Health Risk Assessment and Management Approaches for Recycled Water Irrigation in Agriculture

Christopher William Derry

School of Science and Health
University of Western Sydney
Australia

A portfolio submitted in fulfilment of the requirements for the degree of Doctor of Philosophy by publication

September 2014
Statement of authentication

Author: Christopher William Derry
Degree: Doctor of Philosophy
Date: 20th September 2014

I certify that the work presented in this portfolio in fulfilment of the requirements for the degree of Doctor of Philosophy by publication is, to the best of my knowledge, original, except for those parts as acknowledged in the text by reference, and that the material has not been submitted, either in full or in part, for any degree enrolled at this or any other institution. I certify that I have complied in all other respects with the rules, requirements, procedures and policy relating to the award of this Degree at the University of Western Sydney.

Christopher William Derry
Acknowledgements

I wish to thank Roger Attwater, Senior Manager for Environment and Risk Management at University of Western Sydney, for his friendly co-authorship of a number publications presented in this thesis and for his insight regarding the Hawkesbury Water Recycling Scheme, the land on which it is situated, and its people.

I thank my supervisors Professor Basant Maheshwari and Professor Bill Bellotti for their good guidance and shared knowledge relating to water reuse, peri-urban irrigation, agricultural futures and the production of this thesis. Thanks also to Adjunct Associate Professor Bruce Simmons who facilitated my relocation to Australia from South Africa 16 years ago, for his generous sharing of knowledge of aquatic impact assessment and for introducing me to the magnificent Blue Mountains World Heritage area adjacent to our Hawkesbury campus.
Abstract

This PhD portfolio presents five papers which identify innovative health risk assessment and management approaches for securing safe irrigation with recycled water in agriculture. They are based on a research project from 2002 to 2012 carried out primarily at the Hawkesbury Water Recycling Scheme (HWRS) in Sydney's northwest, which irrigates a wide range of food crops and pasture types using tertiary treated sewage effluent from the Richmond sewage treatment plant (STP). Most of this irrigation takes place on the Hawkesbury agricultural campus of the University of Western Sydney (UWS).

Motivation for the project came from a number of local and international health incidents involving large-scale contamination of food or water with faecal matter, raising concerns which overspilled into the agricultural irrigation sector. Reliance by irrigation schemes on a single set of water quality data supplied by the STP was challenged, given the potential for change in water quality as the result of bacterial growth, or through contamination by farm or wild animals including birds during environmentally-open scheme storage. This and other issues required investigation and a research project was initiated by the author following a request from the HWRS.

An early finding was that control points for monitoring water are needed, principally at reservoir outlets, to facilitate water diversion to irrigation sites where the guideline values will be met in terms of the pertaining water quality. This multiple barrier approach ensures the most productive application of the water while meeting health, agricultural and ecological requirements contained in local or international guidelines.

Seven control points were identified for HWRS as a moderate sized scheme, at which 46 biophysical and microbiological water quality parameters were monitored from 2003 to 2008 yielding over 10,000 data entries. Analysis showed that health risk assessment was possible using a relatively small subset of these parameters, provided that contextualisation using qualitative environmental, exposure and social data was carried out. This necessitated a mixed methodology, with development of innovative approaches for integration of quantitative and qualitative data to generate single risk and uncertainty values, to facilitate rapid health-risk management.

Important changes in physicochemical and microbial parameters were identified when water of varying quality was passed through the same reticulation. A combination of bivariate and multivariate regression analysis identified growth factors for enterococci as a key indicator in recycled water. Modified application of KABP (Knowledge, Attitudes, Beliefs and Practices) surveying was used to build data for analysis of stakeholder acceptance of food-related irrigation. Analysis of the range of functions needed to carry out effective and accountable risk management led to development of a cyclic risk management model which encouraged iterative risk assessment with continuous, multilateral risk communication between management and stakeholders.
Significant research findings related to specific parameter improvements in low quality treated effluent on storage, with deterioration in high quality stored under the same conditions. An important research discovery was that regrowth of enterococci indicator could occur in environmentally-open impoundments, despite information to the contrary in a number of authoritative texts, including WHO guidelines. Resultant false-positive results lead to rejection or over-chlorination of water, presenting potential health and environmental impacts. Through multivariate analysis an equation was developed for correction of false indicator results to facilitate food supply and climate change modelling by other researchers.

Stakeholder acceptability of treated effluent irrigation was found to increase with the perceived number of physical barriers between the point of irrigation and the consumer. This is important in that it supports the engineering concept of a multiple barrier approach, but highlights the need to communicate its existence if product acceptance is to occur.

Overall, the portfolio provides an overarching document which introduces the papers, explains the underpinning research project, and balances the recycling imperative with the need to monitor, assess and manage risk. The five papers are discussed in terms of their content, relevance, impact, methodology, findings and contribution to a collective body of scientific knowledge at the expected academic level. Individual papers are presented in full in published format in the appendices.
# Table of contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><strong>The underpinning research project</strong></td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>2.1 <em>The Hawkesbury Water Recycling Scheme (HWRS)</em></td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>2.2 <em>Local motivation for research engagement</em></td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>2.3 <em>The research project objective and aims</em></td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>2.4 <em>The HWRS research data base</em></td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>2.5 <em>A conceptual risk management framework</em></td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>2.6 <em>Impacts of the project</em></td>
<td>18</td>
</tr>
<tr>
<td></td>
<td><strong>Health risks and indicators</strong></td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>3.1 <em>Health risk determinants</em></td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>3.2 <em>Sewage effluent and disease</em></td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>3.3 <em>Health risk indicators</em></td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>3.4 <em>Treatment-performance indicators</em></td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>3.5 <em>Toxic chemicals</em></td>
<td>31</td>
</tr>
<tr>
<td></td>
<td><strong>The water recycling imperative</strong></td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>4.1 <em>The international recycling imperative</em></td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>4.2 <em>The Australian recycling imperative</em></td>
<td>35</td>
</tr>
<tr>
<td></td>
<td><strong>The five research papers presented for the thesis</strong></td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td><strong>Contextualisation of each thesis paper</strong></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>6.1 <em>Paper 1</em></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>6.2 <em>Paper 2</em></td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>6.3 <em>Paper 3</em></td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>6.4 <em>Paper 4</em></td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>6.5 <em>Paper 5</em></td>
<td>47</td>
</tr>
<tr>
<td></td>
<td><strong>References</strong></td>
<td>49</td>
</tr>
<tr>
<td></td>
<td><strong>Appendix</strong></td>
<td>58</td>
</tr>
<tr>
<td></td>
<td><strong>Thesis papers in published format</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A <em>Paper 1</em></td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>B <em>Paper 2</em></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>C <em>Paper 3</em></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D <em>Paper 4</em></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>E <em>Paper 5</em></td>
<td>E</td>
</tr>
<tr>
<td></td>
<td><strong>Complete list of author’s HWRS research project publications</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F Reviewed papers, presentations, book chapters and major reports generated through the research project</td>
<td>F</td>
</tr>
</tbody>
</table>
List of tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Core water quality parameters included in the Hawkesbury Water Recycling Scheme research data base</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>Incidence rates per 100,000 population for notifiable, potentially waterborne diseases by Australian state and territory for 2011</td>
<td>25</td>
</tr>
<tr>
<td>3.2</td>
<td>Intervention action threshold values for thermotolerant coliform (TC) in regional Australian/New Zealand agricultural irrigation-water guidelines</td>
<td>26</td>
</tr>
<tr>
<td>3.3</td>
<td>Precautionary ceiling values in WHO guidelines for safe use of recycled water in agriculture</td>
<td>27</td>
</tr>
<tr>
<td>3.4</td>
<td>Victoria EPA classes of reclaimed water with quality objectives, treatment processes and agricultural irrigation-use examples</td>
<td>28</td>
</tr>
<tr>
<td>3.5</td>
<td>Recommended treatment-performance indicators to support health risk assessment of water in agricultural irrigation schemes</td>
<td>30</td>
</tr>
<tr>
<td>4.1</td>
<td>Australian agricultural irrigation schemes using treated urban effluent</td>
<td>37</td>
</tr>
</tbody>
</table>

