathers not using a shower before entry ($F_{ns}$) would enable the water exchange value for bathers to be broken down further into a requirement for initial bather contaminant loading ($W_{bi}$) and a requirement for continuous bather contaminant loading ($W_{bc}$).

The following proposal for a modified methodology for calculating the expected water consumption of a swimming pool facility, Equation 6, is therefore generated by combining these developments with the modifications for bather numbers and evaporation losses.

$$W_p = (F_b \times N \times ((F_{ns} \times W_{bi}) + W_{bc})) + W_c + W_{ev} \quad \text{Equation 4-6}$$

This relationship takes account of the variety of uses of water within the facility and also incorporates factors that are affected by the operational management of the facility. By adopting this approach it would enable operators to better understand the impact operational changes would have on their water consumption. Further work is required however to enable a mass balance approach to be used in determining the values for the three new parameters $W_c$, $W_{bi}$ and $W_{bc}$. 
4.7.2.3 Adoption of Seasonal Normal Operating Procedures

The facility is operated in line with a predefined set of normal operating procedures (NOPs). These are produced by senior managers to ensure that all staff operate the facility in an appropriate way. In relation to the swimming pool operation there are two separate NOPs, one for the SSP staff and one for the E&FM staff. Both of these NOPs currently specify that the pool is operated in the same way throughout the year. The bather load study reported in section 4.6 highlighted that there are daily and seasonal trends in pool use. This information could be incorporated into the development of the NOPs to improve the management of the facility. For example, the air and water treatment systems could be operated at a lower intensity during the known low use periods of April, July, August and December.

Similarly, the water quality survey presented in Chapter 2 showed that there were seasonal trends in the mains water temperature. The temperature of the incoming mains was observed to fluctuate by over 10°C over the course of the year. Therefore, there is the potential for energy savings to be possible through adopting modified approach to the water exchange procedures for the facility. Reducing the amount of water exchange that is undertaken during the period when the supply water is at its coldest and increasing the exchange rate in when the temperature is warmer could save significant amounts of energy required for heating. This approach would clearly have an impact on the stability of pool water quality parameters. Further investigation would be required to assess the level to which seasonal variation could be applied to the water exchange rate without the water quality falling outside of suitable parameters.

4.7.3 Potential Improvements through Behavioural Changes at Surrey Sports Park

In addition to infrastructural and operational changes, it is important that the Surrey Sports Park engages with its staff and visitors in order to achieve improvements in the sustainability of the facility. Many of the issues identified throughout the previous chapters are dependent on the people involved making changes to their current behaviours. The following section highlights proposals for encouraging the key behaviour changes needed to assist with optimising the sustainability of the swimming pool. Other general proposals are presented in the corporate social and environmental responsibility (CSER) review in Appendix 4.

4.7.3.1 Improving Bather Hygiene

Pre-swim routines and bather hygiene have been identified as significant factors affecting the intensity of water treatment required. Reducing the number of
bathers that enter the pool without showering or wearing appropriate swimwear would reduce the amount of unwanted chemicals entering the pool. Encouraging the members of the public using the swimming pool to make these behavioural changes will require finding ways to engage with them. The increase in quantitative data in relation to the benefits of good user behaviour has provided new information on which to base public focused campaigns.

The user study presented in Chapter 3 indicated that a program of bather education is required to promote the adoption of good bather behaviours. The profile of environmental responsibility amongst the public audience has increased significantly and therefore campaigns relating user behaviour to energy consumption or carbon emissions are becoming more effective. Using data published by Keuten et al. (2012), it can be estimated that a combination of having a short shower (15-30 seconds) before swimming and refraining from urinating in the pool could almost halve the total DBP precursors and therefore reduce the chlorine demand and DBP formation rate. This in turn would cut the rate of water exchange required per bather and could save in the order of 3,500 m$^3$ of water and 52,800 kWh of heating energy per year. The savings associated with the supply, disposal and heating of this volume of water would be approximately £5,900 per year, approximately 5% of the total utility cost for the SSP swimming pool. In addition, it would reduce the chemicals needed to maintain pool water quality and therefore improve the overall aesthetics of the pool hall.

Although this may not appear significant when applied to a single facility, a much greater impact can be achieved if the savings are put in context of the wider UK swimming industry. Based on the report by the Department for Culture, Media and Sport (DCMS) in 2011, there are approximately 3.9 million adults and 5.5 million children using UK pools every week, therefore up to 5 million m$^3$ of water and over £10 million could be saved if bathers improved their bathing habits. This would be associated with a reduction in energy consumption and carbon emissions of approximately 74 GWh and 15,000 t CO$_2$ respectively.

4.7.3.2 Improving Staff Behaviours

It is also very important that frontline staff engage with the management’s desire to improve the sustainability of the facility. The accurate monitoring and delivery of the operational activities is essential in order to maximise the benefits that can be achieved. It is important that the pool staff are informed with regards to the impacts that their actions and those of the visitors can make on the efficiency of operations. It is therefore important that site specific training is continually given to the E&FM and SSP employees and that feedback on the facility’s progress is given.
4.8 Conclusions

This chapter has presented the outcomes of an in-depth review of the energy and water use associated with the swimming pool at Surrey Sports Park. The work undertaken has highlighted the impact that operational aspects of swimming pool facilities can have on the environmental and financial performance of a facility. The three most important operational aspects in relation to the cost of swimming provision have been identified as the pumping of pool water, the management of the air condition and the loss of heat from the pool water.

The main use of water in the swimming pool was associated with water quality requirements. The study showed that poor communication at facilities can result in inadequate water exchange to be undertaken. A new performance indicator, Water Exchange Deficit, is proposed to assist with identification of long-term trends in water exchange. The correct accounting of bather numbers was also shown to be important in the efficient operation of a swimming pool. Current counting methods were found to overestimate the amount of water required to maintain the water quality of the swimming pool and therefore the use of a correction factor is required. An enhanced relationship is also proposed for calculating expected water use that enables a broader range of factors to be accounted for. This relationship requires further work to be undertaken to establish appropriate values for the new water exchange parameters.

The evaporation of water is also a primary concern in the case of swimming pool efficiency as it not only contributes to the water consumption and heating demand of a facility but also contributes to the energy demand for dehumidification and air handling. The study has validated published theoretical equations that have been proposed for predicting evaporation in swimming pools. The study used this to show that amendments to operational guidance can help to reduce the evaporation in particular increasing the recommended air-water temperature differential to 2°C. The simple addition of a pool cover was also shown to achieve significant improvements to the operational cost of swimming pool facility. The negative impact shown in not having a pool cover strongly suggests that all pool facilities must incorporate a pool cover.

Although the addition of a pool cover would reduce the heat loss from the pool during unoccupied periods, there is little that can be done to reduce the heat loss during occupied periods. Pools will therefore be associated with a large heating demand. The study has shown that although the use of biomass boilers is effective at supplying the heat load and reducing the long-term CO₂ emissions when compared to gas boilers, they are far more expensive to operate because of the
very low price that large organisations, such as the University of Surrey, pay for their standard utilities.

The use of variable speed drives combined with improved knowledge about trends in bather loading presents an opportunity to significantly reduce the energy consumption of the facility. The reduction of pumping speed, however, will have an impact on the distribution of disinfectants and the removal of suspended material from the pool tank. In order to make firm recommendations in relation to how much speed reduction is appropriate, a better understanding of the hydraulic flows in the pool tank is required. This was identified as a significant gap in the current industry knowledge and was therefore selected for further investigation.

The variation in utility price and in the national energy infrastructure can have a significant impact on the analysis of energy data and the outcomes of option appraisal. Since the studies were undertaken in 2010 and 2011, developments in the UK utilities industries have resulted in changes in both the price and CO$_2$ intensity of utilities. It would therefore be recommended that further work investigating the sensitivity of the appraisals presented in this study are undertaken to ensure that future guidance is robust in relation to further changes.
4.9 References


Barnes, G.T. (2008) The potential for monolayers to reduce the evaporation of water from large water storages, Agricultural Water Management 95, 339-353


Carrier (1918) The temperature of evaporation, ASHVE Transactions 24, 25–50


DCMS (2011) This cultural and sporting Life: The taking part 2010/11 adult and child report, Department for Culture Media and Sport, London

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes


Devin (2010) Discussion about the design practices for large swimming pools, Devin Consulting [Telephone Conversation] (Personal Communication April 2010)


Impacts of Operation on Facility Sustainability


Papathanasiou, A. (2011) *Effect of maturation time on the performance of sand filters used for the treatment of swimming pool water*, MSc Dissertation, University of Surrey, UK


Impacts of Operation on Facility Sustainability


SSINA (2001) *Designer handbook: Stainless steel in water handling and delivery systems*, The Specialty Steel Industry of North America, USA


University of Surrey (2011) *Utility pricing for surrey sports park*, [email] (Personal Communication November 2011)


Chapter 5 - An Assessment of the Suitability of Computational and Physical Modelling for Aiding Pool Design and Operation

5.1 Introduction

The hydraulics of the swimming pool is a critical element in ensuring that the water quality is effectively maintained. Areas of poor circulation can increase the risk of microbial pathogens or chemical by-products accumulating to harmful levels (WHO 2006). On the other hand, if water circulation rates are too high it may generate undesired currents in the pool (Devin 2010). In addition, the pumping of water is a significant contributor to the operational cost of a facility, as discussed in the previous chapter. The increase in demand for aquatic activities, coupled with the increasing cost of construction and operation of swimming pools, has resulted in pools being designed to incorporate multiple activities (PWTAG 2009). The installation of internal structures results in pool designs that are far more complex than the rectangular tank on which the existing guidance has been based. A study commissioned by the Sports Council identified the potential for movable floors and bulkheads to impact the circulation of water in the pool tank (Sports Council 1994). The adoption of new treatment technologies has also made large alterations to the operation of swimming pools (HSE 2007).

Currently, the circulation of water within swimming pool tanks is examined using dye tests after the facility is constructed (PWTAG 2009). Although an effective way of assessing the effectiveness of chemical dispersion within the tank, making changes to pool facilities retrospectively is associated with very high costs or in many cases not feasible (Sports Council 1994). Consequently, it is essential that potential issues are identified in the design stage prior to construction. The development of tools and methods for predicting the nature of the pool environment is therefore important.

A core objective of the research was to advance the understanding of the effects of operational practices on pool water quality. Knowledge of the hydraulics in the pool tank under different operating conditions was highlighted, during the review of current guidance, as a fundamental aspect that requires improvement. The research undertaken investigated the potential for hydraulic modelling to address this issue. This chapter presents the analysis undertaken using computational and physical methods for modelling the hydraulics within a conventional competition swimming pool, such as the one at the Surrey Sports Park.
5.2 Literature Review

5.2.1 Use of Modelling in the Prediction of Pool Environments

As mentioned in Chapter 2, there are a number of substances found within the pool environment that can potentially cause harm to bathers and employees through a variety of exposure routes. It is therefore important to be able to predict the concentrations, movement and behaviour of these substances in the air and water within the pool environment. Various studies have attempted to predict the rate of disinfection by-product (DBP) generation in chlorinated water systems through developing mathematical models (Elshorbagy et al. 2000; Gallard and Gunten 2002; Letterman 1999). Pilot-scale physical models have also been used to predict the formation and fate of DBPs in swimming pool water using a mass-balance approach (Judd and Black 2000; Judd and Bullock 2003; Skibinski and Uhl 2011). These studies, together with published data collected from actual pools, provide a basis on which prediction of DBP concentrations within pool water can be based. Erdinger et al. (2004) identified that the majority of trihalomethane (THM) uptake by bathers was via air inhalation, however the extent of the exposure was hard to determine due to the large variability in published air-borne concentrations of DBPs. A mathematical model for the prediction of air-borne chloroform concentrations based on concentrations within the water and air conditions was developed by Hsu et al. (2009). Although the model considered the effects of water circulation rate and bather activity on the rate of liquid to gas transfer, the model assumed a uniform and steady-state water environment.

In order for models like those mentioned above to be accurate, knowledge of the distribution of DBPs within the water body must be known. The nature of mixing and flow conditions within the pool tank are therefore needed to accurately predict the associated health risks. To date, there have been very few studies investigating the hydraulics within swimming pool tanks. The Sports Council (1994) based their concerns in relation to the effects of internal structures on visual dye dispersion and tracer experiments within a full-size swimming pool tank, however details of the experiments undertaken were not presented. A short study, undertaken by an American campaign group looking to ban the use of base outlets, used CFD to investigate the effects of removing base outlets on small domestic pools (ANSYS 2006). The presented study claimed that there was negligible effect on the overall pool circulation when base outlets were not included, however no details were disclosed in relation to the modelling methodologies undertaken in the report and therefore it is not possible to validate the conclusions. A more recent CFD study by Cloteaux et al. (2011) presented an analysis of water flows in a simple domestic
pool using CFD. The study investigated the possibility of using simple numerical models to represent the circulation within the tank and indicated that there is potential for pool tanks to have multiple zones of differing hydraulic characteristics. Although the study by Cloteaux et al. (2011) is likely to be more impartial than the one presented by ANSYS (2006) as it did not set out to prove a specified hypothesis, it also failed to present any validation of the simulation results. This was improved in subsequent research undertaken by Cloteaux et al. (2013). The second publication reported the results of hydraulic modelling on a range of pool tank styles and included further detail on the modelling settings used for the CFD simulations, such as boundary conditions and mesh sizing.

Although the reports by Cloteaux et al. (2011, 2013) and ANSYS (2006) had noteworthy shortcomings, they indicate that CFD presents the swimming industry with a tool for enabling designers to predict pool hydraulics and avoid the potentially high costs of retrospective modification of pool facilities. Historically in the swimming industry, the use of CFD has appeared to have been largely limited to the optimisation of athlete performance. Craik (2011) reported that the successful application of CFD in high profile cases, such as the “supersuit” development, has driven the interest in computational modelling within the industry. A number of studies have been undertaken to investigate ways of improving swimming technique and equipment to reduce drag and ultimately improve performance (Bixler and Riewald 2002; Marinho et al. 2010; Sato and Hino 2010; Silva et al. 2008; Zaidi et al. 2008).

5.2.2 Use of Computational Fluid Dynamics in Other Industries

Although there are not many published hydraulic studies focusing on the swimming industry to draw information from, a review of modelling practices in other industries can be used to provide a broader knowledge base on which to develop appropriate modelling methodologies. CFD has been used extensively in a number of industries ranging from motorsport and aviation to chemical process and equipment design (Behrouzi and McGuirk 1998; Bridgeman et al. 2010, Gosman 1999, Hanna 2012). The use of CFD to investigate hydraulic characteristics of water infrastructure and process vessels has also been widely investigated. Swimming pool tanks rely on the inlet water jets to provide the circulation needed to avoid areas of stagnant water forming (Devin 2010). Studies of the hydraulics of jet-mixed process vessels and disinfection contact tanks were therefore considered to be the most relevant case studies for the swimming pool application.

Rauen et al. (2008) found that a modified k-e model could predict the size of the mixing zone in chlorine contact tanks to within 90% accuracy, when compared to
experimentally generated results. Furman and Stegowski (2011) compared the ability of turbulence models to accurately predict the mean residence time of fluid in a vessel. Residence time distribution (RTD), a measure of the period of time a substance of interest remains within a hydraulic system, was also selected as the method of validation for reactor vessels in the study undertaken by Bai et al (2008). These studies show that although close replication of RTD can be achieved, the use of RTD on its own is not sufficient to conclude whether the flow field is represented accurately (Bai et al. 2008; Furman and Stegowski 2011). Jayanti (2001) investigated the effects of geometry on the flow field within jet-mixed axis-symmetric vessels using the comparison with similar examples, for which there were experimental data, to provide validation for the study. CFD-derived flow through curves, a statistical tool for representing the temporal distribution of tracer concentrations in the system outlet, have been used to determine the appropriate modifications to be made to existing large water storage tanks in order to improve their hydraulic efficiency and reduce short-circuiting (Stamou 2008). Wright and Hargreaves (2001) investigated similar aspects on the much smaller scale of a single ultraviolet treatment unit by focusing on the maximum dosage and outflow achieved by each design.