List of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Research project aims and significant achieved outcomes</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Location of the Hawkesbury Water Recycling Scheme</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>Core components of the Hawkesbury Water Recycling Scheme</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Diagram of main effluent reticulation system with control points</td>
<td>10</td>
</tr>
<tr>
<td>2.4</td>
<td>The proposed risk management framework for recycled water irrigation schemes</td>
<td>17</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT</td>
<td>Australian Capital Territory</td>
</tr>
<tr>
<td>AHMC</td>
<td>Australian Health Ministers Conference</td>
</tr>
<tr>
<td>AIDS</td>
<td>Acquired immune deficiency syndrome</td>
</tr>
<tr>
<td>ANZECC</td>
<td>Australian and New Zealand Environment and Conservation Council</td>
</tr>
<tr>
<td>APHA</td>
<td>American Public Health Association</td>
</tr>
<tr>
<td>ARC</td>
<td>Australian Research Council</td>
</tr>
<tr>
<td>ARMCANZ</td>
<td>Agriculture and Resource Management Council of Australia and New Zealand</td>
</tr>
<tr>
<td>AWWA</td>
<td>American Water Works Association</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical oxygen demand</td>
</tr>
<tr>
<td>CFU</td>
<td>Colony forming units</td>
</tr>
<tr>
<td>Chl-a</td>
<td>Chlorophyll a</td>
</tr>
<tr>
<td>COP</td>
<td>Community of practice</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation (Australia)</td>
</tr>
<tr>
<td>DAF</td>
<td>Dissolved air flotation</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>EC or E.coli</td>
<td><em>Escherichia coli</em></td>
</tr>
<tr>
<td>ECond</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño southern oscillation</td>
</tr>
<tr>
<td>ENT</td>
<td>Enterococci</td>
</tr>
<tr>
<td>EPA</td>
<td>Environment Protection Authority (US), Environment Protection Agency (Australia)</td>
</tr>
<tr>
<td>EPHC</td>
<td>Environment Protection and Heritage Council</td>
</tr>
<tr>
<td>FC</td>
<td>Faecal coliform</td>
</tr>
<tr>
<td>FIB</td>
<td>Faecal indicator bacteria</td>
</tr>
<tr>
<td>GI</td>
<td>gigalitres</td>
</tr>
<tr>
<td>HWRS</td>
<td>Hawkesbury Water Recycling Scheme</td>
</tr>
<tr>
<td>IDAL</td>
<td>Intermittently decanted aerated lagoon</td>
</tr>
<tr>
<td>IOD</td>
<td>Indian ocean dipole</td>
</tr>
<tr>
<td>MEI</td>
<td>Most exposed individual</td>
</tr>
<tr>
<td>MI</td>
<td>megalitres</td>
</tr>
<tr>
<td>MSI</td>
<td>Most sensitive individual</td>
</tr>
<tr>
<td>NHMRC</td>
<td>National Health and Medical Research Council</td>
</tr>
<tr>
<td>NRMMCC</td>
<td>Natural Resource Management Ministerial Council</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales</td>
</tr>
<tr>
<td>NT</td>
<td>Northern Territory</td>
</tr>
<tr>
<td>NTU</td>
<td>Nephelometric turbidity units</td>
</tr>
<tr>
<td>Qld</td>
<td>Queensland</td>
</tr>
<tr>
<td>SA</td>
<td>South Australia</td>
</tr>
<tr>
<td>sat</td>
<td>saturation</td>
</tr>
<tr>
<td>SS</td>
<td>Suspended solids</td>
</tr>
<tr>
<td>STP</td>
<td>Sewage treatment plant</td>
</tr>
<tr>
<td>Tas</td>
<td>Tasmania</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>TC</td>
<td>Thermotolerant coliform</td>
</tr>
<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
</tr>
<tr>
<td>TKN</td>
<td>Total Kjeldahl nitrogen</td>
</tr>
<tr>
<td>TN</td>
<td>total nitrogen</td>
</tr>
<tr>
<td>TOC</td>
<td>Total organic carbon</td>
</tr>
<tr>
<td>TP</td>
<td>Total phosphorus</td>
</tr>
<tr>
<td>TSS</td>
<td>Total suspended solids</td>
</tr>
<tr>
<td>Turb</td>
<td>Turbidity</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>Vic</td>
<td>Victoria</td>
</tr>
<tr>
<td>WA</td>
<td>Western Australia</td>
</tr>
<tr>
<td>WEF</td>
<td>Water Environment Federation</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>
1. Introduction

The portfolio introduces five of the author’s papers which constitute a cohesive and original body of work based on research aimed at identifying health risk assessment and management approaches for securing the safe and sustainable operation of agricultural schemes irrigating with sub-potable quality water, such as recycled sewage effluent. A sequence of aims associated with the research project is presented in Fig 1.1 with significant research outcomes indicating fulfilment of these aims, and relevant papers in terms of the section 5 listing.

Motivation for the research project came from a number of local and international events in which faecal contamination of water led to serious health incidents. These included the presence of hepatitis A virus in Wallis Lake oysters in New South Wales (NSW) resulting in 467 cases in 1997 (Conalty et al., 2000), the discovery of cysts of potentially pathogenic Cryptosporidium and Giardia protozoa in Sydney’s drinking water, leading to a boil-water alert being sent out to almost three quarters of the metropolitan population of 4.7 million in 1998 (Stein, 2000), and enterohaemorrhagic E coli O157:H7 from agricultural runoff entering the water supply of Walkerton, Ontario two years later, resulting in 2,300 cases of bloody diarrhoea with seven deaths (O’Connor, 2002). In the subsequent examination of available water supplies in Australia and elsewhere, the safety of agricultural irrigation of food crops with sub-potable quality water came under scrutiny. Consequently a need for monitoring and risk management of irrigation schemes was identified (Bahri, 1999; Bartram et al., 2002; Fasciolo et al., 2002; Thomas et al., 2000)

There was concern that analytical results for the quality of sewage treatment plant (STP) effluent alone were inadequate in many cases to inform comprehensive on-site risk management of irrigation schemes. To address this, the author, who had experience in advising on water quality upgrading in Southern Africa, Mongolia and China, was invited by the Hawkesbury Water Recycling Scheme (HWRS) to lead a research project in the development of health risk assessment and management approaches for schemes using recycled effluent.
Research project aims

Develop a baseline approach for rapid risk assessment of treated effluent irrigation schemes, validated through application to a medium-scale water reuse scheme (the Hawkesbury Water Recycling Scheme, HWRS)

Explore risk perception and communication relevant to a specific agricultural scheme to understand and demystify public and stakeholder opposition to treated effluent reuse

Investigate physicochemical and microbial changes taking place during onsite storage of low and high quality effluents to understand irrigation effluent as a biochemically “living” entity

Develop an overarching risk management framework by incorporating ideas identified through risk monitoring, assessment and communication research.

Investigate the stability of a key, contemporary health indicator (enterococci) used for assessment of treated effluent recycling schemes, in terms of a common assumption that it does not regrow during environmental storage.

Significant achieved outcomes

An approach was developed for adding value to basic, quantitative chemical and microbial data by contextualising these with qualitative environmental and exposure information. Ordinal data ranking produced single, matched risk and uncertainty indices for rapid risk-management response (Paper 1)

Innovative use of KABP surveying revealed that acceptability of effluent irrigation increased with perceived number of physical barriers between point of irrigation and the consumer, supporting a multiple barrier approach with linked risk communication (Paper 2)

Research revealed improvement of low quality effluents, and deterioration of high quality effluents with passage through scheme storages, emphasising the need for multiple control points with linked diversion facilities to optimise safe and efficient use of effluents in terms of guideline values (Paper 3)

An overarching risk management framework was developed in terms of a cyclic model, enabling intervention to be a multi-staged process with intersectoral risk-communication at the hub for effective and accountable intervention (Paper 4)

Research revealed regrowth to occur, with false positives potentially causing downgrading, rejection or hyper-chlorination of water. The adjustment equation offered will optimise water use, reducing ecological and health impacts of over-chlorination, and facilitate food and climate change modelling (Paper 5)

Fig. 1.1: Research project aims and significant achieved outcomes
The HWRS serves a wide range of irrigation interests at the predominantly agricultural Hawkesbury campus of the University of Western Sydney in the southwestern sector of the Sydney Metropolitan area. The scope of this Scheme is discussed in section 2 of this portfolio.

The goal of the research, which was supported by state and local grants as well as in-kind contributions by the HWRS, was to address the knowledge gap which existed regarding the monitoring and assessment of the safety of irrigation schemes, and to establish an integrated risk communication approach for information exchange between management and stakeholders. An expectation of the research was that it would generate reports and publications which would benefit the HWRS and schemes elsewhere through the transfer of knowledge and the informed revision of water quality and irrigation guidelines. The completion of the five publications as shown in appendices A to E, as presented for the award of Doctor of Philosophy, addressed this expectation.

Section 2 of the portfolio outlines the underpinning research project, discussing the HWRS as field study area where the monitoring, risk assessment and management concepts outlined in the papers were developed and validated.

Section 3 examines health risks associated with treated sewage effluent recycling from an Australian and international perspective, giving relevant disease examples and determinants for their occurrence. Discussion on health risk indicators emphasises the differences which exist from place to place, based on variations in monitoring needs and disease endemicity (local predominance of certain diseases).

Section 4 introduces a balance in the portfolio by introducing local and international recycling as a key strategy for meeting increasing food production demands for growing populations in the face of dwindling water resources. Without this section the portfolio might seem critical of the risk associated with agricultural irrigation using recycled water, whereas an intention is to encourage recycling by providing a safe and sustainable way forward.
Sections 5 and 6 of the portfolio are functional, identifying and discussing the five papers submitted for the award of PhD, the interrelated nature of their content, their relevance to an overall advanced research theme, their contribution to scientific methodology and knowledge, the author's contribution to the papers, and their scientific impact at the expected level. Appendices A to E present the five papers, each with its own abstract, in original publication format.

There is an assumption throughout the portfolio that monitoring and risk assessment should not place undue burden on the existing operational infrastructure or resources of agricultural irrigation schemes, but that they should rather integrate with existing operations, enhancing rather than reducing scheme sustainability. An adopted core process was therefore monitoring of a relatively small subset of microbial and physicochemical indicators to yield fit-for-purpose quantitative data, with subsequent value-adding through contextualisation of these data using qualitative environmental, exposure and social information, including information on stakeholder perspectives (Attwater & Derry, 2005). On this basis a risk assessment process for integrating and presenting data in a way which facilitates intersectoral decision-making by management and stakeholders was developed.

An important realisation articulated in the papers is that treated sewage effluent is a biochemically-active entity, capable of improvement or deterioration with storage. Another is that recyclable water should not be regarded as an already-downgraded resource incapable of further contamination. Scheme reticulations need to be reconceptualised as a continuation of the STP treatment train, with sequential monitoring at strategic control points, where re-direction of water to the most productive use in terms of its quality can be put into effect. Stated another way, an effective multiple barrier approach necessitates a multiple-site monitoring strategy. Given this assumption the futility of relying on a one-point data set as provided by the supplying STP is highlighted.

In the process of risk assessment, access to standardised guidelines which specify the water quality required for safe irrigation of different crop types is essential. In this regard the author did not attempt to "reinvent the wheel" by repeating the advanced microbiological, chemical and epidemiological investigations already
carried out in the development of Australian water and irrigation guidelines. Instead the publications presented in the portfolio attempt to show how use of such guidelines can be optimised in risk monitoring and assessment, while feeding back information for the improvement of the guidelines themselves.

It is hoped that the publications included in this portfolio will continue to be read and cited to transfer knowledge and technology for safe water recycling in agriculture to a broad audience. It is also hoped that by consolidating the papers in a submission for the degree of Doctor of Philosophy by publication, they will be accessible as a consolidated body of information for the stimulation of future research and teaching in the area of safe and sustainable water recycling in agriculture.
2. The Underpinning Research Project

2.1 The Hawkesbury Water Recycling Scheme

The five papers present the results of a targeted research project aimed at developing a health risk assessment and management system for recycled water use in agricultural irrigation. Validation of concepts in the research, including the identification of a fit-for-purpose set of monitoring indicators and the development of a risk assessment and management framework, were carried out at the Hawkesbury Water Recycling Scheme (HWRS) in the northwest of the Sydney Metropolitan area, adjacent to the Blue Mountains National Park/World Heritage Site (Fig. 2.1).

![Location of the Hawkesbury Water Recycling Scheme](image)

**Fig. 2.1: Location of the Hawkesbury Water Recycling Scheme ▲**
(Base: Google Maps)

Tertiary treated effluent is supplied to the Scheme by Sydney Water, a NSW State Government corporation, vested with water supply, sewage removal and treatment,
and some stormwater services for about 4.8 million people in the Sydney Metropolitan, Illawarra and the Blue Mountains regions.

The recycling Scheme, which has been operated by the University of Western Sydney (UWS) over the past 40 years through a formalised agreement with Sydney Water, meets the irrigation needs of the Hawkesbury agricultural campus of UWS, one of the oldest agricultural campuses in Australia. Core components of the Scheme are shown in Fig. 2.2.

Today teaching and research at the University have diversified from an agricultural base into food and nutrition, animal and plant science, environmental science, environmental management and health, medical and forensic science, nursing, and secondary school teaching. The campus houses the Hawkesbury Institute for the Environment, an international research centre with focus on climate change impacts on vegetation and crops, and a number of well-developed research groups and clusters relevant to the disciplinary areas mentioned here.

During the research study from 2002 to 2012, the Scheme received a median volume of 1.35 Ml of treated effluent per day for a range of irrigation activities on the Hawkesbury campus, including the growing of fruit (oranges and apples), vegetables (cabbage, squash, tomatoes, beetroot), grapevines, pasture for dairy cows, ewes and fallow deer, horse paddocks, eucalypt plantations (providing feed for koalas in zoos), sports fields and other recreational areas, lawns, and grassed road verges. A flow diagram of the main reticulation system is shown in Fig. 2.3. It should be noted that some irrigation units shown on this diagram (eg.: horse paddocks and vineyard) are not shown in Fig. 2.2, as they lie outside the frame.

Pasture was also irrigated for about 200 ewes as part of a research scheme, with commercial on-selling, and also for about 100 red and fallow deer as part of a research project with some human consumption of the meat. Paddocks for horses used in teaching and research were also under irrigation, with some commercial stabling.
Contact sports such as rugby football were played on one of the sports fields and lawns and verges were in use mainly for pedestrian access by staff and students. In one area pecan nut trees were under irrigation with members of the public visiting the campus over weekends to collect fallen nuts from irrigated lawns (Booth et al., 2003).

While sewage effluent recycling is the main topic of the papers because of associated risks, untreated stormwater was also harvested from the nearby township of Richmond and from paved campus areas, and supplied to the Richmond College for Technical and Further Education (TAFE), where it was used for agricultural irrigation. This stormwater component is still under research and was not included in the study on which the five papers are based.

Extension of the Scheme through the supply of irrigation water to the Hawkesbury Turf Club and Hawkesbury agricultural showgrounds is under consideration, given the existence of a treated effluent surplus and the potential for “shandyng” effluent and stormwater, or supplying wetland-stabilised stormwater alone. This would reduce the need for the STP to release a proportion of wet weather flows to Rickabys Creek, a tributary of the Hawkesbury Nepean River, Sydney’s largest and possibly most threatened aquatic system (Attwater et al., 2006, Derry et al., 2006). There is also an ambitious UWS greenhouse project to start in 2015 which may extend the recycled water initiative requiring special reuse precautions (Bernstein et al., 2008).

2.2 Local motivation for research engagement

In late 2002 analytical reports from the Richmond STP suggested rapid deterioration in physicochemical and microbial quality of the treated effluent supplied to the Scheme. This was as a result of the unstable biofilter treatment plant which was approaching the end of its service life at a time when regional housing expansion with increased effluent flow was occurring. The addition of excess chlorine to the low quality effluent with subsequent contact-storage in stabilisation ponds was
Fig. 2.3: Diagram of main effluent reticulation system with control points

- (CP_n)
undesirable in terms of cost, and potential health and ecological threats associated with chlorination by-products.

Sydney Water advised that a high-capacity, Intermittently Decanted Aerated Lagoon (IDAL) treatment plant would replace the old plant in 2005, but the interim use of low quality effluent for irrigation was of concern to the Scheme’s operators. At this time local and international health incidents such as those described in subsection 3.1 had awakened concerns regarding the potential for contamination of water reserves with faecal matter, particularly in environmentally-open storage where bacterial growth, or contact with livestock and wild animals could occur.

The simple solution of diverting low quality flows from the STP into Rickabys Creek was not viable because of potentially heavy “load licence” penalties being imposed on Sydney Water by the Department of Environment and Heritage, aimed at reducing the high pollutant load already reaching the Hawkesbury-Nepean River. Diversion would also force the University to rely on costly supplies of potable town water, rendering agricultural operations non-viable.

At this point the author was requested by Scheme management to carry out risk assessment and management, with a view to establishing an ongoing approach to ensure safe future operation of the Scheme. The author is an environmental epidemiologist, known to have research experience in a number of countries relating to the securement of safe water and food supply. The risk assessment was to be carried out as a research project with costs carried by the Scheme, the author having first call on project intellectual property, with an expectation that the work would be published as part of validation, and the results made available for supporting a process of upgrading local and national irrigation and recycling guidelines.

Early scoping revealed that only STP data were available despite the fact that there was potential for microbial and chemical change in water quality under the action of endogenous and exogenous factors with passage through the Scheme’s extensive reticulation. In addition to the inadequacy of this one-point sampling, existing STP monitoring parameters did not include all of those required for safe operation of a recycled water Scheme. Apart from potential health impacts, there was an economic
impact in that selective diversion of available flows within the Scheme to achieve highest economic return was not possible without knowing the water quality at relevant control points (ANZECC/ARMCANZ, 2000).

Given these factors the need for a system offering monitoring and flow diversion at a number of strategic control points was identified, to be integrated with exposure control barriers as part of an overall risk management process.

2.3 The research project objective and aims

Following discussion with the relevant academic and management units of the University and Scheme, the following research objective and aims were identified:

Objective:

To develop an integrated system for risk monitoring, assessment, and communication relevant to the HWRS with a view to informing a multilateral process of risk management in the interests of intervention aimed at overall improvement of Scheme health and safety. This would be carried out in such a way as to make the results of the research available for the improvement of agricultural irrigation schemes elsewhere and to facilitate the improvement of guidelines for healthy and safe agricultural irrigation.

Aims:

1. To develop a baseline risk monitoring and management process for rapid health risk assessment of recycling schemes in agriculture, and to validate this at the HWRS site as providing a good example of a medium-scale agricultural water reuse scheme.

2. To explore stakeholder knowledge, attitudes, beliefs and practices relevant to a typical treated effluent irrigation scheme in order to understand and demystify public reaction to crop irrigation with recycled treated effluent.
3. To research changes taking place during storage of low and high quality effluents.

4. To investigate the incorporation of ideas identified through risk monitoring, assessment and communication research into an overall risk management framework.

5. To identify the stability of a key recycled water quality indicator (enterococci), in terms of a known paucity of information relating to indicator regrowth in environmentally-open storages.

These research project aims are incorporated in Fig 1.1 with a list of significant achieved outcomes. The outcomes are further discussed in section 6, in terms of relevance, impact, and innovation relevant to each paper.

2.4 The HWRS research data base

Following literature survey and preliminary sampling, the author specified the microbiological and physicochemical data to be collected by the Scheme, and this was carried out by the same technician for a six year period from 2003 to 2008. Additional data collection for advanced parameters was carried out by the author. This generated an extensive data base with over 10,000 entries for 46 parameters, with smaller additional bodies of specialised research data. The data base contributed materially to the publication of the five papers, and is today a foundation for additional research by the author and other researchers. After 2008, a reduced, fit-for-purpose data subset was identified for ongoing compliance with Scheme risk assessment needs.