As available computing power has increased, so more sophisticated CFD models have become available. While use of 3D Reynolds-averaged Navier-Stokes (RANS) modelling is now widespread, it is limited by the turbulence modelling assumptions. Large eddy simulation (LES) is now a popular research tool in many areas of fluid mechanics. This is expected to give more reliable predictive capability, but it is itself limited by high computational demand. For turbulent jets, there is still considerable interest in the application of RANS models to mixing problems. The development of CFD capabilities has provided an opportunity for more complex arrangements of jet flows to be investigated more readily and is increasingly becoming an important part of hydrodynamic design processes.

5.2.3 Validation of Computational Fluid Dynamics Modelling

The previously reported studies by Cloteaux et al. (2011) and ANSYS (2006) did not verify the accuracy of the simulation outputs and did not evaluate the effect of key simulation parameters, such as mesh density and turbulence model, on the results. Many similar studies have shown that changes in simulation setup can result in variations in the simulation outputs. Wright and Hargreaves (2001) showed the importance of undertaking sensitivity analysis on the various aspects of the model including mesh size and choice of turbulence model. This is supported in a more recent study by Furman and Stegowski (2011). In order for designers to use the
solutions to support design decisions it is important that the accuracy of the simulations is understood. Undertaking sensitivity analysis and verification is therefore necessary to provide confidence in the results.

Although sensitivity analysis can determine the variability of numerical solutions, the accuracy of the stabilised solution can only be confirmed through the use of experimental data. A variety of methodologies have been proposed as validation methods including visual comparison, residence time distribution (RTD) experiments, laser doppler velocimetry (LDV) and particle image velocimetry (PIV) (Behrouzi and McGuirk 1998; Furman and Stegowski 2011; van Hooff et al. 2012). The choice of validation method is largely dependent on the timescales and budgets available for the study. For example, Cloteaux et al. (2013) applied the use of CFD simulation to investigate the hydraulic behaviour of shallow confined jets in the setting of a swimming pool, however, validation was limited to the use of residence time distribution data from tracer experiments. This is a common approach for validating mixing scenarios with further examples presented by Stamou (2002) and Bai et al. (2008). Many researchers have also based validation of their CFD on free jet data and assumed that the methodology will be applicable for more complex cases. For example, Aziz et al. (2008) validated the CFD methodology using a free jet case before using it to simulate near surface discharge into a river. Similarly Wasewar and Sarathi (2008) used free jet data to support the CFD solutions for jet mixed tank simulations. Jayanti (2001) combined both use of free jet and residence time data of these methods to enhance the confidence in the CFD results. The study by Furman and Stegowski (2011) shows this approach still does not enable details regarding local velocity fields to be validated. Experimental data for shallow, free surface confined jets published by Madina and Bernal (1994) and more recently by Shinneeb et al. (2011) enables further scrutiny of CFD methodologies to be undertaken for shallow confined jet cases, where the jet development is limited by interaction with the water surface and tank walls, such as those used in swimming pool applications.

5.2.4 Turbulent Jet Modelling

Generating experimental data from large water-bodies is often too costly and difficult to undertake and therefore very few examples of validated large-scale CFD simulations exist (Patwardhan 2002). The accuracy of the solution was inferred from the accuracy at which CFD could replicate smaller geometries and key hydraulic phenomena. As mentioned previously, the distribution of disinfectants throughout the swimming pool is achieved using the injection of treated water through multiple
submerged jets. Therefore, formation and decay of turbulent jets was considered to be the most relevant hydraulic phenomena for the current study.

Turbulent jets are found across a wide variety of industries and in a diverse range of applications. Jets are used to provide dispersion, agitation and propulsion of fluids in both unconfined and confined environments. The interaction of jet flows with free surfaces, solid surfaces and other recirculating flows can affect the development and therefore the hydrodynamic characteristics of the jet flow. Knowledge about the behaviour of turbulent jets in different scenarios is therefore of interest to many industries, resulting in a large body of published research. There are three types of jet flow; Plane Jet, Round Jet and Radial Jet. In the case of swimming pools it is the round jet that is of most interest and was therefore the focus of this study. A round jet is created when a jet exits from a nozzle or orifice and enters a body of quiescent fluid. As the jet progresses downstream of the nozzle exit, it entrains fluid from the surrounding body of fluid causing the jet to spread radially, dissipating its energy and causing the jet to decay. A schematic of a round jet is shown in Figure 5-1.

![Figure 5-1 - Schematic of a round jet issuing from a contraction nozzle (Ball et al. 2012)](image)

The case of the free jet, where the jet is not confined by any surfaces or other flows, has been extensively studied both experimentally and theoretically. A recent review is given by Ball et al. (2012). The first reported experimental investigations of the nature of round jet flows were undertaken in the early 1930s, see for example the studies by Ruden (1933) and Kuethe (1935), however comprehensive measurements of the jet flow were not achieved until the late 1950s and 1960s. The experiments conducted by Laurence (1956), Ricou and Spalding (1961) and Wygnanski and Fiedler (1969) provided the first detailed experimental data sets that were needed to characterise the flows associated with round jets. Since these initial investigations, numerous research groups have undertaken experimental investigations using a range of methodologies including hot-wire anemometry.
Modelling for Pool Design and Operation

(Wygnanski and Fiedler 1969; Hussein et al. 1994), laser-Doppler anemometry (Lehrmann 1986; Hussein et al. 1994), dye-visualisation (Bajpai and Tirumkudulu 2008) and pitotstatic probes (Sami et al. 1967). These studies have generated a wealth of experimentally-derived data that can be used to validate and develop fluid dynamic models for computational simulations as discussed, for example, by Wilcox (2006) and Fellouah et al. (2009).

Running alongside the research in free jets, experimental studies have also been used to investigate the characteristics of more complex jets scenarios including jet start up, impinging jets (Gardon and Akfirat 1965), confined jets (Fossett and Prosser 1949), cross flow jets (Smy and Ransom 1976) and free surface jets (Evans 1955). The application of jet mixing in cylindrical tanks has been extensively investigated since the concept was introduced by Fossett and Prosser (1949) as an alternative to mechanical mixing. Such studies have revealed complex flow physics presenting substantial challenges for CFD approaches. A large number of mathematical models have subsequently been developed for approximating fluid flows. The accuracy to which they can represent hydraulic flows is known to vary depending on the dominant hydraulic phenomena in a particular scenario (ANSYS 2009a). For example, the k-ε Re-normalization Group (RNG) model used by Cloteaux (2011) is modified to better accommodate low-Reynolds number flows, which are likely to be present within the pool tank, however Wilcox (2006) reported that it poorly represents jet flows compared to other models.

The comparison between mathematically-derived solutions for round jets and experimental data published by Wygnanski and Fiedler (1969) was carried out by Wilcox (1994) using axial velocity profiles. The work showed that the results generated through the use of the k-ω turbulence model were closer to the experimental data than the results of the longer established k-ε turbulence model. The initial publication highlighted that, for a round jet, the k-ε turbulence model overestimated the rate of decay as it entered a quiescent fluid (Wilcox 1994). The initial model presented by Wilcox had a closer correlation to the experimental data, although it generated a discontinuity in the velocity gradient at the edge of the jet, see Figure 5-2. This did not agree with the experimental data, which indicated that the velocity approached zero asymptotically as the distance from the jet centreline increased. A revised version of the k-ω model was published by Wilcox in 2000. The revised model provided a better fit to the Wygnanski and Fiedler (1969) data, however it also indicated variability in the experimental data by adding additional data published by Rodi (1975). Wilcox (2000) also reported that the outputs of the k-ω model were more sensitive to boundary conditions than those for the k-ε model.
Further revisions in the $k$-$\omega$ model have subsequently been published by Wilcox (2006). Figure 5-3 shows the most recent comparison between results derived using $k$-$\omega$, $k$-$\varepsilon$ and Re-normalization Group (RNG) $k$-$\varepsilon$ mathematical models and experimental data reported by Wygnanski and Fiddler (1969) and Rodi (1975) published by Wilcox (2006). This study shows that standard $k$-$\varepsilon$ and $k$-$\omega$ models generate fairly accurate velocity profiles for round jets. It also shows that the RNG $k$-$\varepsilon$ turbulence model offered a very poor correlation with the experimental data.
The extensive use of CFD to simulate an increasingly broad range of fluid systems has resulted in the continual evolution of the available mathematical models. The version of the ANSYS Fluent software used in this study enables users to select from five different 2-equation turbulence models; standard k-ε, RNG k-ε, realisable k-ε, standard k-ω and k-ω SST (ANSYS 2009a). Each of these methods presents the user with a range of benefits and drawbacks. The appropriate model to use will depend on the nature of the investigation being undertaken and therefore careful consideration of each method is an important stage in the CFD simulation process. Similarly, there are also multiple options for boundary types and solver methods and the sensitivity of solution results to changes in these settings also needs to be considered to enable reliable conclusions to be based upon them.
5.3 Swimming Pool Hydraulics Modelling Overview

The aim of this research work was to investigate the effects of design and operational parameters on the hydraulics of a conventional rectangular swimming pool through the use of CFD. In order to have confidence in the results of CFD solutions, it is essential that the limitations and sensitivities of the software are understood. The use of a detailed full scale pool geometry, incorporating all structural features, for these sensitivity studies would require large amounts of computational time as well as the collection of large amounts of detailed physical data from a pool facility for validation. It was therefore decided that initial testing of the technique would be based on simple scenarios. The CFD study undertaken as part of the research project therefore consisted of four phases.

The first part of the CFD research work evaluated the dependency of the simulation results on aspects of model configuration, such as the mesh density and model assumptions using 2D free jet examples. This modelling was validated using published experimental data. Once sensitivity analysis of the initial case was completed, a protocol for setting up further CFD simulations could be defined. The work undertaken is presented in Section 5.4.

The second stage of the CFD work used this protocol to model a series of increasingly complex 3D single jet scenarios. These scenarios were validated using a combination of published experimental data and original data from lab-scale physical experiments undertaken as part of the research project. Three single jet scenarios were selected for this stage; 3D Free Jet, 3D Shallow Jet and 3D Confined Jet. These scenarios are presented in Sections 5.5, 5.6 and 5.7 respectively.

The third phase of the modelling involved the simulation of multiple jets in a shallow confined tank. The modelling was validated using dye-dispersion observations made during lab-scale physical experiments. The work undertaken is presented in Section 5.8.

The final stage involved the simulation of the water flows within a full-scale swimming pool. At this stage the effects of operational parameters were investigated. The full-scale swimming pool scenarios are presented in Section 5.9.
5.4 2D Single Free Jet Modelling

The study of turbulent flow and in particular free jet flow fields have been studied extensively over the last century. Numerous experimental and computational studies have been undertaken on round free jets providing a substantial amount of literature on which this study could draw. Experimental data sets published by Wilcox (2006) and Wygnanski and Fiedler (1969) were used to provide comparison with the outputs of the single jet CFD modelling undertaken.

5.4.1 2D Single Jet Modelling Methodology

The study of a single axis-symmetric free round jet was used as a starting case as it enabled a greater number of simulations to be undertaken without resulting in long run times or the need for specialist computing facilities.

5.4.1.1 Geometry

The geometry used in the single jet study is shown in Figure 5-4 and represents a free round jet entering a quiescent body of water. The geometry was axis-symmetric about the line AE. Water was injected into the domain through a single jet nozzle (line AB). The quiescent body of water (ACDE) was unbounded with lines BC, CD and DE simply representing the edge of the calculation domain and not a physical boundary.

![Figure 5-4 - Outline of free round jet geometry](image)

It is important to ensure that the domain does not interfere with the flow formation. It is widely reported that free jets expand at an angle of 11.8°, therefore the width of the domain must be at least 1/5 of the length of the domain (Abbott 1989; Cushman-Roisin 2012).

5.4.1.2 Boundary Conditions

The fluid body was defined as water with constant density and constant viscosity as temperature variations throughout the fluid were considered to be negligible.
The maximum recommended inlet water velocity is dependent on the depth of water at the point of injection (PWTAG 2009). For deep areas, over 0.8m, the recommended maximum is 1.5 m/s. This reduces to 0.5m/s for shallower areas. As the study pool incorporated a uniform injection design and a movable floor that could reduce the water depth to within the shallow range, the lower limit of 0.5 m/s was specified at the nozzle. The other three outer boundaries, BC, CD and DE in Figure 5-4, were defined using specified pressure conditions with a gauge pressure of 0 Pa. Water was allowed to enter and leave the domain through these boundaries as required by the formation and decay of the jet flow.

The solution methods for the software also required selection. A double precision, steady-state, pressure-based solver was used to run the CFD simulations together with the following solution methods based on recommendations from the ANSYS user and theory guide (ANSYS 2009a; ANSYS 2009b).

- Pressure-Velocity Coupling Scheme – SIMPLE
- Spatial Discretisation Gradient - Least squares cell based
- Pressure Discretisation – Standard First Order
- Momentum Discretisation – Second Order Upwind
- Turbulent Kinetic Energy Discretisation – Second Order Upwind
- Turbulent Dissipation Rate Discretisation – Second Order Upwind

5.4.1.3 Computational Mesh

A user-specified rectangular mesh was used to generate the numerical domain for the solution. The mesh density was finest along the axis of the jet flow, expanding with increasing x and y distances. This enabled a good resolution near to the nozzle exit whilst also minimising the computational time required for generating converged solutions. Three mesh densities were examined in the study containing 2,500 cells, 10,000 cells and 40,000 cells. The 2500 cell mesh used is shown in Figure 5-5.
5.4.1.4 Convergence Criteria

CFD modelling uses iterative solution methods and therefore it is necessary to define convergence criteria in order to identify when to stop the simulations. This was achieved by monitoring a number of parameters during the calculations. After each of the iterations, the residual sum of each of the conserved variable is calculated. During the simulation these residual values will fall to indicate convergence. The greater the stability of the scenario being modelled the faster and further these residuals will fall. Simulations were run until no further changes were identified in the monitored residuals of velocity and continuity, as well as for the point velocity at the following three locations within the domain, where the origin of the cylindrical coordinate system \((x,y)\) is at point A in Figure 5-4.

- Location A \(-x = 5m, y = 0m\)
- Location B \(-x = 3m, y = 0.5m\)
- Location C \(-x = 4m, y = 1m\)

5.4.1.5 Validation Methodology

In order to validate the CFD results, the simulation outputs were compared to the experimental data published by Wilcox (2006), Wygnanski and Fiedler (1969) and analytical work undertaken by Fellouah et al. (2009). The accuracy of the solution outputs was examined by using the coefficient of determination \((R^2)\) regression value generated by comparing the centreline velocity profile of the simulation to the relationship determined by Fellouah et al. (2009). The \(R^2\) value for each output was calculated as shown in Equation 5-1, where \(SS_{res}\) is the residual sum of squares, \(\Sigma(y_i - \bar{y})^2\), and \(SS_{tot}\) is the total sum of squares, \(\Sigma(y_i - ӯ)^2\) (Peck et al. 2012).

\[
R^2 = 1 - (SS_{res} / SS_{tot}) \quad \text{Equation 5-1}
\]
5.4.2 2D Single Jet Modelling Results

The simulation of the single axis-symmetric jet was undertaken using each of the five 2-equation turbulence models available in the ANSYS Fluent software; standard k-\(\varepsilon\), Re-Normalised Group (RNG) k-\(\varepsilon\), Realizable k-\(\varepsilon\), Standard k-\(\omega\) and Shear Stress Transport (SST) k-\(\omega\). The details of each turbulence model can be found in the Fluent user manual (ANSYS 2009b) and are therefore not presented here. The centreline velocity profiles for each of the model outputs can be seen in Figure 5-6 together with the experimental data from Wygnanski and Fiedler (1969) and mathematical relationship published by Fellouah et al. (2009).