The HWRS research data base includes the core parameters shown in Table 2.1. The data in the base could be temporally divided into two sections; data for March 2002 to April 2005 when the old biofilter STP plant was in operation and relatively low quality treated effluent was supplied, and data for April 2005 to December 2008 when the new IDAL STP plant was in operation supplying high quality effluent. As no major changes were made to the collection procedures, analytical methods and storages throughout the period, comparative research on both high and low quality
irrigation water was possible. Paper 3 concerns the changes which occur in high and low quality waters when stored in the same physical reticulation system. In this paper the capacity of low quality water to improve in terms of a range of important parameters with storage, and for high quality water to deteriorate with storage was noted as a finding of importance for management of recycled water irrigation schemes.
<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Abbreviation</th>
<th>Unit of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faecal indicator bacteria</td>
<td>Total coliform</td>
<td>TC</td>
<td>CFU/100 ml</td>
</tr>
<tr>
<td></td>
<td>Faecal coliform</td>
<td>FC</td>
<td>CFU/100 ml</td>
</tr>
<tr>
<td></td>
<td>Enterococci</td>
<td>ENT</td>
<td>CFU/100 ml</td>
</tr>
<tr>
<td>Algae</td>
<td>Algae in suspension</td>
<td></td>
<td>U/100 ml</td>
</tr>
<tr>
<td></td>
<td>Algae on surface</td>
<td></td>
<td>U/100 ml</td>
</tr>
<tr>
<td></td>
<td>Chlorophyll a</td>
<td>Chl-a</td>
<td>mg/m²</td>
</tr>
<tr>
<td>Treatment-performance indicators</td>
<td>pH</td>
<td>[log]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical conductivity</td>
<td>ECond</td>
<td>µS/cm</td>
</tr>
<tr>
<td></td>
<td>Total dissolved solids</td>
<td>TDS</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Salinity</td>
<td>Sal</td>
<td>g/kg</td>
</tr>
<tr>
<td></td>
<td>Dissolved oxygen (total)</td>
<td>DO</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Dissolved oxygen (percent saturation)</td>
<td>DO (% sat)</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Oxygen reduction potential</td>
<td>ORP</td>
<td>mV</td>
</tr>
<tr>
<td></td>
<td>Turbidity</td>
<td>Turb</td>
<td>NTU</td>
</tr>
<tr>
<td></td>
<td>Total suspended solids</td>
<td>TSS</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>T</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>Biochemical oxygen demand (5 day)</td>
<td>BOD₅</td>
<td>mg/l</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Total nitrogen</td>
<td>TN</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Total Kjeldahl nitrogen</td>
<td>TKN</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Total phosphorus</td>
<td>TP</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>UV₃₅⁰ (unfiltered) [Total organic carbon proxy]</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UV₃₅⁰ (filtered) [Dissolved organic carbon proxy]</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Toxic metals and metalloids</td>
<td>Copper</td>
<td>Cu</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Lead</td>
<td>Pb</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Zinc</td>
<td>Zn</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Nickel</td>
<td>Ni</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Mercury</td>
<td>Hg</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Chromium</td>
<td>Cr</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Cadmium</td>
<td>Cd</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Boron</td>
<td>B</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Aluminium</td>
<td>Al</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Arsenic</td>
<td>As</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>UV₅₅⁰ (unfiltered) [proxy for total iron]</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UV₅₅⁰ (filtered) [proxy for total iron]</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Anions</td>
<td>Sodium</td>
<td>Na</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Potassium</td>
<td>K</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Magnesium</td>
<td>Mg</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Calcium</td>
<td>Ca</td>
<td>mg/l</td>
</tr>
<tr>
<td>Cations</td>
<td>Chlorine</td>
<td>Cl</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Sulphate</td>
<td>SO₄</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Bicarbonate</td>
<td>HCO₃</td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Carbonate</td>
<td>CO₂</td>
<td>mg/l</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>Alkalinity hydroxide (CaCO₃)</td>
<td></td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Alkalinity carbonate (CaCO₃)</td>
<td></td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Alkalinity bicarbonate (CaCO₃)</td>
<td></td>
<td>mg/l</td>
</tr>
<tr>
<td></td>
<td>Total alkalinity (CaCO₃)</td>
<td></td>
<td>mg/l</td>
</tr>
</tbody>
</table>
2.5 A conceptual risk management framework

After review of the literature, a conceptual framework was proposed to provide initial scaffolding for the risk assessment and management research (Fig. 2.4). This framework is loosely based on a model for environmental risk assessment proposed in a seminal report on the topic (Ommen Commission, 1997).

The framework includes the following sequential activities:

- Identification of hazards (unmeasured risks). This might be in terms of a large-scale transdisciplinary process at the start of an assessment scheme, but could also include routine onsite monitoring of an irrigation scheme by scheme staff, such as the risk assessor or manager, to identify emerging hazards.
- Risk monitoring and assessment to characterise and quantify the hazard, and to provide a system of ranking to assist management in determining intervention priority.
- The development of risk policy by health risk management, including a plan for interventive action.
- The implementation of intervention to ameliorate a specific hazard or hazards.
- Monitoring of interventions to ensure effectiveness of hazard amelioration, and to assist in the identification of new hazards to be targeted.

Being cyclic, risk management activity does not stop when one group of hazards has been identified and ameliorated, but continues indefinitely, resulting in identification of new hazards as they arise. Risk management activity can be initiated at any stage in the cycle; for example, when first starting the HWRS project the author identified that there was already implementation of policy to engage stakeholder groups. The author triggered the subsequent step in the management cycle, which was the monitoring of this specific intervention (Attwater & Derry, 2005). This action not only encouraged early engagement of stakeholder groups as essential to efficient and accountable project implementation, but also enabled monitoring of the effectiveness of this measure while setting the cyclic management process in motion (Salgot, 2008). Risk communication was conceptually located at the hub of the model to
ensure multilateral flow of information of an intersectoral and interdisciplinary nature. As discussed in subsection 3.1, lack of risk communication has been responsible for management inactivation in a number of preventable, water-related health incidents.

The model was further developed through presentation at workshops in Australia, China and India, with incorporation into a chapter of a book on the management of water scarcity and climate change risks in agriculture (Huda et al., 2007). It also appeared in an invited journal paper on modern agriculture in Israel, the country recycling the highest percentage of urban effluents for irrigation internationally (Derry, 2011).

![Diagram]

Fig. 2.4: The proposed risk management framework for recycled water irrigation schemes
2.6 Impacts of the project

The research project has resulted in the production of nine peer-reviewed papers (including the five as presented in this portfolio), 12 conference presentations, three book chapters and three reports of national or international importance. A further five papers on the data series introduced in subsection 2.4 are planned. The results have also been presented at a number of fora and meetings directed at safe water use and the upgrading of Australian water quality guidelines. Through association with the project the author was invited to sit on NSW Health’s Wastewater Management Advisory Committee where an objective is the informed revision of reuse guidelines for food protection.

A number of important alliances and co-authorships grew from the research process, with consulting visits by the author to China, Mongolia, India, Bangladesh and South Africa. On these visits aspects of the risk assessment and management process were presented and feedback recorded as part of the research validation process.

Through the HWRS project the author has been invited to lead research into the effectiveness of stormwater bioretention units being installed by eight local authorities, including the City of Sydney, for the treatment of urban stormwater runoff with intended recharge of the Botany Sand Beds aquifer with potential abstraction for irrigation and other uses. Some of the water will be diverted to Botany Bay via the Alexandra Canal for improvement of environmental water quality in this important heritage, ecological and aquaculture site. A 150-page report has recently been completed by the author on a monitoring strategy for this project.

With the growth of international recognition of the research project, the author was approached by the WHO’s Collaborating Centre for Environmental Health Development in Australia to work with leading Chinese state scientists on the monitoring of impacts of rural crop irrigation with recycled effluents on health in that country. The research was also instrumental in securing an Asia Pacific Network grant for scientific workshops in Hyderabad, Indi and Dhaka, Bangladesh with a view to studying impacts of water availability and climate change on agricultural sustainability in regional dryland areas. This resulted in the risk
management framework being investigated with a view to future use across a wide regional area (Huda, et al., 2007).
3. Health Risks and Indicators

3.1 Health risk determinants

There are a number of key health risk determinants associated with treated sewage effluent irrigation schemes which required consideration in developing an assessment framework (APHA/AWWA/WEF, 2012; Asano, 1998; Lazarova & Bahri, 2005; Toze, 2006). These include:

1. epidemiological considerations relating to specific waterborne diseases in the population residing in the sewage catchment area. Here disease endemicity, potential epidemic spikes, and the presence of undetected carriers have particular relevance.
2. the level of treatment applied to the water supplied to the irrigation scheme.
3. potential for faecal indicator and pathogen regrowth in the treated water while in the scheme’s reticulation, including storages.
4. potential for on-site contamination while in the scheme’s reticulation, in particular in open dams to which farm or wild animals, including water birds, have access.
5. the correct matching of the water quality to the irrigation usage, usually by means of faecal indicator bacteria (FIB) monitoring and comparison with action values in relevant guidelines.
6. the risk of exposure of foodstuffs through incorrect water quality or that specific type, or incorrect irrigation procedure.
7. the risk of exposure of staff, contractors and those living adjacent to irrigation areas, particularly where overhead (spray) irrigation is practiced.
8. absence or ineffectual nature of a stage in a multiple-barrier exposure-reduction process.
9. level of risk monitoring, assessment, intervention and management applicable to the scheme.
10. the effectiveness of multilateral risk communication between scheme management and stakeholders.
Aspects of these determinants relevant to the underpinning research project are covered on an ad hoc basis in the five papers, with portfolio paper 1 (appendix A) providing a broad introduction to determinants 4 to 9.

Determinant 1 (epidemiology) is not discussed in detail in the five papers because the relevant research project made use of regional water quality guidelines which already incorporate regional epidemiological considerations. An example is shown in Table 3.2, which summarises information from the ANZECC/ARMCANZ guidelines for fresh and marine water quality relevant to agricultural use. Here intervention action thresholds for thermotolerant coliform (TC) are given for a range of agricultural uses enabling a risk value to be assigned to an available water supply in terms of its level of compliance with the guideline value (ANZECC/ARMCANZ, 2000). Where specific local guideline values are not available, international values could be substituted (Asano, 1998; Carr, 2005; WHO, 1989). In transferring the concept to another country, it should be noted that each country has its own requirements for recycled water based on local disease endemicity as referred to in paper 4 (appendix D), and this would need to be taken into account when designing assessment protocols elsewhere (Lazarova & Bahri, 2005; Salgot et al., 2006).

An important aspect of irrigation scheme health management is multilateral risk communication between the scheme's management and stakeholder communities of practice (COPs), in order that qualitative and quantitative monitoring results can be successfully integrated, communicated and acted on (determinant 10). This receives mention in papers 1, 2 and 4 (appendices A, B and D respectively).

When the water supply to a scheme is tertiary treated (settled, biofiltered and chlorinated to a level which controls health indicator microorganisms in the final flow), as is the case with all schemes listed in Table 4.1, accuracy of estimation of disease exposure risk can change through pathogen die-off or regrowth in storages as discussed in papers 3 and 5 (appendices C and E).

When endemic diseases in the catchment area (determinant 1) have been effectively controlled in terms of the level of sewage treatment applied (determinant 2), risk assessment can focus on the remaining determinants, as was the case in the HWRS
project. A few organisms will survive disinfection as clumped organisms, detached biofilm or in a spore state, to regrow with passage through the irrigation scheme’s reticulation including storages (determinant 3). There are numerous reports of such regrowth in closed reticulation systems transporting and storing treated town water (Carter et al., 2000; Escobar, et al., 2001; Jjemba et al., 2010; LeChevallier et al., 1991; Zhang & DiGiano, 2002). There are, however, very few reports identifying such regrowth for any indicators in treated irrigation water (Derry, 2014). As regrowth of faecal indicators and pathogens in warm, nutrient rich recycled water is likely to be a common phenomenon the paucity of publications probably relates more to a lack of research than the unlikelihood of the phenomenon. This makes the findings contained in paper 5 (appendix E) of particular importance.

Of particular concern in irrigation schemes is the recontamination of stored water in open impoundments by bacteria from farm livestock or even wild animals (determinant 4). In the year 2000, almost three quarters of Sydney’s four million Metropolitan residents were sent boil-water alerts by the NSW Health Department following the discovery of cystic forms of potentially pathogenic Cryptosporidia and Giardia protozoa in chlorinated but unfiltered sectors of the City’s main water supply, as sourced from the Warragamba Dam on the Hawkesbury-Nepean River (Byleveld et al., 2008). Although no human cases occurred the event resulted in international media coverage and a top level restructure of Sydney Water, the supplying authority.

In this case, independent inquiry based on 200 written and 130 verbal submissions concluded that contamination had occurred following faecal runoff from domestic livestock and wild animals into the main Warragamba storage dam and associated Hawkesbury-Nepean river system (Stein, 2000). An underlying factor was exceptional climatic variation resulting in accumulation of a high level of animal faecal matter on poorly foliated land during extreme drought, with subsequent wash-off of contaminants into receiving waters during the subsequent heavy rainfall period. While early action by health and water authorities prevented the occurrence of human cases, a conclusion was that there was a need for improved catchment monitoring and management, and for more effective risk communication between all
sectors (determinant 10) At the time this finding acted as an important motivator for
the research project on which the five research papers are based.

Barely two years later, the ease of contamination of environmental water through
animal faecal runoff was again brought to international attention through the
notorious outbreak of enterohaemorrhagic \( E \text{ coli} \) O157:H7 in Walkerton, Ontario,
which resulted in 2,300 cases of bloody diarrhoea with seven deaths (Danon-
Schaffer, 2001; O’Connor, 2002). Here runoff carried animal faeces from manured
pastureland into corroded and leaking conduits leading to sumps serving the Town’s
main water supply. Investigation revealed that while bacteriological analysis of
water was regularly carried out and results were available, risk analysis was not
carried out to identify the relevance of bacteriological results, and no framework
existed for multilateral risk communication despite a range of control services being
in place (determinants 9 and 10).

In irrigation schemes it is important that crops with high disease transmission
potential (eg: salad crops eaten raw or unpeeled) are not irrigated with low quality
effluent (determinant 5). Lower quality effluent could, however, be used for a range
of other less contaminable crop types, as shown in Table 3.2. Not only do such
graded tabulations ensure safe irrigation, they also enable risk assessment as
discussed in paper 1, and the attainment of the most economically productive use for
the water under consideration.

Correct irrigation procedure is an important predictor of health risk (determinant 6),
with subsurface irrigation giving substantial reductions in indicator bacteria and
selected pathogen counts (Campos, 2000; Kouznetsov, 2004). Where erosion of soil
above subsurface irrigation systems has occurred, the effect of the soil barrier will be
lost.

Risk assessment and management of irrigation schemes involves not only indirect
exposure to effluent through food produce but also direct exposure of staff employed
or contracted by the scheme, and of members of the general public who may visit the
irrigation site or live in the adjacent area, where spray drift may occur (determinant
7). Here the presence of “most exposed individuals” (MEIs) and “most sensitive

23
individuals” (MSIs) has to be taken into account, along with general exposure, as discussed in the presented papers.

Given the range of health risk determinants operating in any one irrigation scheme, intervention is likely to involve a combination of barriers, with sufficient redundancy built into the irrigation system.

3.2 Sewage effluent and disease

Untreated sewage is known to present a very high risk of waterborne disease transmission when used for agricultural irrigation (Ensink et al., 2005; Ensink et al., 2006; Srinivasan and Reddy, 2009; Trang et al., 2007). The importance of disease endemcity has been discussed in subsection 3.1, although the underpinning epidemiological record may be incomplete because of mild, missed or symptomless cases (carriers) going unnotified. Even with adequate sewage treatment using UV light, ozone or chlorine disinfection, there is potential for the few cells which have escaped disinfection to escape unharmed and regrow in stored water (Ajibode et al., 2013; Jjemba et al., 2010).

Waterborne diseases in areas where drinking water and sewage are inadequately treated include the bacterial conditions cholera, typhoid and paratyphoid fevers, bacillary dysentery, campylobacteriosis, leptospirosis, *Escherichia coli* diarrhoea (enteropathogenic, enterotoxigenic enterohaemorrhagic and others); the protozoal diseases amoebic dysentery, giardiasis and cryptosporidiosis; the helminthic (worm) infections ascariasis, trichuriasis and hookworm diseases through indirect exposure to contaminated soil; and viral diseases hepatitis A, E and others and Norwalk and rotaviral diseases (APHA, 2008). In addition to adequacy of water and sewage treatment, a number of other environmental, climatic, socioeconomic and population factors play a role in disease endemcity, which varies highly with place (APHA, 2008).

Table 3.1 gives an indication of the occurrence of potentially-waterborne diseases in Australia by state and territory for the most recent data publication year (Australian
Government Department of Health, 2011). These diseases may also have a number of other transmission modes, including food and, in some cases, direct contact. Where a disease mentioned in the above paragraph has been omitted then it is not notifiable in Australia because of low incidence.

### Table 3.1: Incidence rates per 100,000 population for notifiable, potentially waterborne diseases by Australian state and territory for 2011.

<table>
<thead>
<tr>
<th>Notifiable waterborne disease</th>
<th>Notifications by state or territory</th>
<th>Australian incidence rate per 100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACT</td>
<td>NSW</td>
</tr>
<tr>
<td>Campylobacteriosis</td>
<td>135.7</td>
<td>NN</td>
</tr>
<tr>
<td>Cholera</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cryptosporidiosis</td>
<td>3.6</td>
<td>4.9</td>
</tr>
<tr>
<td>Haemolytic uraemic syndrome</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Hepatitis E</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Leptospirosis</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Shigellosis</td>
<td>2.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Shiga- and verotoxin E coli</td>
<td>1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>intoxication</td>
<td>Typhoid fever</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Note:** NN means not notifiable for a specific state or territory.

#### 3.3 Health risk indicators

The principle microorganisms used to indicate the health risk status of water are the faecal indicator bacteria (FIB) of which *Escherichia coli* (EC) of the coliform group is today the most widely used, owing to simplified analytical laboratory procedures (Yakub, 2002). Australian guidelines have been slow to change and still give action thresholds in terms of thermotolerant coliform (TC), also known as faecal coliform (FC) (ANZECC/ARMCANZ, 2000; ANZECC/ARMCANZ/NHMRC, 2000; NHMRC, 2004; NRMMC/EPHC/ AHMC, 2009).
An Australian Government report has suggested that enterococci indicator (ENT) should be substituted for the coliform group because of its relative resistance to inactivation in biochemically active water, and its ability to accurately reflect pathogen number in complex environmental settings (Stephens et al., 2003). A long standing position by the WHO that this indicator organism does not regrow in recycled water is challenged by the findings of paper 5 (appendix E), making this paper of particular importance (World Health Organization, 2011). Many authoritative monitoring texts have echoed the WHO’s position on this indicator, without evidence of reliable supporting research (Bartram and Rees, 2000; Hurst et al., 2007; Mara & Horan, 2003; Nollet, 2007).

The Australian and New Zealand guidelines for water quality have not undergone substantial revision since 2000, and still contain reference to TC (Table 3.2), which was therefore used as the primary health risk indicator in the HWRS study on which the five papers are based (ANZECC/ARMCANZ, 2000).