![Figure 5-6 – Centreline velocity variation for 2D free jet with distance from jet exit for various turbulence models](image)

The k-\(\varepsilon\) RNG model output was the least accurate fit to the data range (\(R^2 = 0.222\)) with the simulation, overestimating the rate of jet decay for \(x/D > 15\). The standard k-\(\varepsilon\) and Realizable k-\(\varepsilon\) models also overestimated the rate of jet decay by approximately 18% for \(15 < x/D > 60\), however, the outputs were much closer to the experimental data range than that of the k-\(\varepsilon\) RNG model with \(R^2\) values of 0.897 and 0.965 respectively. The Realizable k-\(\varepsilon\) model generated a jet decay rate closer to the experimental data than the standard k-\(\varepsilon\) model for \(x/D > 40\) with the output closely matching the experimental data for \(x/D > 60\). The k-\(\omega\) model was found to generate a jet decay rate that closely fit the experimental data for \(x/D < 60\) after which it underestimated the decay rate by approximately 15%. The k-\(\omega\) model curve had an overall \(R^2\) value of 0.936. The k-\(\omega\) SST model was observed to generate a very similar output to the standard k-\(\varepsilon\) model with an \(R^2 = 0.859\) as expected.
The axial velocity profiles generated by the k-ε, RNG k-ε and standard k-ω simulations were plotted for x/D = 40 to enable comparison with the results of Wilcox (2006). The modelled results are presented in Figure 5-7 below together with the data from Wygnanski and Fiedler (1969) and Wilcox (2006). The results generated in this study show good comparison to those presented by Wilcox for k-ε and k-ω. There is a larger difference between the RNG k-ε results, however they both indicate this model produces the least accurate results. The k-ω model was observed to generate the closest agreement to the experimental data published by Wygnanski and Fiedler (1969).

![Graph](image)

**Figure 5-7 - Comparison of computed axial velocity profiles against data from Wilcox (2006) and Wygnanski & Fiedler (1969)**

5.4.3 Sensitivity Analysis

The results shown in Figure 5-6 highlight that the turbulence model selected can have a major impact on the results generated by the CFD modelling. It was reported by Wilcox (2006) that the k-ω model is sensitive to the specification of boundary conditions and other aspects of simulation setup. The sensitivity of the k-ω model to the specification of initial conditions and free stream values has also been reported by Morgans et al. (1999) and Menter (1992). A sensitivity analysis of was therefore undertaken. Three key aspects of the CFD simulation setup were examined in the sensitivity analysis; Mesh Size, Boundary Conditions and Domain Size. The effects of each of these aspects are discussed in this section.
5.4.3.1 Mesh Dependency

The detail at which a system can be analysed and the accuracy of the results are dependent on the number of cells the solution domain is divided into. The greater the number of cells the smaller each control volume is and therefore the flow can be modelled in more accurately. The number of cells in the numerical grid also has an effect on the time needed for each of the iterations to be completed by the solver and the total number of iterations required. The desire is to use the minimum number of cells possible without compromising the accuracy of the simulation output. This minimum mesh density will depend on the nature of the system under investigation and therefore it is not possible to define it without undertaking sensitivity analysis.

In order to evaluate whether the minimum mesh density required was dependent on the turbulence model selected, all five of the available 2-equation models were used for this study. Three numerical meshes were constructed with 2,500 cells, 10,000 cells and 40,000 cells respectively. Each side of the mesh was biased so that the mesh was finest close to the inlet and became progressively coarser with increasing distance from the origin in both the x and y direction.

![Figure 5-8 – Output results for mesh dependency study](image)

Figure 5-8 shows the output results for the three velocity monitoring points as well as the overall $R^2$ value for the modelled centreline velocity profiles. In all cases the k-$\varepsilon$ RNG output was observed to produce a very different output value to the other turbulence models. Large changes were identified for all five turbulence models between the 2,500 cell mesh and the 10,000 cell mesh. The increase to 40,000 cells...
also resulted in a change in the output, however, it was much smaller than between the previous two meshes. The number of iterations required to generate a stable solution also greatly increased as shown in Table 5-1. It was therefore decided that the mesh settings relating to the 10,000 cell case would be used for the remainder of the 2D study.

Table 5-1 – Number of computational iterations required for each mesh

<table>
<thead>
<tr>
<th>Turbulence Model</th>
<th>Velocities Stabilise</th>
<th>Residuals Stabilise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2500 Cells</td>
<td>10000 Cells</td>
</tr>
<tr>
<td>Standard k-ε</td>
<td>400</td>
<td>1250</td>
</tr>
<tr>
<td>RNG k-ε</td>
<td>450</td>
<td>1500</td>
</tr>
<tr>
<td>Realizable k-ε</td>
<td>450</td>
<td>2000</td>
</tr>
<tr>
<td>Standard k-ω</td>
<td>550</td>
<td>3000</td>
</tr>
<tr>
<td>k-ω SST</td>
<td>400</td>
<td>1400</td>
</tr>
</tbody>
</table>

5.4.3.2 Turbulence Boundary Conditions Dependency

An investigation into the effects of inlet and farfield turbulence on the simulations was undertaken using the 10,000 cell mesh case and the standard k-ε, realizable k-ε and k-ω turbulence models. The methodology involved the systematic alteration of the boundary conditions to generate a series of solutions. The velocity profiles were then compared in a similar way to that used for the mesh dependency study. A total of 8 cases were studied for each turbulence model with the boundary conditions specified as shown in Table 5-2.

Table 5-2 - Boundary condition settings for study

<table>
<thead>
<tr>
<th>Case</th>
<th>Inlet Turbulence Intensity</th>
<th>Farfield Turbulent Intensity</th>
<th>Farfield Viscosity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4%</td>
<td>0.05%</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1%</td>
<td>0.05%</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>10%</td>
<td>0.05%</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4%</td>
<td>0.50%</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>4%</td>
<td>1%</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>4%</td>
<td>0.05%</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>4%</td>
<td>0.05%</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>10%</td>
<td>1%</td>
<td>1</td>
</tr>
</tbody>
</table>

Only the turbulence intensity setting was altered for the inlet jets as the turbulence length scale \(l_t\) was defined using Equation 5-2, where \(d\) is the jet diameter. All other solver settings were kept constant.

\[ l_t = 0.07d \]

Equation 5-2
The initial case settings were specified based on recommendations in the Fluent theory guide (ANSYS 2009a). The turbulence intensity (I) for the inlet boundary was estimated using Equation 5-3:

\[ I = 0.016 \text{Re}^{-1.8} \]  

\textbf{Equation 5-3}

Where Re is the Reynolds Number at the nozzle exit based on the specified velocity of 0.5 m/s calculated using Equation 5-4.

\[ \text{Re} = \left( \frac{\rho u d}{\mu} \right) \]  

\textbf{Equation 5-4}

Where,

\( \rho \) = Fluid Density (kg/m\(^3\))

\( u \) = Nozzle velocity (m/s)

\( d \) = Nozzle exit diameter (m)

\( \mu \) = Fluid viscosity (kg/ms)

Farfield boundary conditions specified turbulence intensity and the ratio of turbulent viscosity to molecular viscosity for incoming flow. Initially a turbulence intensity of 0.05% and a viscosity ratio of 1 were selected for the free stream boundary conditions based on recommendations in the Fluent user guide (ANSYS 2009b).

The k-\( \varepsilon \) model centreline velocity output was observed not to be greatly affected by changes in the inlet turbulence intensity value with the output changing by less than 1%. The k-\( \varepsilon \) solution was also observed to be unaffected by changes in outlet turbulence intensity and viscosity ratio values as shown in Figure 5-9. Similarly, the axial velocity profile of the simulation output was also unaffected by changes in farfield boundary conditions, see Figure 5-10. Increasing the inlet turbulence intensity resulted in a slight increase in the spreading rate of the jet as can be seen by comparing case 1 and case 8 in Figure 5-10. Similar observations were seen with the realizable k-\( \varepsilon \) sensitivity analysis.
Modelling for Pool Design and Operation

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes

Figure 5-9 - Centreline velocity decay of 2D k-ε model for different boundary conditions

Figure 5-10 - Axial velocity profile of 2D k-ε model at x/D = 40 for different boundary conditions

The centreline and axial velocity profile outputs from the k-ω simulations can be seen in Figure 5-11 and Figure 5-12 respectively. Changes in the inlet and farfield boundary conditions were observed to have large effects on the k-ω model solution. The effects of the farfield boundary conditions are considered to be due to
the inflow occurring along boundaries BC and CD as a result of entrained fluid entering the domain.

![Graph showing centreline velocity decay of 2D k-ω model for different boundary conditions](image1)

**Figure 5.11 - Centreline velocity decay of 2D k-ω model for different boundary conditions**

![Graph showing axial velocity profile of 2D k-ω model at x/D = 40 for different boundary conditions](image2)

**Figure 5.12 - Axial velocity profile of 2D k-ω model at x/D = 40 for different boundary conditions**

The variation in jet decay observed in the simulation outputs from the k-ω model agree with the reports of Wilcox (2006), Morgans *et al.* (1999) and Menter (1992). This study demonstrates that knowledge of the boundary conditions is extremely...

Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes
important when setting up CFD simulations using the k-ω turbulence model. The sensitivity exhibited by the k-ω model during this study raises concerns about the potential robustness of simulation outputs of more complicated modelling scenarios.

5.4.3.3 Domain Size Dependency

The initial geometry was specified based on the reported experimental evidence that showed that free round jets entering a quiescent fluid form a plume with a spreading angle of 11.8° from the centreline (Abbott 1989; Cushman-Roisin 2012). It is important to minimise the size of the domain in order to reduce computational time, however it must be checked that this theoretical minimum domain height is functional in this study. In order to assess this, the simulations were repeated using a 3m and 5m domain height and the outputs were compared with the results of the 2m domain height. The length of the domain was kept constant at 10m in both cases and the number of mesh points was increased proportionally to maintain the mesh density. The height of the domain was observed to have no effect on the outputs of any of the simulations, with identical outputs generated for each one. This indicated that the 2m domain height was suitable for the study.

5.4.4 2D Single Jet Modelling Conclusions

This study examined the accuracy at which CFD modelling could predict the flows associated with a free round jet when entering a quiescent fluid. Five different 2-equation turbulence models were used during the study and the sensitivity of the outputs produced from each was investigated by manipulating the numerical mesh, boundary conditions and domain size.

The k-ε RNG turbulence model was found to be an unsuitable model for cases involving free jet flows. It overestimated the rate of jet decay compared to experimental data and was therefore ruled out for future studies. The other four turbulence models all generated results reasonably close to the experimental data but still overestimated the rate of jet axial dispersion to some extent.

The k-ω model produced the results closest to the experimental data, however, the model output was found to be highly sensitive to the selection of simulation settings. The confidence in the k-ω outputs is therefore reduced, as small inaccuracies in boundary conditions can have a significant effect on the flow calculations. The k-ω model was also found to be far more demanding in terms of computational time, requiring on average 8 times as many iterations to reach a fully converged result than the standard k-ε model.
The standard $k$-$\varepsilon$ and realizable $k$-$\varepsilon$ model were found to produce very robust results that were only marginally affected by changes in simulation settings. Although the outputs consistently exhibited a slight overestimation of the rate of jet decay when compared to the experimental data, the stability of the results means that more confidence can be held in the outputs when applied to more complex flow scenarios where exact boundary conditions may not be known. The $k$-$\varepsilon$ realizable model outputs were closer to the experimental data for $x/D > 60$, however, it required twice as much computational time on average than the standard $k$-$\varepsilon$ model.
5.5 3D Single Free Jet Modelling

Following the completion of the initial 2D free jet simulation, a series of 3D single free jet simulations were undertaken to investigate the sensitivity to meshing and model settings for the 3D solver. The results of a simple 3D free jet simulation are presented in this section.

5.5.1 3D Single Jet Modelling Methodology

5.5.1.1 Geometry and Boundary Conditions

A 3D cylindrical geometry with a single jet inlet on the centre horizontal axis was used for the free jet domain. The geometry is shown in Figure 5-13 and was defined as 60 jet diameters in diameter and 100 jet diameters in length. The modelling was conducted using a jet velocity that equated to a Reynolds number of 49,750, which is representative of the jets in the swimming pool application that the wider research is based on.

![Figure 5-13 – Geometry used for the 3D single free jet CFD simulations](image)

The jet inlet was defined by specifying a uniform inlet velocity, turbulence intensity and turbulence length scale. The farfield boundaries and inlet domains were defined by specifying pressure, turbulence intensity and eddy viscosity to molecular viscosity ratio for any inflow in the same way as undertaken in the 2D study.

5.5.1.2 Mesh Generation

Multiple options for meshing the 3D free jet geometry were initially investigated. Each meshing methodology resulted in similar outputs, however the ease of controlling the quality of the mesh led to the selection of the sweep meshing method. The geometry was split into two parts for the meshing process; one aligned with the jet inlet and one for the rest of the domain. In both parts a plane triangular mesh was created on the inlet plane (y-z plane) and swept across the domain along the x axis. Mesh density and structure were guided by the initial 2D
studies of a free jet and verified by comparing the outputs of the 3D free jet case with those of the 2D simulations.

5.5.1.3 Turbulence Modelling

The use of published data on free jets, as has been common practice in previous research, was used to initially verify aspects of the CFD methodology including the choice of turbulence model. Five different 2-equation turbulence models (standard k-ε, Realised k-ε, Re-Normalised Group (RNG) k-ε, Realisable k-ε, Standard k-ω and Shear Stress Transport (SST) k-ω) were used to model the 3D free jet case and compared with the results of the 2D studies.

5.5.1.4 Solver Settings and Convergence Criteria

The solver settings and convergence criteria used for the 3D free jet simulation were the same as those described for the 2D case in Section 5.4.

5.5.1.5 Validation Methodology

The validation of the 3D jet results was performed by comparing the solution outputs with both the earlier 2D solution outputs and experimental data published by Wygnanski and Fiedler (1969) and Quinn (2006). The Reynolds numbers used in these published experiments were $1.84 \times 10^5$ and $1 \times 10^5$ respectively. The correlation published by Fellouah et al. (2009) for free jets with a Reynolds number in the range 6,000 to 30,000 was also used to provide comparison over a wider range of Reynolds numbers.

5.5.2 3D Single Jet Modelling Results

The outputs of the 3D free jet solutions were found to match those of the 2D free jet solutions presented in Section 5.4. Figure 5-14 shows the centreline velocity profile for each of the turbulence models together with experimental data published by Wygnanski and Fiedler (1969) and Quinn (2006). The velocity profiles can be observed to be similar to the 2D profiles presented in Figure 5-6.

The sensitivity of the k-ω solution output to changes in far field boundary conditions was again observed in the 3D simulations. Although inlet boundary conditions can be fairly easily approximated using the relationship shown in Equation 5-3 above, the far field boundaries are more difficult to determine. For the case of the free jet, where there is entrained flow entering the domain through the far field boundary, the confidence in the k-ω outputs is therefore reduced as small inaccuracies in boundary conditions have a major effect on the flow calculations.
5.5.3 3D Single Jet Modelling Conclusions

The CFD solutions for the 3D single free jet agreed closely with the outputs of the previous 2D CFD simulations. Using the results of the 2D and 3D single jet studies, decisions in relation to the selection of the turbulence model for future simulations were made. Although the standard k-ε and realizable k-ε models were observed to overestimate the rate of jet decay when compared to the experimental data, the comparative insensitivity to far field conditions gives confidence they can be used in more complex scenarios. This agrees with the findings of Hajikandi and Mansoori (2007) in their study of axis-symmetric confined jets. As the k-ε realizable output was closest to the experimental data, it was decided that the k-ε realizable turbulence model was the most appropriate option. The application of jets in swimming pools, however, is more complex than a simple free jet scenario. It is therefore necessary to also confirm that the turbulence model is suitable for recirculating flows.
5.6 Single Shallow Jet Modelling

In the case of swimming pools, the jets are often limited in the vertical plane by the base of the pool tank and the open surface. In addition, the jet inlet plane is also usually a solid surface therefore preventing inflow on this domain boundary. It is therefore necessary to confirm that the CFD modelling is able to accurately represent the effects of the jet flow interacting with these solid and free surfaces. The results of a 3D shallow jet simulation are presented in this section.

5.6.1 Single Shallow Jet Modelling Methodology

5.6.1.1 Geometry and Boundary Conditions

A shallow jet was defined as a round jet that is limited in the vertical plane by two surfaces but unbounded in the horizontal plane. The geometry used in this study was a 3D representation of the experimental geometry used by Shinneeb et al. (2011) in order to enable validation of the solution outputs. A single jet orifice was located in a solid vertical wall midway between a solid base and a free surface. The domain was sufficiently wide to ensure that the jet spreading in the horizontal plane was unrestricted. The geometry is shown in Figure 5-15. In order to evaluate the effect of tank depth \((h)\) on the jet flows, four values for \(h/d\) were selected between 5 and 20. In all cases, the outer domain was 110 jet diameters in width and 110 jet diameters in length.

![Figure 5-15 – Geometry used for the shallow jet CFD simulations](image)

The vertical plane containing the jet orifice and the bottom surface of the domain were defined as walls with a no slip boundary condition. The top surface of the domain was defined as a wall with a zero shear stress boundary condition. This was considered an appropriate approximation for the free surface, as surface...
Modelling for Pool Design and Operation

deformations were observed to be negligible in the large scale application of submerged jets in swimming pools and, as gravity was also not included, Froude number effects were not being modelled. The jet inlet was defined using a velocity specified boundary condition using the same parameters as in the 3D free jet case. The remaining boundaries were defined as pressure specified farfield boundaries using the same parameters as described in the 3D free jet case. A range of inlet velocities were modelled using this geometry to enable Reynolds number effects to be assessed.

5.6.1.2 Mesh Generation, Turbulence Modelling and Convergence Criteria

The meshing process used for the 3D free jet was used for the shallow jet geometry. A triangular mesh was created on the surface containing the jet orifice and swept across the domain to create prism cells. The number of cells created varied for each of the values of $h/d$ to maintain the same mesh density. Due to the nature of the flow in this study the value of $y+$ was expected to vary throughout the domain. Enhanced wall functions were therefore used to approximate near-wall interactions to avoid the need to create a complex variable mesh to maintain a similar $y+$ value. A maximum $y+$ value of 85 was calculated in the shallow jet experiment.

The $k$-$\varepsilon$ realizable turbulence model was selected for the shallow jet simulations for the reasons discussed in the previous section. The solver settings and convergence criteria described for the 2D case in Section 5.4 were again used for the shallow jet case.

5.6.1.3 Validation Methodology

The case of shallow jets has been investigated experimentally by Madina and Bernal (1994) and more recently by Shinneeb et al. (2011). Validation of the shallow jet CFD solution outputs was therefore undertaken through comparison with experimental data published by these authors. In order to make direct comparisons, a series of simulations were performed using a Reynolds number of 22,388 which matched the conditions used in the experiments undertaken by Shinneeb et al. (2011).

5.6.2 Single Shallow Jet Modelling Results

Shinneeb et al. (2011) reported that the confinement in the shallow jet case caused the jet centreline velocity decay rate to reduce. This reduction was also observed to be dependent on the ratio between the depth of water and inlet diameter ($h/d$). Figure 5-16 shows the geometric centreline velocity profiles from the CFD solutions together with experimental data published by Shinneeb et al. (2011) and Madina and Bernal (1994).
The CFD results show that the jet profiles follow the free jet case initially before deviating further downstream. The point at which the free jet similarity ends, defined as the point when the difference in values for $U_{\text{inlet}}/U_{\text{centreline}}$ exceeded 1%, was found to be dependent on the depth of the tank. The similarity was observed to end in the CFD simulations at $x/d = 53$ and 79 for $h/d = 10$ and 15, respectively. This is in close agreement with the values of $x/d = 55$ and 80 quoted by Shinneeb et al. (2011) in relation to their physical experiments. The shallowest case ($h/d = 5$), however, differs from some of the experimental data with the free jet similarity ending at $x/d = 23$ in the CFD compared to $x/d = 50$ quoted by Shinneeb et al. (2011). This indicates that the CFD approach used in the study may not be applicable for values of $h/d < 10$, however, the CFD results did show good correlation to the results of Madina and Bernal (1994) although their experimental range was limited to a maximum of $x/d = 40$. In the experiments, the measured departure from the free jet is quite small. It is therefore not possible to conclude whether there is a limit to the applicability of the CFD approach with respect to values of $h/d$. The shallow jet case was investigated further to develop confidence in the CFD approach before applying it to more complex cases.

![CFD generated centreline velocity profiles and experimental data for the shallow jet case at different values of h/d.](image.png)

Figure 5-16 - CFD generated centreline velocity profiles and experimental data for the shallow jet case at different values of h/d. (◊) Madina and Bernal (1994), (×) Shinneeb et al. (2011), (—) CFD results, (---) Free Jet CFD results

Figure 5-17 shows the turbulent kinetic energy along the centreline for the CFD simulation for each of the shallow jet cases together with the experimental data published by Shinneeb et al. (2011). The turbulent kinetic energy profiles for $h/d =$ Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes
10 and h/d = 15 compared closely with the data presented by Shinneeb et al. (2011). The reduction in turbulent kinetic energy for x/d < 25 in the h/d = 5 case that was observed by Shinneeb et al. (2011) was not identified in the CFD simulations. This could be the result of insufficient sensitivity to inlet turbulence. The CFD produced similar turbulent kinetic energy profiles for all values of h/d.

![Figure 5-17 - Turbulent kinetic energy along the centreline for different values of h/d.](image)

A comparison of the free surface pressure profiles indicated that the pressure variations along the surface were greater in the h/d = 5 case. The maximum pressure differential in the h/d = 5 case equates to approximately 0.4 mmH₂O compared to 0.08 mmH₂O for the h/d = 10 case. Although the surface fluctuations are expected to be five times larger in the shallow case, they are still small compared to the jet inlet size of 9 mm and overall tank depth of 45 mm. These pressure differentials are therefore considered to be small and that the free surface approximation is still reasonable.

A comparison of the velocity profiles on both the horizontal (x,z) and vertical (x,y) planes that contained the inlet centre point was undertaken to assess the effect of wall proximity to the jet direction and shape. The change in h/d was not observed to have any substantial effect on the horizontal velocity profile, however, the profile on the vertical plane exhibited two distinct changes. The vertical profiles are shown in Figure 5-18. The first observed effect was a deviation in the jet direction, away from the geometric centreline and towards the solid surface. This agrees with the
experimental observations by Madina and Bernal (1994) and Shinneeb et al. (2011). The second observed effect is seen only in the h/d = 10 and h/d = 5 cases. In these cases, the leading edge of the jet profile no longer maintains a convex shape about the jet centreline as it develops downstream. For the h/d = 10 case, the jet profile begins to develop a secondary peak in velocity towards the free surface that eventually sees the maximum velocity shifting from the jet centreline to the top of the water body.

The effect is even more dramatic in the h/d = 5 case, where the maximum velocity moves towards the free surface before the jet begins to deviate towards the base. These effects have important implications on the chosen definition of $u_{centreline}$ when evaluating the jet decay curve of confined jets, as there can not only be a difference between the velocities on the geometric centreline and the jet centreline, as shown in Figure 5-18, but also the maximum velocity at a specific value $x/d$ may not be on the jet centreline.

![CFD generated velocity contours on the central vertical plan at Reynolds Number of 22,388 for different values of h/d](image)

**Figure 5-18 – CFD generated velocity contours on the central vertical plan at Reynolds Number of 22,388 for different values of h/d**
The final part of the shallow jet study involved the investigation of the effects of Reynolds number on the jet profiles. Each case was modelled using inlet velocities equating to Reynolds numbers ranging from 4,476 to 89,551. The critical Reynolds number, the value below which variations in centreline velocity profile were observed, was found to vary with the value of h/d. Figure 5-20 shows the Reynolds number dependency, according to the CFD, for the h/d = 10 and h/d = 20 cases. The critical Reynolds number observed for each case is shown in Table 5-3. Below these critical values the rate of centreline velocity decay was observed to reduce with reducing Reynolds number for x/d > 30.
Table 5-3 - Values of critical Reynolds number for the shallow cases with h/d values of 5, 10, 15 and 20

<table>
<thead>
<tr>
<th>Case</th>
<th>Critical Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>h/d = 5</td>
<td>7,000</td>
</tr>
<tr>
<td>h/d = 10</td>
<td>13,000</td>
</tr>
<tr>
<td>h/d = 15</td>
<td>20,000</td>
</tr>
<tr>
<td>h/d = 20</td>
<td>30,000</td>
</tr>
</tbody>
</table>

5.6.3 Single Shallow Jet Modelling Conclusions

The agreement with experimental data shown, justifies the use of the selected CFD methodology for the case of vertically confined jets and provides support for using it more complex cases. The approximation of the free surface with a zero-shear boundary condition was shown to be appropriate for this application through comparison of CFD simulation results for a vertically confined jet with previously published experimental data. Calculated pressure differentials across the modelled free surface were found to be small for the conditions considered. This agrees with visual observations of full-scale unoccupied swimming pools, in which the free surface does not exhibit noticeable deformations.

The study also highlighted that, for h/d < 20, the presence of free and solid surfaces have an impact on the jet flow. The jet development was seen to deviate away from the ideal free jet case. The extent of the deviation was observed to be inversely related to the value of h/d. At h/d = 20, the geometric configuration most relevant to the swimming pool application considered in this research, the deviation was only observed after x/d = 80. In the swimming pool case, the line of symmetry for the tank is at x/d = 100, therefore minimal surface and base effects are expected to be observed.

The effect of Reynolds number on the jet development in the CFD for the h/d = 20 case was observed to be limited to Reynolds numbers below 30,000. As the swimming pool case is above this range, it is expected that no significant Reynolds number effects will be observed.
5.7 Single Confined Jet Modelling

The modelled cases above have not included recirculating water or jet impingement. In the case of swimming pools, the water flows are confined within the tank with outflow restricted to surface overflow or base extraction. The confinement of the flow is therefore expected to introduce regions of recirculating flow which may have an impact on the accuracy of the simulation outputs. The modelling of a single confined jet was used to examine this.

5.7.1 Single Confined Jet Computational Fluid Dynamics Modelling Methodology

5.7.1.1 Geometry and Boundary Conditions

The 3D geometry used in the shallow jet modelling was adapted to create a domain to examine the effects of confinement. The new modified domain still consisted of a single jet orifice with vertical confinement resulting from a solid bottom surface and a free top surface, as had been the case in the shallow jet geometry. The remaining vertical boundaries, however were changed to walls to enclose the fluid domain. The confined jet domain is shown in Figure 5-21.

![Figure 5-21 – Geometry used for single confined jet CFD simulations](image)

The domain was 250 jet diameters in length, 500 jet diameters in width and 20 jet diameters in depth in order to make it geometrically similar to the experimental tank used in the small-scale physical modelling undertaken by Williams (2012). The jet inlet was located midway on the vertical wall, 10 jet diameters from the base of the tank. A narrow outlet, 0.1 jet diameters in size, was located in the top surface along the whole edge that joined with the vertical wall containing the jet inlet to enable fluid to leave the domain. This was a departure from the experimental setup as the experimental tank did not have any outlets. As the change in water depth was observed in the experiments to be no more than 5%, the use of a fixed domain...
size with an outlet was considered to be a suitable approximation for the CFD modelling. A range of scales and Reynolds numbers were used with this geometry to enable both the comparison with experimental data from small-scale experiments and to examine the scalability of the CFD approach. The solid surfaces were all defined as walls with a no slip boundary condition, whilst the outlet was defined using a pressure specified boundary condition.

Two sets of simulations were undertaken in this study. The first involved the modelling of an instantaneous injection of dye into a quiescent body of water. This was defined as a start-up confined jet scenario. The second set of simulations involved the addition of dye to the inlet flow after the water flows in the tank had developed. This was defined as a steady state confined jet scenario.

5.7.1.2 Mesh Generation, Turbulence Modelling and Convergence Criteria

The meshing process used for the 3D free jet was once again used for the confined jet geometry. The confined jet mesh consisted of approximately 1.5 million prism cells. Enhanced wall functions were used to avoid the requirement for resolving the mesh next to each wall. A bias was applied to the mesh to result in a finer numerical grid close to the jet inlet. As with the shallow jet case, the $y+$ value was allowed to vary throughout the domain, however, it was ensured that the maximum value was kept below 300 as recommended in the Fluent user guide (Ansys 2009b).

![Graphical representation of the numerical mesh used for the single confined jet CFD simulations](image)

The k-$\varepsilon$ realizable turbulence model was again selected for the confined jet simulations for the reasons discussed earlier and the solver settings and
convergence criteria described for the 2D case in Section 5.4 were again used for the confined jet case.

5.7.1.3 Validation Methodology

Validation of the CFD simulations for the start-up confined jet scenario was undertaken using the physical experimental flow visualisation results presented by Williams (2012). The validation of the steady state confined jet scenario was undertaken using original flow visualisation physical experiments. These physical experiments are described in more detail later.

In both cases, a non-dimensional timestep (τ) was used in the analysis of the experimental footage. This was defined as shown in Equation 5-5 below, where u, t and l are the dimensional velocity (m/s), time (s) and the tank width (m) respectively.

\[ τ = t \left( \frac{u}{l} \right) \]

Equation 5-5

5.7.1.4 Computational Fluid Dynamics Flow Visualisation

In order to produce images from the CFD for comparison with the experimental flow visualisation, it was necessary to simulate the spread of dye in the tank. Unsteady CFD solutions were required to model the dye injection using the transient solver. The species modelling function available in the software was used to create a two component mixture of water and dye. The dye was given the same density and viscosity as water and a mass diffusion rate of \( 1 \times 10^{-9} \) m\(^2\)/s was selected, based on available literature (Coulson and Richardson 2000). The amount of dye in the inlet was set to have a constant mass fraction of 0.0015 to correlate with the experimental usage of 1.5 grams of dye per litre of water. The results of the solution were saved at regular intervals to enable specific snapshots to be generated in the post-processing software. Post-processing software was used to generate 3D representations of the dye plume in order to compare the simulation results with the images from the physical experiments.