**Table 3.2: Intervention action threshold values for thermotolerant coliform (TC) in regional Australian/New Zealand agricultural irrigation-water guidelines (ANZECC/ARMCANZ, 2000)**

<table>
<thead>
<tr>
<th>Intended use</th>
<th>Thermotolerant coliform (TC) intervention action threshold value (median) in CFU/100 ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw human food crops in direct contact with irrigation water (eg: via sprays, irrigation of salad vegetables)</td>
<td>&lt;10 CFU/100 ml</td>
</tr>
<tr>
<td>Raw human food crops not in direct contact with irrigation water (edible product separated from contact with water, eg: by peel, use of trickle irrigation; or crops sold to consumers cooked or processed)</td>
<td>&lt;1,000 CFU/100 ml</td>
</tr>
<tr>
<td>Pasture and fodder for dairy animals (without withholding period)</td>
<td>&lt;100 CFU/100 ml</td>
</tr>
<tr>
<td>Pasture and fodder for dairy animals (withholding period of five days)</td>
<td>&lt;1,000 CFU/100 ml</td>
</tr>
<tr>
<td>Pasture and fodder for grazing animals (except pigs and dairy animals, i.e. cattle, sheep and goats)</td>
<td>&lt;1,000 CFU/100 ml</td>
</tr>
<tr>
<td>Silviculture, turf, cotton, etc. (with restricted public access)</td>
<td>&lt;10,000 CFU/100 ml</td>
</tr>
</tbody>
</table>

World Health Organization guidelines (Table 3.3) similarly rely on TC/FC as the indicator of choice. These guidelines are intended for international application, particularly in developing areas, and lack the precision of the Australian/New Zealand guidelines, which allow risk analysis to become a tool for matching water
quality to most economic use. Offering a range of guideline thresholds such as those in Table 3.2 makes risk assessment more acceptable to scheme operators than the use of a single threshold as contained in the WHO guidelines because health risk assessment then also becomes a tool for cost-effective food production (Hespanhol & Prost, 1993; WHO, 2006).

Compliance with the precautionary ceiling value of 1,000 CFU FC per 100 ml as contained in the WHO guidelines is unlikely to be achieved without disinfection or at least very robust secondary treatment, such as horizontal sand bank filtration as sometimes applied in Israel (Avnimelech, 1997; Gray, 2005). These guidelines also contain reference to intestinal worms common in developing areas with poor sanitation but uncommon in most of urbanised Australia and New Zealand.

Table 3.3: Precautionary ceiling values in WHO guidelines for safe use of recycled water in agriculture (WHO, 2006).

<table>
<thead>
<tr>
<th>Category</th>
<th>Reuse conditions</th>
<th>Intestinal nematodes (Ascaris and Trichuris species and hookworms) (mean number of eggs/l)</th>
<th>Faecal coliform (FC) precautionary ceiling value (mean) (mean CFU per 100 ml)</th>
<th>Primary treatment expected to achieve the required microbiological quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Crops eaten uncooked</td>
<td>&lt;1</td>
<td>&lt;1000</td>
<td>A series of stabilisation ponds or equivalent treatment</td>
</tr>
<tr>
<td>B</td>
<td>Cereal crops, fodder crops, industrial crops, pasture, trees</td>
<td>&lt;1</td>
<td>No standard</td>
<td>Retention in stabilisation ponds for 8-10 days or equivalent</td>
</tr>
<tr>
<td>C</td>
<td>Localised irrigation of crops in category B if exposure of workers and the public does not occur</td>
<td>N/A</td>
<td>N/A</td>
<td>Primary sedimentation</td>
</tr>
</tbody>
</table>

One Australian State, Victoria, has developed a system for managing irrigation with recycled water based on the identification of four classes, as shown in Table 3.4. This system is widely known throughout Australia and is occasionally used as a benchmarking tool by other states and territories (EPA Victoria, 2003).
Despite some level of National acceptance there is some ambiguity in the system relating to water quality objectives and treatment processes. Units for measurement of organisms (i.e.: CFU or MPN) are also not given to guide analytical procedure. The Department of Human Services, Victoria now moved away from imposing the Class A requirements towards a complex “fit for purpose” model, suggesting acceptance of a scheme specific, risk management approach, as supported in the submitted papers (DHS Victoria, 2008).

### Table 3.4: Victoria EPA classes of reclaimed water with quality objectives, treatment processes and agricultural irrigation-use examples (DHS Victoria, 2008).

<table>
<thead>
<tr>
<th>Class</th>
<th>Water quality objectives (12-month medians)</th>
<th>Treatment processes</th>
<th>Agricultural irrigation use example</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Indicative objectives:</td>
<td>Tertiary and pathogen reduction with sufficient log reductions to achieve:</td>
<td>Human food crops consumed raw</td>
</tr>
<tr>
<td></td>
<td>• &lt;10 E coli org/100 ml</td>
<td>&lt;10 E coli per 100 mL;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Turbidity &lt; 2 NTU</td>
<td>&lt;1 helmint per litre;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• &lt; 10/5 mg/l BOD/SS</td>
<td>&lt; 1 protozoa per 50 litres</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• pH 6 – 9</td>
<td>&lt;1 virus per 50 litres.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 1 mg/L Cl₂ residual for equivalent disinfection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>• &lt;100 E coli org/100 ml</td>
<td>Secondary and pathogen reduction (including helmint reduction for cattle grazing)</td>
<td>Dairy cattle grazing</td>
</tr>
<tr>
<td></td>
<td>• pH 6-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• &lt;20/30 mg/l BOD/SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>• &lt;1000 E coli org/100 mL</td>
<td>Secondary and pathogen reduction (including helmint reduction for cattle grazing)</td>
<td>Human food crops cooked/processed, grazing /fodder for livestock</td>
</tr>
<tr>
<td></td>
<td>• pH 6-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• &lt;20/30 mg/l BOD/SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>• &lt;10000 E coli org/100 mL</td>
<td>Secondary</td>
<td>Non-food crops including instant turf, woodlots, flowers</td>
</tr>
<tr>
<td></td>
<td>• pH 6-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• &lt;20/30 mg/L BOD/SS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.4 Treatment-performance indicators

As previously discussed, the water reticulation of agricultural irrigation schemes is an extension of the STP treatment train and in this regard monitoring of physicochemical performance indicators needs discussion. Table 3.5 sets out
recommend treatment performance indicators based on the literature and the HWRS research experience, and the relevant condition indicated (ANZECC/ARMCANZ, 2000; Asano, 1998; Derry et al., 2006; Lazarova & Bahri, 2005). For associated units of measurement Table 2.1 should be consulted.

Frequency of sampling depends on water quality and statistical variation noted in indicator levels with an elevated frequency of monitoring required for low quality waters with high levels of parameter variability. The first six indicators, however, are critical to short-term performance and should be monitored on a weekly basis by scheme staff using a hand-held field water quality analyser, ensuring acceptability in terms of ease of monitoring and cost containment.

These indicators are adequate to identify undesirable treatment changes taking place in open storages, such as chemical contamination from an event in the STP catchment. Another change involves the potential growth of algae or toxic blue-green algae (cyanobacteria), which at some times of year need to be monitored with a relatively high frequency.

While the monitoring of algal and cyanobacterial growth is a specialised topic which has been mentioned in the submitted papers, ongoing postdoctoral research is continuing in this area.
Table 3.5: Recommended treatment-performance indicators to support health risk assessment of water in agricultural irrigation schemes

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Abbreviation</th>
<th>Conditions indicated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved oxygen (percent saturation)</td>
<td>DO (%) sat</td>
<td>Ecological health of storage dams. Organic loading. Inorganic pollutants. Potential algal or toxic cyanobacterial bloom</td>
</tr>
<tr>
<td>pH</td>
<td>pH</td>
<td>Exogenous inorganic chemical pollution. Potential endogenous chemical releases from dam sediments. Aerobic stabilisation. Potential algal or toxic cyanobacterial bloom.</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>Potential for indicator and pathogen regrowth, hence indicator reliability and pathogen risk.</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>ECond</td>
<td>Exogenous inorganic chemical pollution. Potential endogenous chemical releases from dam sediments. Proxy for TDS.</td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>TDS</td>
<td>Organic and inorganic pollutants dissolved in water. Ionic equilibrium. Potential metal or nutrient release from dam sediments.</td>
</tr>
<tr>
<td>Turbidity or suspended solids the latter can be derived from Turbidity using a local correlation curve</td>
<td>Turb SS</td>
<td>Potential attachment and therefore survival of pathogens. Level of settlement, hence purification performance. Proxy for biomass hence potential algal or toxic cyanobacterial bloom.</td>
</tr>
<tr>
<td>Secchi disk</td>
<td></td>
<td>Clarity as rapid indication of turbidity</td>
</tr>
<tr>
<td>UV_{254} filtered and unfiltered</td>
<td></td>
<td>Proxy for dissolved and total organic carbon, an important bacterial and cyanobacterial nutrient in recycled water.</td>
</tr>
<tr>
<td>Biochemical oxygen demand (five day)</td>
<td>BOD_{5}</td>
<td>Amount of unstable organic matter in the irrigation water. Potential offensiveness on irrigation (eg: odour).</td>
</tr>
<tr>
<td>Total Kjeldahl nitrogen</td>
<td>TKN</td>
<td>Organic nitrogen level requiring stabilisation. Potential nutrient for algal or toxic cyanobacterial bloom.</td>
</tr>
<tr>
<td>Ammonium nitrogen, nitrite nitrogen and nitrate nitrogen</td>
<td>NH_{3}-N, NO_{2}-N, NO_{3}-N</td>
<td>Oxidation-reduction state of nitrogen indicative of anaerobic/aerobic status of aquatic zone. Level of stabilisation, group of treatment bacteria likely to be present, treatment challenge, and potential oxygen demand. Collectively indicate nitrogen available for indicator and pathogen regrowth, and algal or toxic cyanobacterial bloom.</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>TP</td>
<td>Nutrient from organic and inorganic sources available for indicator and pathogen regrowth, and algal or toxic cyanobacterial bloom.</td>
</tr>
<tr>
<td>Chlorine residual</td>
<td></td>
<td>Disinfection residual indicative of disinfection potential in water.</td>
</tr>
<tr>
<td>Total organic carbon, or spectro-photometric proxy UV_{254}</td>
<td>TOC</td>
<td>Available carbon source, as an expression of food availability for microorganisms, indicators and potential pathogens.</td>
</tr>
<tr>
<td>Chlorophyll-a</td>
<td>Chl-a</td>
<td>Biomass production in high nutrient effluent. Potential algal or toxic cyanobacterial bloom.</td>
</tr>
<tr>
<td>Phycocyanin</td>
<td></td>
<td>Cyanobacterial bloom.</td>
</tr>
<tr>
<td>Toxic metals and metalloids copper, lead, zinc, nickel, mercury, chromium, cadmium and arsenic</td>
<td>Cu, Pb, Zn, Ni, Hg, Cr, Cd and As</td>
<td>Industrial pollution or leaching from dam sediment or walls. Threat to plant health. Possible threat to human health at high concentrations. Potential wear on pumps, reticulation pipework or microfiltration equipment removing bacteria and algae from water. Downgrading dams as an ecological entity.</td>
</tr>
</tbody>
</table>
3.5 Toxic chemicals