The process of generating 3D rendered images of the CFD simulations required the specification of rendering criteria, therefore a visual calibration test with Ponceau 4R, the dye used in the physical experiments, was undertaken. The calibration test started with a solution of 1.5 grams of dye per litre of water. This solution was placed into a clear glass container 45mm in width so that the depth of water being viewed in the test was similar to that of the experiments. After the colour intensity of the water was recorded by taking a photograph, the water sample was diluted with fresh water in a 1:1 ratio and re-photographed. This process continued until the camera was unable to capture a visible difference between the water sample.
and a blank sample containing no dye. The water was observed to be opaque for Ponceau 4R concentrations greater than 9.38x10^{-2} g/l and is not clearly distinguishable from the blank sample below a dye concentration of 3.66x10^{4} g/l as shown in Figure 5-23.

![Figure 5-23 - Calibration images for the Ponceau 4R dye used in physical experiments](image)

This information was used to specify the following rendering settings in post-processing CFD results:

- Render Type: Volume Rendering
- Variable: Dye Mass Fraction
- Transparent Mass Fraction: 1x10^{-7}
- Opaque Mass Fraction: 1x10^{-4}

In order to maintain consistency in presenting the CFD output images, the above rendering criteria were used for the single confined jet simulation outputs.

5.7.2 Single Confined Jet Physical Modelling Methodology

The single confined jet modelling study used physical modelling by Williams (2012) to compare with the CFD results generated for the start-up case. The CFD results of the steady state case, where the water circulation was allowed to establish prior to the addition of the dye, required new physical modelling to be undertaken to generate comparable data. The methodology presented here is therefore in relation to the generation of physical modelling results for the steady state case.

5.7.2.1 Experimental Apparatus

The experiments for this study were conducted on a rectangular open surfaced tank measuring 50cm long, 100cm wide and 6cm deep. The tank was large enough for visualisation to be possible whilst small enough to be a practical size for filling and emptying. An inlet was installed along one side of the tank at a height of 2cm from the base and measured 2mm in diameter. The inlet was connected to a pipe network that was fed with mains water via an adjustable header tank. This allowed
for the experiments to be operated in a controlled manner at a range of inlet velocities. A volumetric flow meter was installed to enable the flow rate of water from each header tank position to be measured. The experimental apparatus is shown in Figure 5-24.

![Figure 5-24 - Schematic of single confined jet physical experimental apparatus](image)

5.7.2.2 Dye Injection

In order to inject dye into the inlet water stream a hand-pressurised tank was connected to a hypodermic needle located within the inlet pipework. A concentrated dye solution was prepared and placed in the injection tank before being pressurised to 1.5 bar. The hypodermic needle enabled the impact on the inlet flow rate to be minimised whilst maintaining the injection of a reliable stream of dye. The injection of dye had to be moved to after the flow meter to avoid issues with dye entrapment within the meter that was making the undertaking of repeat experiments very difficult. The flow rate of dye from the injector at 1.5 bar was calculated to be 0.08 litres/minute by recording the time taken to discharge 1 litre of water. This volume was added to the fresh water flow rate, measured by the flow meter, in order to calculate the jet velocity at the inlet for each header tank location.

5.7.2.3 Experimental Procedure

Three inlet velocities were used in the experiments to give Reynolds Numbers of 3,224, 12,497 and 15,701. Water meter readings had an accuracy of ±2% in the range of flowrates used in the experiments.
The experiments aimed to investigate the development and mixing achieved at steady state, therefore it was necessary to allow the circulation within the tank to develop prior to starting the dye injection. This was achieved by filling the tank through the inlet itself. Once the depth of water in the tank had reached 4cm, the dye injection valve was opened and the dye dispersion experiment started. The dye injection was run continuously until the tank appeared to be an even colour.

The dispersion of dye was recorded using a video camera fixed above the tank to enable subsequent analysis of the dispersion patterns and the generation of images that could be compared with CFD outputs.

The water level in the tank rose during the experiment as water could not leave the tank. The water level was observed to rise by approximately 2 mm during each experiment, which represents a 5% increase in the tank depth. This was considered to be small enough to be neglected in the CFD modelling. Each experiment was repeated multiple times and showed a good level of repeatability, as illustrated in the results presented later.

5.7.3 Start-Up Confined Jet Modelling Results

The images of dye dispersion generated by the CFD methodology are shown alongside the images presented by Williams (2012) for inlet velocities of 5.63m/s (Re = 12,601) and 10.6m/s (Re = 23,733) in Figure 5-25 to Figure 5-28. The images are shown for six selected non-dimensional timesteps calculated using Equation 5-6.

The dye dispersion patterns displayed in both the CFD simulation outputs and the small-scale experiment were found to be very similar in shape. There was, however, a noticeable difference in the rate of development of the dye dispersion plume. The CFD solution appeared to lag behind the small-scale physical experiment. This can be clearly seen by comparing the physical model and CFD outputs for $\tau = 134$ onwards in Figure 5-25 and Figure 5-26. A potential reason for this discrepancy was the inherent inaccuracies in the reported experimental inlet velocities. In the CFD solution, a constant velocity was initialised at the inlet at $t_m = 0s$. In the small-scale experiments, it was the tank pressure that was controlled and the velocities were derived from the time taken to inject the control volume of 1 litre at specified pressures (Williams 2012). Using a pressure boundary condition for the inlet resulted in a time dependent inlet velocity as the jet starts. Using an average velocity for the entire solution would result in an underestimation of the inlet velocity in the first instance causing the simulated jet profile to be behind that of the physical experiment.
Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes
The CFD simulation was repeated using a constant pressure boundary condition of 100kPa as reported by Williams (2012) in the 10.6 m/s small-scale experiments. The output results are shown in Figure 5-29. The progression of the jet plume in the pressure boundary case is closer to that observed in Williams' experiments.

![Figure 5-29 - CFD generated images for an inlet pressure of 100kPa](image)

5.7.3.1 Computational Fluid Dynamics Plume Shape

The initial dye plume, $\tau < 100$, generated by the CFD simulation has a larger diameter than observed in the physical experiments. Examination of the flow field in the simulation indicates that the spherical shape, as opposed to the teardrop shape observed in the physical experiments, of the plume appears to result from lateral flows generated when the jet makes contact with the upper surface in the model. It was noted by Williams (2012) that substantial surface rippling occurred at the point at which the developing jet contacted the surface, at approximately $x/d = 55$. In the simulation a free slip wall is used to represent the surface which does not allow for any surface deformations and ignores the effects associated with the Froude number.

An additional CFD case was undertaken to assess the significance of ignoring surface effects. This involved relaxing geometric similarity by increasing the distance between the jet and the free surface, referred to as the deep pool case. The depth of the pool was increased to $h = 50d$ with the distance between the top of the pool and the inlet set to $40d$. All other aspects of the geometry were kept the same, therefore the jet would not make contact with the upper surface until much further
into the tank, approximately $x/d = 225$. The shape of the simulated plume in the deep pool case was observed to be much closer to the experimental plume as shown in Figure 5-30.

![Figure 5-30 - Deep pool CFD images for an inlet pressure of 100kPa at $\tau=34$ and $\tau=67$](image)

It is therefore reasoned that the spherical plume shape may be due to the use of a free slip boundary condition to represent the free surface in the modelling. The phenomenon is limited to the start-up period of the jet and is no longer present once the jet has developed. Hence such effects might be reduced for steady state pool modelling.

5.7.3.2 Reynolds Number Dependency

It was shown by Williams (2012) that the initial non-dimensional rate of plume development varied with inlet velocity. This is also found to be the case when the CFD images for $\tau = 34$ are compared, indicating Reynolds number dependency. The greater the Reynolds number the slower the initial non-dimensional rate of plume development. These Reynolds number effects are related to the initial period of time in which the inertia of the quiescent body of water has to be overcome. This start-up effect impacts on the centreline velocity of the jet and therefore causes the rate of dye penetration into the main water body to be affected. It was observed, in both the physical model and CFD results, that the difference between the images for different Reynolds numbers reduced as time progressed. This indicates that Reynolds number effects may be limited to the start-up period and may be much weaker in steady state pool modelling.
5.7.4 Steady State Confined Jet Computational Fluid Dynamics Modelling Results

5.7.4.1 Jet Development

Comparison of the solutions confirmed that scaling had no effect on the non-dimensional simulation outputs. As the jet is predicted to interact with both the free and solid surfaces, as well as recirculating flow within the tank, during its development, it was desirable to compare the jet development for the confined jet with those of the shallow jet case. Figure 5-31 shows the centreline velocity profiles for the small scale confined jet and shallow jet h/d = 20 steady state solver simulations for a Reynolds number of approximately 50,000. Three regions were observed in the confined jet profile. The jet acts as a free jet initially before a region of lower velocity decay, similar to that observed in the shallow jet case. Finally, the jet velocity rapidly decays as it approaches the end wall of the tank. It was, however, observed that the rate of velocity decay for the steady state confined jet case was even lower than for the shallow jet case.

In order to further confirm the impact of the recirculation flow, a time accurate simulation was also undertaken. The centreline velocity profile was observed to change as the tank flows develop. Prior to the large recirculation flows establishing, for example at $\tau = 113$, the rate of centreline velocity decay is the same as observed in the shallow jet case. The recirculation of the water flow in the confined case, however, results in the jet velocity decaying less than was observed in the shallow jet case once the tank flows have fully established, for example at $\tau = 625$. The transient profiles are also shown on Figure 5-31 for comparison with the steady state and shallow jet profiles.

The recirculating flow performs a similar function to the free surface and the base of the tank, effectively confining the jet flow, reducing the spread of the jet and as a result reducing the loss of momentum. The steady state solutions for both large scale and small scale confined jet flows showed close comparison to those generated by the long run transient solution. Some variation is observed in the velocity profiles, however, the observed variation equates to differences in flow velocity of less than 0.5% of inlet velocity.
The additional complexity of the Confined Jet geometry resulted in additional unsteadiness within the system. The recirculating flow was observed to cause continual fluctuations in the direction of the jet, preventing a stable steady state solution being generated. Monitoring of the velocity at point locations within the tank enabled the fluctuations to be analysed. The standard deviations of the velocity variations at the chosen locations were calculated to be 20-30\% of the mean value when using the steady state solver. Performing the same simulations in a time accurate manner was observed to reduce the standard deviation of the velocity variations to between 5-10\% of the mean value. The mean value of the transient solution, however, was found to be very similar to that of the steady state solution.

5.7.4.2 Dye Dispersion

In order to model the spread of dye in the water tank, the transient solver is required following initial flow establishment. This allows for the fluctuations to be accounted for during dye dispersion. The results obtained following simulations using both the steady state solver and the transient solver for the flow initialisation were compared and showed that the larger variations identified in the steady state solver did not greatly impact the subsequent dye dispersion modelling. The larger variations in the steady state solver solution does however result in less confidence...
in the flow field at the start of jet injection compared to using the transient solver. Stopping the simulation when the solution monitors are close to the mean values increases the confidence in the results but it is still less than using the transient solver from the outset. The use of the transient solver to generate the initial flow field, however, adds significantly to the simulation time. Combining the use of a well monitored steady-state solver for initial flow establishment with the use of the transient solver was determined to be an efficient procedure for modelling dye dispersion from a submerged jet.

5.7.5 Steady State Confined Jet Physical Modelling Results

The video footage recorded during each of the dye dispersion experiments was split into individual frames using video editing software. The frame in which the dye first enters the pool model was designated as $t = 0$. Images for each of the selected timesteps were then extracted from the footage using the information presented in Table 5-4.

<table>
<thead>
<tr>
<th>Timestep</th>
<th>$\tau$</th>
<th>Time for Re = 3224 (s)</th>
<th>Time for Re = 12497 (s)</th>
<th>Time for Re = 15701 (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>1.5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>3.1</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>4.6</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>6.2</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>7.7</td>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>9.3</td>
<td>2.4</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
<td>34</td>
<td>10.5</td>
<td>2.7</td>
<td>2.2</td>
</tr>
<tr>
<td>8</td>
<td>67</td>
<td>20.7</td>
<td>5.3</td>
<td>4.2</td>
</tr>
<tr>
<td>9</td>
<td>101</td>
<td>31.2</td>
<td>8</td>
<td>6.4</td>
</tr>
<tr>
<td>10</td>
<td>134</td>
<td>41.4</td>
<td>10.7</td>
<td>8.5</td>
</tr>
<tr>
<td>11</td>
<td>168</td>
<td>51.9</td>
<td>13.4</td>
<td>10.6</td>
</tr>
<tr>
<td>12</td>
<td>201</td>
<td>62</td>
<td>16</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Repeatability of the physical modelling experiments was examined by running each of the inlet velocities multiple times. Figure 5-32 shows still images taken from the repeated experiments for a Reynolds number of 15,701. The variation between the repeated experiments was observed to be small. The images for runs 2 and 3 appear darker compared to run 1 due to a change in the ambient lighting in the laboratory during the later experiments.
Figure 5-32 - Still images taken from repeated physical modelling experiments for jet inlet Reynolds Number of Re 15701

Figure 5-33 shows images taken from the video footage for each of the experiments at $\tau=20$, $\tau=67$ and $\tau=101$. It was observed that the size of the surface disturbances increased as Reynolds number and Froude number increased, however the distribution of the dye in each of the experiments was observed to be very similar when compared at the same non-dimensional timestep. This indicates that, within the ranges used in this study, the small scale tank flows are reasonably independent of Reynolds number and Froude number. The use of a constant rate of dye addition in the physical experiments meant that the actual concentration of dye in the inlet varied with Reynolds number. This resulted in a fading of the jet plume as the Reynolds number increased and makes the extent of the jet plume development difficult to see in the reproductions of the video footage excerpts shown in Figure 5-33.
5.7.5.1 Comparison of Computational Fluid Dynamics and Experiments

Comparison of CFD and experimental flow visualisation is given in Figure 5-34 and Figure 5-35. The initial plume development, for non-dimensional times $\tau < 25$, was observed to be very similar in both the CFD generated outputs and the experimental images as shown in Figure 5-34.

Greater differences were observed between the experiment and CFD in the later timesteps, as the flow begins to recirculate back towards the inlet. The CFD
appeared to underestimate the turbulent dispersion observed in the experiments following the impingement of the jet on the tank wall, as shown in Figure 5-35. Overall agreement between the CFD and experimental images is still good, therefore it is considered that the application of the above CFD methodology in similar cases is appropriate.

Figure 5-35 - Comparison of CFD and experimental images for the confined jet case following jet impingement with the wall at $\tau = 134$

5.7.6 Single Confined Jet Modelling Conclusions

Images collected during single jet small-scale model dye dispersion experiments have been used to validate the output solutions of CFD simulations undertaken on small scale and full scale geometries. The CFD simulations were able to reproduce results close to those collected in the small-scale physical model experiments undertaken by Williams (2012) and the additional steady state physical experiments undertaken in this research.

The comparison of start-up experimental results showed that the use of a pressure defined inlet boundary condition is required in order to accurately represent the initiation of a jet entering a quiescent fluid. For fully developed, steady state flows this is not necessary and therefore either pressure-defined or velocity-defined boundary conditions are appropriate.

The results show there is a start-up effect associated with the injection of a jet into a quiescent fluid. The study also indicates that the greater the inlet velocity the more significant the initial time lag in the distribution of the dye. This is of interest to pool operators as it indicates that it may take longer for chemical adjustments to come into effect following a period without water circulation, such as after the backwash procedure, than it takes during periods of normal operation. Further investigation into these Reynolds number effects is required to determine whether they are significant for the full-scale pool.