The substantial volume of water required by agricultural irrigation schemes necessitates sourcing from a large, reliable supply which, in Australia, is typically tertiary-treated urban sewage, sometimes combined or "shandied" with smaller quantities of harvested urban stormwater (Table 4.1). Water from industries may be added to this flow following treatment at the factory to remove unwanted substances; a process typically controlled by a national or local trade waste inspectorate in terms of strict industrial legislation (Bisset & Green, 2003; DWE, NSW Government, 2009). Up to 90% of remaining organic and inorganic toxic substances are subsequently removed in settled sludge at the STP, sometimes causing a solid waste disposal problem (Lazarova & Bahri, 2005; Venkatesan & Halden, 2014).

The resultant small traces of toxic chemicals in irrigation water seldom present a problem to crops or consumers, and metals may even act as a source of trace elements, stimulating crop growth (Mañas et al., 2009). Quality control sampling for metals and other toxic substances at the irrigation site should, however, be occasionally carried out, possibly annually. This is, however, a specialised activity outside the scope of a rapid risk assessment system aimed at detecting short-term microbiological or performance-indicator changes.

Chemicals of health concern which pass through typical water and sewage treatment process are the endocrine disrupting chemicals (EDCs) which have a persistence allowing them to pass many times through the sewage/water treatment cycle resulting in potential bioamplification in aquatic food chains. EDCs include certain pesticides, herbicides, fungicides, plasticisers, surfactants, organometals, halogenated polyaromatic hydrocarbons, phytoestrogens and pharmaceuticals (Bologn et al., 2009; Lim, et al., 2001).

In laboratory experiments EDCs have been associated with hormonal mimicking and disruption of specific biochemical pathways, and this has been hypothesised to contribute to the population burden of cardiovascular disease, obesity, diabetes, cancers, birth defects, and certain renal, hepatic and neurological disorders. With a
possibility of uptake of such chemicals by food and fodder crops further research into the environmental stability of EDCs is required, but this was again outside the scope of developing a routine health risk assessment system which is the topic of the five papers (Klaassen, 2013).
4. The Water Recycling Imperative

4.1 The International recycling imperative

To strike a balance in a thesis on hazard associated with agricultural irrigation using recycled water, discussion is needed on the original imperative for water recycling.

There can be no doubt that without water recycling the world would not be able to feed a substantial number of its 7.3 billion people. The United Nations has declared the lives of 3.5 billion people in 40 countries as being under threat because of increasing water scarcity, with water supply being the most critical factor in achieving world food security (United Nations, 2014). Given that agriculture uses 70% to 80% of available supply internationally, safe water recycling has been identified as a key strategy in meeting global irrigation demands (O’Neill & Dobrowolski, 2011, Wyman, 2013). With ground and surface water reserves already dwindling in many world regions, the need to increase the use of urban effluent as a recyclable irrigation resource has been identified (Asano, 2005; Chen et al., 2013).

With growing reliance on recycled water, however, there is increasing pressure to use lower quality recycled supplies, including tertiary and even secondary treated effluent, the latter presenting a potential risk of pathogen uptake through root systems (Bernstein, 2011). To ensure safe use of low quality effluents it is essential, therefore, that the intended application is matched to the quality of the available water, necessitating on-site monitoring and management of agricultural irrigation schemes. While the imperative for this level of control has grown, relevant research has lagged behind the demand to use a wide quality-range of recycled waters, particularly where the production of salad and other contaminable food crops is intended (Battilani et al., 2010; Jensen et al., 2014; Pavione et al., 2013; Plauborg et al., 2010).

At this point the key drivers for the global water shortage underpinning the recycling initiative need introduction. The first driver is anthropogenic, involving population
growth, urbanisation and dietary change, the second infrastructural, involving the manufacturing industry, power generation and urban residential construction, and the third is climatic, involving local or global rainfall and temperature variation, which is the least predictable of the three drivers (Chartres, 2014; United Nations, 2014; Wyman, 2013). These drivers have been identified as influencing global water availability, although local level research is needed to identify place-relevant solutions including safe recycling strategies.

In terms of the anthropogenic driver, by 2050 there will be an additional two billion people in the world with most of the increase taking place in developing (industrialising) regions where demands for a Western diet will place additional pressure on agriculture to exploit remaining water reserves. This is particularly the case where westernisation of diet leads to an increase in demand for meat and sugar (Ercin & Hoekstra, 2014; Springer & Duchin, 2014). In affected regions population growth is typically accompanied by urban population drift, predominantly to towns with existing populations of less than 500,000. This phenomenon is already advanced in Asia, Africa and Latin America and there is an anticipated doubling of population in such settlements by 2025 (Verbyla et al., 2013). In such settings, urban populations maintain strong ties with ancestry and family in rural areas, and this in combination with the large rural-urban interface promotes agricultural activity in peri-urban and intra-urban zones which coalesce as informal or formal agricultural schemes, typically relying on low quality recycled water.

The infrastructural driver results from an ultimately improved regional economy based on nodes of industrialisation, with a rise in consumerism generating growth in the manufacturing industry, thermal electricity generation and formal housing construction. These activities are anticipated to increase global water demand by 400%, 140% and 130% respectively by 2050 (United Nations, 2014). Housing development results in effluents high in nutrients such as nitrate and phosphate which have potential to cause hyper-eutrophication in receiving waters. To avoid impacts on drinking water and aquatic food supplies, a simple and economical urban solution is to direct such effluents to agricultural land with water quality lagging behind bacteriological requirements for safe and sustainable agricultural production (de Fraiture et al., 2010).
With global warming concerns, the climatic driver has recently been subjected to extensive modelling with wide variation in anticipated outcomes. Consensus has been reached, however, that wet areas of the world will become wetter, dry areas drier, and in most areas there will be a lower predictability of rainfall volume and occurrence (IPCC, 2012). Rainfall predictability is a critical factor in agriculture, determining the cycle of planting, fertilising, pest control and cropping. Irrigation schemes will therefore tend to be based closer to the urban areas they serve, dependent on urban effluent as a supply with a high level of volumetric stabilisation based in turn on the stability of potable supplies sourced from strategic and sometimes distant reserves. To ensure cost effective, safe use of this resource varying supply quality needs to be matched to specific irrigation use. Change in water quality with storage in on-site irrigation scheme dams, used to buffer the variable irrigation demand against a fixed-volume input, is also an important consideration if exposure risk to food consumers and scheme operators is to be controlled.

The international increase in demand for low-quality recyclable water in areas of population growth or industrialisation, and the potential for water quality variation will present a growing challenge to new schemes, highlighting the importance and international relevance of the scientific information contained in the five papers (Hanjra & Qureshi, 2010; Huda et al., 2007; Thornton et al, 2014).

4.2 The Australian recycling imperative

Water security in the principal food producing areas of Australia is threatened by extreme climate variability under the action of large-scale atmospheric circulations, including the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Ashcroft et al., 2014).

In mean precipitation terms, Australia is the driest continent after Antarctica, with one of the World's most unpredictable climates, the coefficient of variation of river flow being 0.70 compared with a World average of 0.43. During the course of the research project on which the papers are based, Australia underwent extreme
drought from 2001 to 2003 (sometimes known as the millennium drought), with significantly decreased rainfall from 2000 to 2010, highlighting the imperative for research into sustainable water recycling (Department of the Environment, Australian Government 2011; Tan & Rhodes, 2013).

Australian agriculture places a very heavy demand on water supply compared to most other countries with 75% of Australia's total available water being used for agricultural irrigation (Hussey & Dovers, 2007; Risbey et al., 2009). Despite this only 9% of Australia's urban effluent is currently recycled, and as a result research into extended safe recycling has been identified as an urgent priority (Radcliffe, 2006).

In addition to the low use of recycled treated urban effluent, most current recycling is carried out by relatively few schemes, as shown in Table 4.1. From this list it is apparent that New South Wales (NSW), the most populous state, lags behind other states and territories in embracing urban treated effluent recycling for agricultural food production (Apostolidis et al., 2011; Stevens et al., 2006; Hamilton et al., 2005). At present most of the schemes rely solely on monitoring by the sewage treatment plant (STP) to ensure the quality of water used throughout the scheme.

Increased recycling is inevitable with current agricultural use frequently outstripping available water supply in irrigation areas. Exacerbating this are calls for reduced irrigation water extraction from major natural watercourses to improve their condition by effectively increasing sustainable environmental flows (Foerster, 2013; Kiem, 2013). This creates a tension between environmental and agricultural demands, leading to progressively decreasing water supply for large-scale agriculture in established irrigation areas (Chen et al., 2013; Department of the Environment: Australian Government, 2011).