The majority of pool treatment systems are operated continuously and therefore it was important to validate the ability of CFD to represent the hydraulics of swimming pools on a steady state basis. The flow recirculation in the confined case
was found to introduce unsteadiness within the system and reduced the level of convergence achievable using the steady state CFD solver. The use of the steady state solver to generate an initial flow solution did, however, not greatly affect the simulation outputs for the subsequent transient prediction of dye dispersion within the tank. The method of combining the steady state solver and the time-accurate solver, generated simulation outputs that were in reasonable agreement with dye-visualisation results obtained in small scale physical experiments.
5.8 Multiple Confined Jet Modelling

The earlier work that focused on the flow of a single jet enabled initial validation to be undertaken with a reduced level of system complexity. The application of jet mixing in a swimming pool involves the interacting flow of multiple jets to achieve efficient chemical distribution and contaminant removal. It is therefore necessary to increase the complexity of the modelled system by increasing the number of jets in the domain.

5.8.1 Multiple Confined Jet Methodology

Additional changes to the experimental setup were required to enable multiple jets to be used in the small scale physical models. Firstly, a network of equal length delivery pipes was required to enable dye to enter the pool at multiple locations at the same time. Secondly, the pool tank itself required modification to enable a constant water depth to be maintained throughout the experiments. In the single jet experiments the water depth was observed to increase by between 2 mm and 4 mm (5% to 10% of initial water depth) during each experiment. Increasing the number of jets entering the pool would result in an increase in the flow rate of water entering the model tank and therefore increase the rate at which the water level would rise. The model was adapted to enable a constant outflow of water to occur in a similar fashion to that of a full scale swimming pool.

Overflow weirs were installed along both sides of the tank creating a “deck-level” type pool. The modified pool tank was created to be geometrically similar to the actual pool tank at the Surrey Sports Park and was therefore 500d long, 200d wide and 20d deep. Fifteen inlets were installed equally spaced along the length of both weirs at a depth of 10d. The distribution pipework could be easily adapted to vary the number of jets being used in the experiment. The ends of the pool were raised above the weir height to allow water to only overflow along the sides of the pool. The overflow water was collected on the other side of the weir and discharged to a drain. This enabled the small scale model to be operated continuously and allowed the tank flows to develop prior to dye injection. It was not possible to install base outlets in the physical model and presented a departure from an actual swimming pool scenario. The modified pool tank is shown in Figure 5-36 below.
In addition to the physical modifications made to the experimental setup, modifications were made to the selection of non-dimensional timesteps used in the experiments. Increasing the number of jets resulted in a reduction in the time that the jet flow could be observed for. As the aim of these simulations is to move towards a better representation of the full-scale pool application, the timescales of interest were evaluated and the relevant non-dimensional timesteps re-calculated.

Current guidance recommends that the hydraulic design of a swimming pool should be able to achieve chlorine distribution throughout the body of the pool within 15 minutes (PWTAG 2009). Using this desired timescale together with the equation 5-5 resulted in a target non-dimensional time ($\tau$) of 22.5. This is a shorter time period than those considered in the earlier studies. Still images from the video footage were therefore taken at times corresponding to $\tau$ values of 5, 10, 15, 20, 22.5 and 25.

The CFD methodology adopted for the single jet modelling was used for the multiple jet modelling. The multiple jet modelling was undertaken in two stages. The first replicated the small scale physical experiments by omitting any base outlets from the geometry. The second stage involved modelling the pool tank including base outlets as shown in Figure 5-37. The volume of water exiting the pool tank through the base outlets was set to 20% of the total flow rate to match the operational settings of the SSP pool. In order to control the flow of water through the base outlets a velocity specified boundary condition was used.
The multiple jet physical modelling experiments were also undertaken with a different dye, Brilliant Blue FCF, meaning that a recalibration of the rendering criteria was necessary. The switch to the blue dye enabled the distribution to be visible at lower concentrations than was possible for the red dye used in the single jet experiments.

5.8.1.1 Dimensional Analysis

To assess the dynamic similarity with large scale tanks or swimming pools, non-dimensional analysis was undertaken. Assuming jet width (w) is dependent on inlet jet velocity (u), gravity (g), density and viscosity, application of the Buckingham Pi Theorem shows that jet width to inlet diameter (d) ratio, w/d, and other non-dimensional flow parameters, will depend on Reynolds number (Re) and Froude number (Fr) only. The application of the Buckingham Pi Theorem is not presented in full as it is a well-known procedure, however the resulting non-dimensional Froude numbers is defined in Equation 5-6 below, where h is the depth of the tank. The Reynolds number was defined earlier in Equation 5-4. This non-dimensional analysis neglects any surface tension and buoyancy effects.

\[ Fr = \frac{u}{\sqrt{gh}} \]  

Equation 5-6

Considering the definitions of Froude number and Reynolds number it is not possible to satisfy both Froude number similarity and Reynolds number similarity requirements for different scales without changing the kinematic viscosity of the fluid. Dynamic similarity requires the relationship shown in Equation 5-7 between the scaling factor for kinematic viscosity (\( F_\nu \)) and the scaling factor for the geometry (\( F_i \)) (Hughes 1993).
\[ F_v = F_i^{3.2} \]  

Equation 5-7

It follows that in order to have hydrodynamic similarity with a water tank 50 times larger than the experimental model, which would represent a full-scale 50 m swimming pool, a fluid with a kinematic viscosity of approximately 3x10^{-9} m^2/s (1/350th of water) would be required. No such fluid exists and therefore it is necessary to make compromises in relation to the dynamic similarity.

5.8.2 Multiple Confined Jet Physical Modelling Results

The scale of the physical model used (1:50) introduced the need for a compromise between Froude similarity and Reynolds similarity. The reduction in scale increased the significance of surface deformations in the physical experiments. This study highlighted that reasonable accuracy can still be achieved at the higher end of the velocity range by modelling the surface with a free-slip boundary condition.

The inlet velocity achievable in the physical modelling experiments was limited by the practical capacity of the drainage system. Two inlet velocities representing Reynolds numbers of 4,602 and 5,589 were used for the multiple jet modelling. Still images taken from the video footage for each of the selected non-dimensional timesteps are shown in Figure 5-39 and Figure 5-41.

Although great effort was spent preparing the model prior to the experiments, it was not practically possible to get all of the jets to start at the same time. This can be clearly seen in the \( \tau = 5 \) images. The cause of this is likely to be due to the tight tolerances that were required at such a small scale. Slight inaccuracies in the drilling of the inlet holes resulted in deviations in the angle of some of the jets. In order to maintain consistency the \( t = 0 \) point was defined as the time the first observable dye jet entered the tank.

The physical experiments showed that the areas closest to the jet inlets were the last areas to become dyed. It was, however, not possible to generate an even overflow of water over the entire length of both weirs. At the 1:50 scale used in the physical experiments, surface tension effects were observed to be important. The confidence in the water flows in the areas close to the overflow weirs was therefore reduced. In areas where the water was overflowing, the water was observed to become coloured faster than in the areas without water overflow.

The dye was observed to reach the majority of the model tank within the desired target non-dimensional time of \( \tau = 22.5 \). This suggests that the current pool design of 15 paired inlets is capable of distributing disinfectant throughout the water body within an acceptable time frame.
5.8.3 Multiple Confined Jet Computational Fluid Dynamics Results

5.8.3.1 Computational Fluid Dynamics Simulation without Base Outlets

CFD simulations were undertaken using the small scale geometry used in the physical modelling for Reynolds numbers of 4,602 and 5,589 using a time-accurate solver. Images were generated for each of the timesteps used in the physical experiments to enable comparison. These are shown in Figure 5-40 and Figure 5-42. The CFD images were observed to be very similar to the physical modelling images. Unlike the physical experiments, there was no issue in getting the jets to all start at the same time. Although not visible in the latter stages of Figure 5-40 or Figure 5-42, the dye was found to reach the areas close to the jet inlets last as had been the case in the physical experiments.

The practical limits on inlet velocity associated with physical modelling do not exist within CFD modelling. Therefore, a simulation was undertaken using a Reynolds Number of 50,000 to broaden the range of results. The output images for the Re = 50,000 case, although similar to those for the other cases, showed that the spread of dye into the central part of the tank was slower than had been observed in the lower Reynolds number cases. Figure 5-38 shows a comparison of the output images at τ = 20 for the Re = 50,000 and Re = 4,602 case.

![Figure 5-38 – Comparison of the CFD generated images for dye spreading for the small scale multiple confined jet without base outlets case at τ = 20 for Reynolds Numbers 4,602 and 50,000](image_url)
Figure 5-39 - Experimental images for multiple jets with Reynolds number = 4,602

Figure 5-40 - CFD generated images for multiple jets with Reynolds number = 4,602

Figure 5-41 - Experimental images for multiple jets with Reynolds number = 5,589

Figure 5-42 - CFD generated images for multiple jets with Reynolds number = 5,589
The central area of the tank was observed to exhibit the greatest surface deformations in the physical modelling and therefore the visible differences may be associated with the approximation of using a wall with zero shear stress for modelling the surface. The prevention of surface deformations means that the pressure in the middle of the tank can be slightly elevated and therefore inhibit the dye dispersion.

The multiple jet scenario was also undertaken using a full scale geometry and an inlet flow rate matching those used in the Surrey Sports Park. Chlorine was added to the inlet water using the species modelling tool at a mass fraction of $1.5 \times 10^{-3}$. The spread of chlorine after 15 minutes injection, $\tau = 22.5$, was examined by producing iso-volume plots at various mass fractions of chlorine ($F_c$). These are show in Figure 5-43.

![Figure 5-43](image-url)
In addition to dye dispersion, it was possible to track the exchange of water in the CFD simulations through the use of the multiphase solver. The water added along with the dye was defined as a separate phase. The mass fraction of original water present within the pool tank could therefore be recorded during simulation of the scenario. The modelled water exchange profile, defined as the percentage of initial water replaced by injected water, for the multiple jet case without base outlet scenario is shown in Figure 5-44. The theoretical water exchange profile based on assumptions made in the current PWTAG (2009) guidance is also shown for comparison. This guidance assumes that the hydraulics of the pool tank is plug flow in nature. However, a significant amount of mixing takes place within the pool tank reducing the rate at which water exchange takes place. The modelled proportion of original water exchanged during the design specified turnover period of 3.7 hours was found to be 62%. The simulation indicated that a 90% removal of original water was not achieved until more than double the designed turnover period. The exchange profile is slightly lower than that of an ideal fully mixed scenario and therefore indicates that dead spots are likely to exist within the pool tank.

![Figure 5-44](image)

**Figure 5-44 – A comparison between the modelled and theoretical proportion of original water removed from the full scale pool tank over time for a multiple confined jet scenario without base outlets**

The uniformity of the water in the pool tank was examined using the CFD outputs. Figure 5-45 shows the areas of the pool tank that contained greater than 70% of the original water after 6 hours of simulation. It indicates that, in the current configuration, the exchange of water is not uniform across the pool tank and that...
there is the potential for areas of the pool tank to retain contaminated water for a substantial period of time. The simulation also shows that the dead spots in this common configuration are likely to occur at either end of the pool tank. The presence of chlorine resistant pathogens, such as Cryptosporidium, in these areas is therefore likely to persist longer than in other areas of the pool. This is of concern as bathers often spend most time at the end of the pool rather than in the middle of the pool. This not only increases the probability of contaminants to be introduced in these locations initially but also the risk of potential exposure to persistent pathogens.

5.8.3.2 Computational Fluid Dynamics Simulation with Base Outlets

The full scale geometry including base outlets, as shown in Figure 5-37, was used to model the tank hydraulics using the inlet flow rate stated in the SSP design specification (542 m³/hr) and at the reduced flow rate (405 m³/hr) recently proposed in an independent efficiency review by ABS Consulting (2013). The addition of base outlets removing 20% of the total water flow rate had very little effect on the overall dispersion of dye. The jets closest to the base outlets were slightly deviated downwards towards the base, however there were no observable differences in the time taken for the dye to spread around the model. It was observed that the addition of base outlets also introduced additional unsteadiness.
in the CFD solution as a result of some short circuiting. This had the effect of making the exchange of water to be less even during the simulation.

The reduced flow rate simulation did not make any difference to the hydraulic pattern as expected, however, the timescales for the dispersion of dye and the exchange of water were increased. This is shown in Figure 5-46, where the turnover time for ideal plug flow hydraulics was 4.9 hours. The modelled water exchange after this time was observed to be very similar to the full rate output at 63%.

![Figure 5-46](image)

**Figure 5-46 - A comparison between the modelled and theoretical proportion of original water exchanged from the full scale pool tank over time for the multiple confined jet scenario with base outlets operating at 75% of designed flow rate (406 m³/hr)**
5.9 Implications on Pool Design and Operation

The studies undertaken as part of this project provided some support for the current design practice of using equidistant, paired side inlets for rectangular, deck level competition pools. The design of the SSP pool was shown to be effective at distributing disinfectants throughout the majority of the pool tank within the desired timescale of 15 minutes when operated at the full design flow rate. This suggests that there should be a restriction on bathing in the pool for 15 minutes following any periods of disinfection system downtime. The areas of the pool that were last to be reached by the chemical dispersion were observed to be close to the sides of the pool between the inlets. This indicates that the current practice of taking water samples from the sides of the pool is appropriate. If the residual chlorine levels at these points are above target levels the concentrations in the rest of the pool are likely to also be sufficient.

The distribution of chemicals is just one important aspect of swimming pool hydraulics. The presence of chlorine resistant pathogens, such as Cryptosporidium, means that it is also important that the residence time of water in the pool tank is considered. These pathogens can only be effectively managed through physical filtration or through intense treatment by UV or ozone. These techniques can only be undertaken outside of the pool tank and therefore require the pathogens to be efficiently removed from the pool tank. The study highlighted that, despite the current design effectively distributing chemicals throughout the tank, some areas of the pool were seen to have a very long residence time. The modelling identified that some of the water can take in excess of 9 hours to exit the pool. This indicates that chlorine resistant pathogens could present a risk to bathers if the design approach is not modified.

The current practice of dye testing following construction is not able to identify potential residence time issues. The use of measureable tracer compounds would enable residence time experiments to be undertaken in swimming pools, although this could be difficult to be undertaken practically. The option of undertaking residence time experiments within CFD modelling is therefore the most practical solution to this issue. Designing pools to meet low residence time criteria rather than aiming for well mixed pool tanks could require radical changes to the current design approaches. Reducing the residence time of the pool may require fundamental changes to the nature of the hydraulics within the tank and may compromise the ability for swimmer performance to remain unaffected. This additional requirement for competition pools may mean that future pools need to be designed with the ability to operate in multiple modes.
5.10 Conclusions

Knowledge of the hydraulic flows within a swimming pool tank is needed to ensure that health risks to bathers can be minimised. Retrospective changes to the pool tank are very costly and therefore it is important to reduce the chance of pool tanks being initially constructed with poor hydraulics. This study investigated the potential for small scale physical modelling and computational modelling to be used to aid the pool design process.

Small scale physical experiments were conducted at a 1:50 scale. These experiments showed that the dispersal of disinfectants could be predicted through simple dye visualisation methods. The benefits of this technique were that it did not require any specialist equipment and that once the model was constructed it was very quick to conduct a range of experiments. The main drawback with the physical method was the time required to prepare the apparatus. The small scale used in the study reduced the acceptable tolerances in model construction compared to full-scale construction. In addition the small scale also introduced surface tension effects with the overflowing water. The physical models were found to be effective at representing overall tank flows, however, information about more detailed aspects such as surface flows or base outlet effects could not be easily gathered. Creating more complex and larger physical models would likely increase the range of experiments that could be undertaken.

Computational fluid dynamics modelling was also undertaken on small-scale and full scale geometries. The small scale experiments were undertaken to provide validation of the CFD methodology whilst the full scale CFD was undertaken to provide data from which pool tank hydraulics could be evaluated. This study showed that the tank hydraulics could be effectively modelled by CFD. The main benefit of this technique was that a greater amount of flow analysis could be undertaken compared to the physical modelling experiments. The dispersion of chemicals and the removal of the existing water from the tank were both modelled using transient RANS models. In addition, it was possible to use full scale geometries in CFD modelling, removing the need for scaling effects to be considered.

The CFD modelling showed that, although dye could be effectively distributed within the short time frame desired, current pool design approaches are not as effective at exchanging the water within the tank. A common misconception in the industry is that the turnover time is only dependent on the volume of the tank and the water flow rate. The CFD modelling showed that approximately only 60% of the water volume is exchanged during the turnover time calculated using current
methods. This is due to a combination of mixing, dead spots and short circuiting within the pool tank hydraulics.

This study confirmed the potential for both small scale physical models and CFD modelling to benefit the design process. The flexibility and ability of CFD methods to handle more complex geometries, however, means that this is recommended as the preferred method for pre-construction hydraulic design. The meshing and modelling approaches validated in the present study could form the basis of best practice guidelines or examples for the application of CFD in swimming pool design.
5.11 References


ANSYS (2009a) Fluent 12.0 Theory Guide, ANSYS

ANSYS (2009b) Fluent 12.0 User Guide, ANSYS


Modelling for Pool Design and Operation


Furman L., Stegowski Z. (2011) CFD models of jet mixing and their validation by trace experiments, Chemical Engineering and Processing 50, 300-304


Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes 5-63


Laurence, J.C. (1956) Intensity, scale and spectra of turbulence in mixing region of free subsonic jet, *National Advisory Committee for Aeronautics*


Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes


Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes
Chapter 6 – Key Research Findings and Policy Recommendations for Integrating Sustainable Practices in the UK Swimming Pool Industry

Throughout the preceding five chapters, a wide range of analysis and discussion on the aspects of swimming pool design and operation investigated in the current research project has been presented. This chapter summarises the key findings and proposes how changes could be made to the existing guidance and legislative structure associated with pool design and operation to encourage the uptake of sustainable practices within the industry. The contributions to knowledge that have resulted from the current research are clearly presented and areas that require additional research in order to develop the knowledge of the recreational water industry further are suggested.

6.1 Summary of Key Findings

6.1.1 Existing Policy and Guidance

There is a body of existing national and international guidance on various aspects of swimming pool safety and water quality. This has generally been developed on an ad-hoc and informal basis. As a consequence, it is somewhat disjointed and in some cases conflicting, for example with references to hydraulic design criteria. In the UK, the guidance is not supported by specific legal duties for swimming pool operators beyond their general duties in relation to the management of health and safety aspects. This has the result of generating a set of guidance that is open to interpretation and therefore the application of guidance can be inconsistent throughout the industry.

**Recommendation:** Guidance should be improved by specifying required water quality and safety standards in terms of outcomes. The use of specific design and operational methods should be provided as best practice examples. This would ensure that the guidance can be applied to a wide range of different design and operating scenarios whilst also enabling innovation without compromising operational effectiveness and public health.

The current situation of voluntary codes of practice and operational requirements coupled loosely to the existing health and safety law is ineffective at ensuring that operators and designers do not cut corners and increase the risk of health impacts on their bathers and staff. At present, a poor pool operator is unlikely to be
Research Findings and Policy Recommendations

prosecuted for failing to follow even the most basic recommendations set out in guidance. The lack of perceived consequences for failing to observe the guidance means that facility operators are more open to prioritising other aspects, such as activity demands or financial savings. In addition, the swimming industry has been slow to adopt successful practices from other industries in a timely manner. For example, the adoption of risk-based assessments for pool water management has only started to be included in the guidance despite being implemented in the drinking-water industry in 2004.

**Recommendation**: Creation of a new policy framework is recommended to encourage compliance with guidance by pool designers and operators as well as enable best practice learning from other related industries. A proposal for a new policy framework is presented and discussed later in this chapter.

6.1.2 Water Quality

The water quality survey undertaken as part of this research project provided a broad assessment of water quality within a new and fully operational pool for the first 20 months following its commissioning. The study identified that there is a period of time before pool water quality at a facility stabilises. In the case of the Surrey Sports Park, the pool water characteristics developed over approximately a 10-month period. This highlights that it may not be adequate to confirm the performance of a facility in a single commissioning event following the construction of a facility as is currently common practice. The existing recommendation that pool water is routinely analysed for a range of parameters is therefore an essential part of good pool management.

The water quality survey also identified that the variation in chemical water quality was greater between sampling dates than it was between sampling locations. This indicated that the overall hydraulics at the pool facility used in this study was adequate and that the pool tank facilitated a fairly well-mixed and uniform water quality. The monitoring of key chemical indicators, such as free chlorine, calcium hardness and alkalinity, at a single sample location is therefore appropriate for general operational control purposes. However, the situation was different for indicators of microbiological water quality, where large variations between sample locations on the same date were frequently observed. This finding is to be expected given that organisms are particles and therefore will be dispersed in water differently to water soluble substances. The collection of representative microbiological samples remains a significant challenge for the industry and therefore it is important that operators do not become complacent following...
receipt of microbiological test results indicating concentrations below the recommended limits. The inability to ensure the samples are representative reduces the confidence in the analytical results.

**Recommendation:** It is recommended that existing water quality guidance is re-phrased so that positive microbiology test results are used as triggers for an operational intervention but negative test results are not taken as proof of adequate operation.

The water survey highlighted that there are health-related chemical parameters that are not well controlled by the current guidance. For example, bromate and chlorate were both present at concentrations far exceeding the recommended maximum limits for drinking water quality. The concentration of these disinfection by-products has been successfully controlled in the drinking water industry through the use of a purer grade of treatment chemical, by avoiding the accumulation of bromide and chloride salts in the pool water and by setting upper limits on the doses of UV, chlorine and ozone applied to the water. This knowledge from the drinking-water industry needs to be appropriately transferred to the recreational water industry through additional specific studies.

**Recommendation:** The swimming industry is very similar to a number of other industries, especially in relation to its water treatment requirements. It is recommended that additional research with a specific focus of transferring knowledge from these industries to the swimming industry is undertaken.

The water quality survey also showed that a number of characteristics associated with potential operational risks fall outside of the currently recommended monitoring parameters. The most prevalent of these was chloride, which is important due to its associated potential for damaging pool-related equipment. The choice of materials for use in swimming pools needs to better consider the actual ranges of chloride content, as observations were made of equipment suffering from chloride corrosion due to contact with pool water.

**Recommendation:** It is recommended that the guidance on water quality testing includes additional relevant operational parameters, such as chloride, so that the risk to the facility infrastructure is minimised.

Structures such as moveable booms and floors were observed to have noticeable effects on the water body. This confirmed the need for more information to be gathered about the effects of these structures on the water circulation achieved in the pool tank. This fell out of the scope of the current project and is therefore recommended as a topic for further work.
Research Findings and Policy Recommendations

**Recommendation:** It is recommended that a requirement for an assessment of the impact of internal structures on the water flow to be included within pool design and construction guidance.

6.1.3 User Aspects

The factors considered to impact the water quality in swimming pools were identified as the number of bathers using the facility, the activity type, the uptake of pre-swim showering, the extent of pool water surface disturbance, the use of equipment and accessories and the configuration of the pool tank. This study provided evidence that the current guidance is not sufficiently clear about the importance of instantaneous bather load on the water quality as the advice presently focuses on matters of physical safety. The opportunity for operators to reduce operating costs by adjusting treatment during periods of low instantaneous bather loading was suggested. Similarly, it was shown that some activities potentially present a higher risk to bather health. This highlights the importance of planning pool schedules to manage health risks or designing pool treatment systems to cope with fluctuating impacts of different activities.

**Recommendation:** It is recommended that a requirement is introduced for pool designers to ensure that the treatment system is operationally flexible such that changes of use can be addressed. It is also recommended that a requirement is introduced for pool operators to ensure a competent person, who is aware of the various implications of activity type and bather numbers, is be responsible for the scheduling of pool activities.

The actions of bathers are known to impact on the water quality, therefore it was important for an accurate assessment of public knowledge to be undertaken. The study highlighted that achieving a change of bather behaviour is fundamental to a move towards more sustainable pool facilities. The broad range of users, and their varied and often conflicting needs and interests, means that the pool facility managers are best placed to deliver a meaningful program of bather education. For example, the activity survey undertaken in this research identified a broad range of clothing, accessories and equipment used by the various bathers in the pool. Pool managers should therefore be able to provide information to the bathers on the requirements for these aspects.

**Recommendation:** It is recommended that a requirement is introduced for pool operators to provide inductions to bathers covering how to use the facility and their associated responsibilities before they are permitted to use
Research Findings and Policy Recommendations

the facility in a similar way that access to fitness centres and gyms is commonly managed.

6.1.4 Operational Aspects

The three most important operational aspects in relation to the cost of swimming provision have been identified as the pumping of pool water, the management of the air condition and the loss of heat from the pool water. Adopting the use of variable speed drives on air and water treatment systems, combined with improved knowledge about trends in bather loading, presents an opportunity to greatly reduce the energy consumption of a facility. The reduction of pumping speed, however, will have an impact on the distribution of disinfectants and the removal of suspended material from the pool tank. In order to make firm recommendations in relation to how much speed reduction is appropriate, a better understanding of the hydraulic flows in the pool tank is required. This was identified as a significant gap in the current industry knowledge and was selected for further investigation.

The research into operational impacts found that amendments to operational guidance could help to reduce the rate of pool water evaporation, for example an increase of the recommended air-water temperature differential to 2°C. The consequences of not having a pool cover strongly suggest that all pool facilities must incorporate a pool cover for use during un-occupied periods.

**Recommendation:** It is recommended that a requirement is introduced for pools to have a pool cover installed during construction or refurbishment as a prerequisite for obtaining planning approval.

There are limited opportunities for reducing the evaporative losses during occupied periods and therefore pools are likely to always be associated with a large heating demand. In addition, the common practice of managing the concentrations of dissolved compounds in the pool water is inherently associated with a large water demand. There are currently very few drivers aimed at reducing the water use associated with buildings. This is something that needs to be improved to enable more focus to be placed on developing alternative processes.

**Recommendation:** It is recommended that the emissions associated with the production, delivery and disposal of water is included in carbon reporting mechanisms for industries that have a high demand for water, such as the swimming pool industry.

The research highlighted that the current water management guidance for swimming pools was inadequate at ensuring appropriate water exchange was taking place. For instance, pools used well below their capacity using a fixed...
exchange rate could result in insufficient water to be exchanged and the potential for unwanted chemicals to accumulate. Conversely, those pools experiencing high use and implementing good bather management could potentially be overestimating the water exchange requirements, wasting both an increasingly precious resource and energy.

**Recommendation:** It is recommended that a more developed relationship is used to determine water exchange requirements, such as the one proposed in Chapter 4, to enable relevant factors to be taken into account and enable increased efficiency in facility operation.

It was also identified that current methods of counting bather visits can greatly overestimate the number of bathers actually using a pool. This in turn also results in the potential for large amounts of water and energy being wasted through excessive dumping of pool water.

**Recommendation:** It is recommended that a weighting factor should be applied to daily bather loads calculated using half-hourly head count data. The current research indicates that the overestimation could be as large as 20%.

Tracking of operator performance from a water replenishment perspective was also found to be difficult using current management practices. This presents the opportunity for small but cumulative errors in pool management to occur and potentially lead to more serious issues with water quality.

**Recommendation:** It is recommended that a new performance indicator, the Water Exchange Deficit, is added to pool management guidance to assist with the monitoring of operational practices.

### 6.1.5 Computational Fluid Dynamics Aspects

Knowledge of the hydraulic flows within a swimming pool tank is needed to ensure that that the potential health risks to users can be minimised, whilst also reducing energy requirements. Retrospective changes to the pool tank are very costly and therefore it is important to reduce the chance of pool tanks being initially constructed with inappropriate hydraulics.

**Recommendation:** It is recommended that the consideration of hydraulics in the expected use modes is included and evidenced during the design process of new pools or refurbishments. The outcomes of design appraisals of hydraulics should be passed onto pool operators as part of the operation and maintenance procedures.
The CFD verification work undertaken during this project highlighted that the common use of the k-ε RNG turbulence model for the simulation of swimming pools may not be the most appropriate method. This is based on the understanding that the jet flows are the dominant phenomenon in the swimming pool application. Verification of the full pool environment was not possible during this research and therefore additional work is required to confirm the accuracy of the simulations when applied to a complete pool environment.

**Recommendation:** A full-scale pool hydraulic investigation should be undertaken to verify the accuracy of the simulation settings for the application of CFD on the whole pool. A combination of residence time experiments using tracer injection and dye dispersion experiments would likely be the most appropriate at this scale.

CFD modelling showed that, although dye could be effectively distributed within the short time frame desired, current pool design approaches are not effective at exchanging the water within the tank. A common misconception in the industry is that the turnover time is only dependent on the volume of the tank and the water flow rate. The CFD modelling showed that only around 60% of the water volume is exchanged during the turnover time calculated using current methods. The adoption of a well-mixed flow strategy for the swimming pool application, as done in current industry practice, is effective at maximising disinfection efficiency. However, the further from a plug flow scenario a pool is the greater the risk of other hazards existing, such as the exposure of chlorine-resistant pathogens. The inclusion of modern ex-situ based treatment technologies, such as UV units, reduces the reliance on pool-based disinfection and therefore supports the case for moving away from well-mixed flow strategies.

**Recommendation:** It is recommended that a risk-based analysis of moving from a well-mixed to a plug flow-based strategy is undertaken to assess whether the suggestion that the benefits of a reduce residence time of water in the pool tank and more efficient plantroom-based treatment are not offset by other increases in risk elsewhere.
6.2 UK Policy Development Options

6.2.1 Introduction of New Industry Focused Legislation

The first option considered for encouraging the swimming pool industry to adopt better design and operational practices was the adoption of a new legal framework through a “Swimming Pool Act”. This could directly place legal responsibilities on the various stakeholders including owners, designers, builders and operators. Acts of Parliament are the primary statutory vehicle in the UK and are used to define duties, powers and sanctions and create the basis on which an enforcement regime for compliance can be set up, usually through the making of secondary legislation in the form of regulations or formal codes of practice. The process of introducing new Acts of Parliament was discussed with experienced practitioners during a workshop, entitled “Life Cycle of a Bill” (UKGOV 2014), hosted by the Cabinet Office as part of UK Parliamentary Week. The creation of primary legislation in the UK is a time consuming process that requires significant parliamentary time for a Bill to be presented which, if passed, then becomes an Act (UKGOV 2014).

This route is usually only attempted if there is significant support for the policies amongst the parliamentary parties. The allocation of parliamentary time to prepare, discuss and implement new legislation is generally prioritised based on the political support for each policy (UKGOV 2014). In most cases the first two sessions of parliament are reserved for delivering the policies included in the incoming government’s election manifesto. The third session of parliament tends to be focused on delivering policies that address issues that have arisen during the first half of the government’s term in office. This means that many policies that are not considered to have political significance are likely to only be considered for the fourth session of any parliament (UKGOV 2014).

In order to increase the political support for policies, a process of governmental lobbying is often required. In relation to the aspects associated with this research, this could either be undertaken directly by industry-related bodies, such as the Pool Water Treatment Advisory Group (PWTAG) or the Chartered Institute for the Management of Sport and Physical Activity (CIMSPA), or via independent policy and research institutes, such as Policy Exchange. It is currently advised that, in order to gain the attention of those responsible for selecting work streams for organisations like Policy Exchange, focus is given to specific recommendations that have wide-ranging implications or have significant measurable public benefits and are a good fit with the interests of the lobbying policy research institute (Drayson 2014).
6.2.2 Introduction of New Regulations under Existing Acts of Parliament

The regulation of swimming pools is unlikely to justify a specific piece of new primary legislation not least because many of the issues concerned would be considered as being amenable to being captured adequately under the existing framework of other acts such as the Health and Safety at Work Act (HMSO 1974), Sustainable and Secure Buildings Act (HMSO 2004), Climate Change Act (HMSO 2008a) and the Planning and Energy Act (HMSO 2008b).

The introduction of regulations under an existing Act is still far from straightforward. In 2010, the incoming UK Government made a pledge to reduce the amount of unnecessary regulation that impacts businesses. As part of this, a “one in, one out” rule was enforced in relation to the creation of new regulations (BIS 2013). This was further developed to a “one in, two out” rule for regulations introduced after December 2012. In addition to the requirement to identify and gain support for the removal of existing pieces of legislation, the creation of new regulations is a very heavily involved process that follows the framework shown in Figure 6-1. Following the successful completion of this process, the new regulations then need to be brought into law by being ratified by Parliament. The limited time available for such actions can result in very long time frames for the delivery of new regulations.

![Figure 6-1 - UK framework for domestic regulations (BIS 2013)](image-url)
6.2.3 Amendments to the Implementation of Existing Regulations

Another approach that can be used to introduce new requirements within an existing framework of legislation is through the creation of Approved Documents published by the enforcement bodies responsible for compliance with the existing legislation. This approach has been used historically where industry support for better uptake of best practice is strong and there is a need to avoid translating specific technical requirements directly into law which is challenging and error prone, and can make the legislation difficult to navigate for those who have to comply with it. In addition, embedding technical criteria into law also means frequent amendments of law are needed in order to keep it up to date as knowledge develops. A further benefit of this approach is that the promulgation of mandatory, formal guidance creates an environment and market that is focused on compliance with best practice. This subsequently marginalises organisations that cut corners in their business practices and can create a commercial advantage for responsible businesses.

An example of where this approach has been successfully adopted is in the control of Legionella. An Approved Code of Practice (ACOP), “L8 - Legionnaires' disease: The control of legionella bacteria in water systems” (HSE 2013), has been developed as the means by which the Health and Safety Executive (HSE) prescribes the legal requirements for legionella control under the broader Control of Substances Hazardous to Health Regulations (HMSO 2002) enforced by the Health and Safety at Work Act (HMSO 1974). Similar, Approved Documents have been produced by the Department for Communities and Local Government (DCLG) to detail best practice and the expected minimum actions required for compliance with the legal requirements enforced by the Building Regulations under the Building Act (HMSO 1984).

As mentioned above this route avoids complicated processes for keeping the requirements up to date. Modifying approved documents is a comparably straightforward process carried out by the relevant “competent authority”, rather than government itself, whose powers and duties are already defined within the overarching primary legislation, therefore largely avoiding the complications of the parliamentary approval process. This enables the requirements placed on industry to be developed by the enforcing body through consultative processes that draw on the technical knowledge of its industry stakeholders. It also enables the requirements to be updated relatively frequently to account for developments in available technologies or academic literature.
6.2.4 Generation of New Voluntary Guidance or Informative Documents

The provision of voluntary guidance and information documents is the final mechanism that could be used to develop the existing policy landscape. As highlighted in Chapter 1 of this thesis, this is the approach that has been relied on to date with the publishing of both national and international guidance documents aimed at the swimming pool industry.

The benefit of this approach is that it offers the greatest flexibility in terms of scope and the ease of updating. It enables anyone to promulgate advice for specific applications, issues or user groups without the need for any process of approval or endorsement by enforcement bodies or government. Whilst this approach avoids the imposition of the cost of compliance on either the public sector or business during the current climate of austerity, a disadvantage is that there is no specific incentive for the guidance to be followed.

In many cases, poor operational practices are a result of the lack of understanding of the implications of the recommended practices not being followed. This is where the generation of infographics and other documents aimed at raising awareness of issues can help if they are promulgated by reputable and relevant organisations with a wide outreach. For example, providing information and guidance to bodies such as the Association for Public Sector Excellence (APSE) could be a pathway to disseminating key information to local authorities, who are responsible for the majority of large swimming pools in the UK. At present, the awareness of available guidance is fairly poor due to the absence of targeted distribution and publicity of new guidance when it is made available. A number of organisations, including PWTAG and British Swimming, have recently improved the availability of guidance through their websites, however the onus is on stakeholders to look for guidance rather than active dissemination of material.

A recent addition to the list of available guidance is the new code of practice for swimming pool management published by PWTAG (2014). This document has adopted the concept of Water Safety Plans (WSP) that was introduced for the drinking-water industry by the World Health Organisation in 2004 (WHO 2009). The new code of practice now recommends that all swimming pool operators have a documented WSP that incorporates a risk-based assessment covering all elements of swimming pool water management. This will help to address some of the issues highlighted earlier in this thesis in relation to the inadequate scoping of current water quality assessments by broadening the scope of risk assessments beyond those of physical safety.
6.3 Policy Development Recommendations

Based on the failure of existing voluntary guidance to have delivered a structured and integrated approach to pool design and operation in the UK, it is recommended that a legal driver for the most important aspects is introduced. As a first step, and recognising the difficulty of making new legislation, it is recommended that a package of policy improvements using an approach similar to that used for legionella control and building regulations should be considered.

PWTAG has recently released a voluntary approved code of practice for swimming pool management (PWTAG 2014). This, together with the existing HSE Guidance (HSE 2006) could form the basis for the development of an HSE ACOP on Swimming Pool Management. This ACOP should attempt to focus on four key principles:

- Induction of users to the swimming pool environment
- Prevention of exposure to, and regular monitoring of, substances harmful to health using a risk-based approach such as the creation of a Water Safety Plan.
- Training of staff responsible for operating and supervising pool facilities
- Responsibilities of designers, suppliers and installers for the provision of safe facilities

The formation of an ACOP under the Health and Safety at Work Act 1974 would encourage an integrated approach for better pool management by placing more legal responsibilities on operators, designers and installers. The main feature of the Legionella ACOP is a requirement for a formal risk assessment by a nominated responsible person. These requirements are directly applicable to the management of risk relating to the swimming pool environment. It is recommended that a requirement to induct users to the swimming pool environment should be included in the ACOP to address the educational issues that were highlighted during the user-focused studies undertaken as part of this research.

Although health and safety responsibilities can be used as the basis for many of the recommended improvements to swimming pool policy, there are a number of other aspects that would not fit easily within the Health and Safety legal framework, specifically the energy and water efficiency aspects needed to achieve a sustainable swimming industry. It is a common issue found throughout most industries in the UK that very little importance is placed on water efficiency. This is a major environmental aspect for the swimming industry, however, due to the relatively low profile in existing environmental benchmarking systems, such as the Building Research Establishment Environmental Assessment Methodology (BREEAM), very
little focus is given to reducing water consumption. Recent amendments to Part G (DCLG 2010) of the building regulations have introduced requirements in relation to water efficiency in domestic buildings. The addition of requirements for non-domestic buildings would be a logical progression that would help ensure that water use was considered appropriately in the design stage. In addition it is recommended that requirements for modelling the hydraulics of the pool tank are included at the design stage. Inclusion of these requirements within the framework of the CDM regulations could be a feasible option as tank hydraulics are critical to the ability of operators to adequately manage water quality during the use phase.

In order to increase the importance of efficient use of water in the operation of a swimming facility, a piece of existing environmental legislation could be used. As public buildings, most swimming pools are required to report operational environmental information in the form of Display Energy Certificates (DEC) under the Energy Performance in Buildings Directive. At present, these include the carbon emissions from all primary energy that is used in the building, including the emissions associated with the generation and transmission of electricity to the building. It is recommended that a similar approach is applied to water consumption, with the emissions associated with supply and disposal of water included in reporting requirements. This would provide an incentive for operators to implement opportunities to reduce water consumption as it would impact their publicly visible indicator of environmental performance.

Another piece of existing environmental legislation provides a potential delivery vehicle to implement the recommendation of incorporating life cycle assessments within the design phase of new construction and refurbishment projects. The powers given to local planning authorities via the Planning and Energy Act 2008 enable them to create policies for developments that require:

- a proportion of energy used in development to be from renewable sources
- a proportion of energy used in development to be from low carbon sources
- developments to comply with energy efficiency standards that exceed the energy requirements of building regulations

This presents a possible route for ensuring aspects of facility design that realise financial benefits over the longer term are incorporated in the initial design and construction phases. It is recommended that a guidance document is created for local authorities that details design recommendations that reduce the lifecycle cost of swimming pool operation.
6.3.1 Implementation of Policy Recommendations

Pulling these recommendations together requires a new conceptual framework in which the existing legislation can be integrated with the ability for broader voluntary guidance. Figure 6-2 shows a proposal for what such a framework may look like.

![Diagram showing a proposal for a new conceptual framework for the recreational water industry]

The formation of a “Knowledge Gateway” is needed to provide a central information hub from which support for both voluntary guidance and legal requirements can be drawn. Sources of information to the “Knowledge Gateway” could be from academic research, changes in UK or EU legislation or companies presenting new technological solutions as well as from feedback for the entire industry through stakeholder engagement activities. This central hub of information would ensure that the broadest range of information is captured during the appraisal and development of new policy or recommendations. This task of combining the best available information and creating policy would be best suited to a collaborative organisation containing a wide range of industry and policy experts.

The role of the collaborative organisation would be to provide the relevant enforcement bodies with the knowledge required to develop appropriate Optimising Sustainability, Performance and Public Health Protection in the Design and Operational Life Cycle of Sports and Leisure Pool Complexes.
supporting documents within the existing legal framework. Their ability to review new information presented via the “Knowledge Gateway” would enable a process of continual review of the current requirements. This process would help keep the legal requirements up to date by making modifications where necessary to the three key pieces of existing legislation identified previously.

6.4 Contributions to Knowledge

There are four primary contributions to knowledge that have resulted from the research undertaken. These contributions are summarised below.

6.4.1 Identification of the Relationship between Activity Type and Water Quality

The outcome of the analysis of the primary data collected during the activity survey undertaken as part of the research project was the identification of large variations in the measured impacts of different activities on the water quality in the pool. To date, the industry guidance has not made reference to the potential impact that activity type may have on water quality and therefore accounts for all bathers in the same way irrespective of the activity they are participating in. The reporting of the variable impact associated with activities enables pool operators to optimise their pool schedules and treatment practices.

6.4.2 Proposal of Water Exchange Deficit as a New Performance Indicator

The definition of the Water Exchange Deficit (WED) was proposed as a solution to the operational challenges of assessing long-term performance of pool operation. The manual nature of water disposal methods and the fluctuation in bather numbers can make it difficult for operators to judge how adequate their water disposal and replenishment rates have been. The WED is defined as the cumulative difference between actual and recommended water exchange rate based on the bather loading of the swimming pool and current exchange recommendations.

6.4.3 Proposal of an Enhanced Methodology for Calculating the Expected Water Consumption of an Indoor Swimming Pool

Investigation into the operation of a swimming pool also indicated that the over-simplified method for estimating water consumption in the current guidance was not effective at delivering efficient water management. An enhanced methodology was proposed in this research that allowed several different factors to be taken into account when calculating the water consumption requirements associated with pool operation. The new methodology enables the benefits of good bather management and implementation of evaporation prevention measures to be
accounted for and therefore could help to encourage operators to use more sustainable practices.

6.4.4 Proposal of a New Framework for Guidance and Regulation of the UK Swimming Industry

The final contribution to knowledge is the proposal of a new framework for guidance and regulation for the swimming industry in the UK. The new framework aims to use existing legislation to ensure minimum standards are adopted across the entire swimming industry whilst also including all stakeholders in the process of developing standards that complement each other. Key aspects of the proposed framework include the requirement for bather education through pool-related inductions, the requirement for assessment of competency for those involved with designing and managing swimming facilities and a clear route for new developments and stakeholder engagement to be incorporated in the industry guidance.

6.4.5 Other Industry-Related Contributions

In addition to the four contributions mentioned above that are relevant to the wider industry as a whole, the research also resulted in the development of information relevant to the Surrey Sports Park. This information can be used as the basis upon which future contributions to the whole industry could be made.

Computational and physical modelling experiments were used to develop an initial modelling strategy for the swimming pool context. The modelling showed that use of RANS modelling was a suitable method for undertaking prediction of pool tank hydraulics. The modelling undertaken identified that the current hydraulic strategy of the pool was effective at achieving disinfectant distribution throughout the tank within the currently recommended maximum time of 15 minutes but not at achieving the desired pool turnover rate. This shows that fundamental decisions on appropriate hydraulic strategies for swimming pools needs to be re-examined.
6.5 Further Work

During the research process, a number of areas of knowledge were identified as needing improvement in order to further the development of the understanding of interactions in the swimming pool context.

The concentration of bromate and chlorate in the pool water was identified as being significantly higher than the expected levels during initial surveys. Although this is a relatively new finding in the context of swimming pools, it is a common issue that has been widely studied and addressed in the drinking water industry. Similarly, the use of computational modelling in the design of process vessels and the analysis of chemical and particle dispersal has been widely adopted. It is recommended that a further study that specifically aims to transfer the knowledge from these industries into the swimming pool industry is undertaken.

Pool tank hydraulics was also highlighted as an area of increasing significance. Although the research presented in this body of work indicated that a move toward a plug flow strategy for pool hydraulics, rather than a well-mixed strategy, could be beneficial, this area is in need of much deeper analysis of the implications of changes in the hydraulics in the pool tank. Additional development of modelling tools is recommended to undertake this assessment. Chemical and particle dispersion modelling and residence time distribution assessments would greatly enhance the knowledge base on which hydraulic guidance can draw from.

The incorporation of new methods of disinfection such as UV and ozone, presents potential risks for additional more complex harmful disinfection by-products to be formed. A detailed assessment of the effects of these technologies on the various constituents in the pool water is needed in order to predict the fate of contaminants in the water. This will become increasingly important if a plug flow strategy, where the main water treatment is undertaken outside of the pool tank, is adopted for pool hydraulics or if new chemicals are added to the pool system, such as monolayer liquid pool covers.

It was highlighted that two of the most significant stakeholders that need to be engaged in the process of improving the swimming industry are the Local Authorities, as the majority pool operator in the UK, and the bathing public. The actions of these two stakeholders could have significant impact on the industry and therefore in depth studies to assess the level of awareness of pool-related issues and behavioural drivers in these stakeholders would assist in the identification of the requirements for educational and training interventions and strategies.
The final area of research that could yield significant benefits to the sustainability of swimming pools relates to alternative heat sources for the pool application. A large amount of low grade heating is required to maintain a comfortable swimming environment and could potentially be sourced from low carbon technologies or, especially in large facilities with significant air-conditioned areas, from waste heat generated elsewhere in the facility. Broadening the boundary of energy management considerations to encompass the entire facility could present further opportunities to reduce the overall energy consumption of a facility. Some initial research into these opportunities has been previously published. It is recommended that this area is developed further in order to result in the design of facilities with enhanced environmental performance and reduced operational costs.
Research Findings and Policy Recommendations

6.6 References


Drayson, K. (2014) Discussion on the role of policy institutes with Dr Katherine Drayson, Research Fellow, Environment and Energy Unit, Policy Exchange, UK [Conversation] (Personal Communication December 2014)


HSE (2013) *L8 – Legionnaires’ Disease: The Control of Legionella Bacteria in Water Systems*, Health and Safety Executive, UK