In recent years there has been a marked increase in the number of small, peri-urban agricultural and horticultural operations ("market gardens") in Australia in response to a demand for high value, labour-intensive products such as salad crops, cauliflower, broccoli, herbs and asparagus, produced close to urban points of sale (Mason & Knowd, 2010; Zasada, 2011). As a result agricultural infilling of urban
Table 4.1: Australian agricultural irrigation schemes using treated urban effluent

<table>
<thead>
<tr>
<th>Name of scheme</th>
<th>Location</th>
<th>Irrigation uses, and number of commercial users</th>
<th>Sewage treatment and control standard</th>
<th>Usage volume (ML) per annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Treatment Plant Water Recycling Scheme</td>
<td>Melbourne, Victoria</td>
<td>Market gardening of fruit and vegetables, including salad crops (120 users)</td>
<td>Tertiary by filtration, ozone, UV light and chlorination, to potable standard</td>
<td>120,500</td>
</tr>
<tr>
<td>Western Treatment Scheme (oldest in Australia, established 1879)</td>
<td>Melbourne, Victoria</td>
<td>Market gardening of fruit and vegetables, particularly cauliflower and broccoli (226 users)</td>
<td>Secondary, in one of the world’s largest aerobic/anaerobic lagoon schemes. Also tertiary, by UV light and chlorination, to sub-potable standard</td>
<td>57,000</td>
</tr>
<tr>
<td>Lower Molonglo Scheme</td>
<td>Canberra, ACT</td>
<td>Viticulture (one main user)</td>
<td>Tertiary by chlorination to sub-potable standard</td>
<td>50,000</td>
</tr>
<tr>
<td>Virginia Water Recycling Scheme</td>
<td>Virginia, South Australia</td>
<td>Horticulture and agriculture, including salad crops (240 users)</td>
<td>Tertiary by filtration and chlorination to sub-potable standard</td>
<td>20,000</td>
</tr>
<tr>
<td>Virginia Angle Vale Reuse Extension</td>
<td>Virginia, South Australia</td>
<td>Horticulture and agriculture, including salad crops (160 users)</td>
<td>Tertiary by filtration and chlorination to sub-potable standard</td>
<td>5,800</td>
</tr>
<tr>
<td>Willunga Basin Scheme</td>
<td>McLaren Vale, South Australia</td>
<td>Mostly viticulture, but some horticulture, including olives (150 users)</td>
<td>Tertiary by chlorination to sub-potable standard</td>
<td>5,500</td>
</tr>
<tr>
<td>Wide Bay Recycled Water Scheme</td>
<td>Wide Bay, Queensland</td>
<td>Sugar cane, and silviculture (one main user)</td>
<td>Tertiary by chlorination to sub-potable standard</td>
<td>2,500</td>
</tr>
<tr>
<td>Clarence Water Recycling Scheme</td>
<td>Hobart region, Tasmania</td>
<td>Mostly grain, some viticulture and horticulture (29 users)</td>
<td>Tertiary by chlorination to sub-potable standard</td>
<td>1,400</td>
</tr>
<tr>
<td>Hervey Bay Effluent Reuse Scheme</td>
<td>Hervey Bay, Queensland</td>
<td>Mostly silviculture, some turf and sugar cane (one user)</td>
<td>Tertiary by chlorination to sub-potable standard</td>
<td>1,000</td>
</tr>
<tr>
<td>Power Water Alice Springs Water Reuse Project</td>
<td>Alice Springs, Northern Territory</td>
<td>Silviculture, horticulture, Australian “bush foods”, herbs, viticulture research (one main user)</td>
<td>Tertiary by DAF-flotation and chlorination to sub-potable standard</td>
<td>600</td>
</tr>
<tr>
<td>Hawkesbury Water Recycling Scheme</td>
<td>Richmond, New South Wales</td>
<td>Pasture for dairy cattle (up to 2006), beef cattle, sheep, deer, horses, experimental horticulture, etc. (one main user)</td>
<td>Tertiary, by chlorination of biofilter effluent up to 2006. Subsequently filtration and chlorination of IDAL plant effluent to sub-potable standard. On-site risk assessment and management introduced after 2002</td>
<td>500</td>
</tr>
</tbody>
</table>
and peri-urban land not yet earmarked for urban development is occurring, echoing a phenomenon observed internationally in developing areas (Verbyla et al., 2013). Such agriculture may depend on riparian right to abstract water from riverine sources, often polluted by land runoff carrying faecal matter from livestock or wild animals, or effluent from sewage treatment plants and septic tanks. In this regard further opportunity for transfer of assessment and management approaches outlined in the five publications exists (Loff & Fairley, 1998; Tyrrel et al., 2006).

Safe water recycling not only has important implications for Australia, but also for regional and potentially global food security, given that more than half of Australia’s food production is currently widely exported (Ejaz Qureshi et al., 2013). In the past 15 years, strong Chinese economic growth and increasing demand for western and luxury food items has placed considerable political and economic pressure on Australian agribusiness to increase food production for export to China (Sun & Collins, 2009). The value of Australia’s food exports, however, peaked at US $35.2 billion in 2001/2 and has declined since then because of unfavourable climatic conditions with unsatisfactory rainfall to sustain the required production growth. At the same time exports to New Zealand and the United Kingdom have increased, leaving little leeway for future participation in the free trade agreement currently being negotiated with China, unless alternative water supplies are brought into play (Kim et al., 2010).

Water recycling offers a viable alternative, although the potential for endogenous pathogen growth or exogenous runoff contamination of stored, treated effluent emphasises the value of the research described in the five papers.
5. The Five Research Papers Presented for the Thesis

Note: The full, published version of each paper as presented for the award of PhD by publication is given in appendices A to E. Appendix F gives a list of other DEST registered papers and presentations relevant to the research project which were not included for the award.

Paper 1:

Paper 2:

Paper 3:

Paper 4:

Paper 5:
6. Contextualisation of Each Thesis Paper

In this section each paper is discussed in terms of its:

i. content

ii. relevance

iii. impact and the applicant’s contribution

iv. methodology and innovations

v. findings and contribution to scientific knowledge

vi. place in an integrated portfolio of work.

Paper 1


i. **Content:** The paper lays the foundation for other papers in the series by describing an approach for rapid health risk assessment of effluent irrigation using basic, quantitative microbial and physicochemical indicators, to which value is added by using contextualising, qualitative environmental, exposure and social information. Single values are derived for each risk and matched uncertainty factor to simplify management decision making, and a number of intervention strategies are suggested to facilitate this.

ii. **Contemporary relevance, impact and applicant’s contribution:** The paper was published in a respected international journal with the aim of attracting wide comment on the proposed risk assessment process. The journal’s IF is 3.045, 5-year IF 3.371, Scopus-SJR 1.302 and Scopus-SNIP 1.569. The paper was cited 8 times and 12 written communications were received from five countries. The candidate is principal author, having developed and tested the risk assessment system, collected the preliminary data, specified the parameters to be collected for the larger research data base, carried out data analysis and determined and
interpreted the results. The candidate conceptualised and wrote the paper, attending to all revisions.

iii. **Methodology and related innovations:** The paper sets out an innovative methodology for integrating quantitative microbial and physicochemical monitoring data with qualitative environmental, exposure and social data, adding value to a minimal monitoring data set. This provides a viable monitoring system which can easily be integrated into daily operations of each scheme at minimal cost. It describes an innovative approach for integrating quantitative and qualitative data using ordinal ranking tables. A measure of uncertainty in the assessment process is provided through the use of uncertainty values. The method was validated through application to the HWRS; the first time the Scheme had been used as an outdoor research laboratory, opening the way for further water recycling research. The data base established for the research provided the starting point for two honours and a PhD candidate.

iv. **Findings and contribution to scientific knowledge:** The paper identifies a novel approach for integrating comprehensive health risk assessment with routine activities at irrigation schemes. During validation the method showed its value by identifying important potential health hazards associated with the HWRS. These included the exposure of infants and immunocompromised individuals to low-quality irrigation water, the existence of a closed loop in the dairy pasture irrigation system with a build-up of health indicators to excessive levels, and the contamination of stormwater assumed safe for irrigation with backwash water from sand filters used to polish effluent. The paper showed how local exposure hazards can arise through classical but missed engineering problems even in well managed schemes. In this regard the need for a multiple-barrier approach offering redundancies for proactive exposure control was identified. The innovative methodologies expounded in this paper were not challenged in citation but used as a basis by other authors to support their scientific work.

v. **Place in an integrated portfolio of work:** The paper laid a scientific foundation for research by establishing the fundamentals of a feasible health risk assessment system for irrigation schemes, which was built on in later papers.
Knowledge gaps were also identified for ongoing research by other water, health and irrigation scientists.

**Paper 2**


i. **Content:** The paper reports key findings relating to stakeholder risk perception as a key factor in determining the acceptability of water recycling schemes, and the nature of risk communication needed to reassure the public of scheme safety, and ensure a culture of safe practice among scheme operators and others.

ii. **Relevance, impact and applicant’s contribution:** Once technical monitoring practices had been established in paper 1, it was highly relevant that social aspects of water reuse be addressed. The Toowoomba debacle of 2006 in which residents of a small Australian town refused indirect recycling largely because of inadequate preparatory work by Council to identify and address public perceptions, resulted in rejection of the scheme (Hurlimann & Dolnicar, 2010). A local journal (*Water, Australian Water Association*) was chosen for publication of this paper as it is widely read by Australian irrigation practitioners, and was therefore well placed to gather local, culturally-relevant feedback which would help in assessing user acceptability. The journal is Scopus searchable with a Scopus SNIP of 0.145, with IFs and SJR still under evaluation. The paper was cited 3 times and the author received nine written communications. The author successfully sought approval from the UWS Ethics Committee to engage the communities, organised and carried out the survey of communities of practice relevant to the scheme using peer interviewers, analysed the data and interpreted the results, and wrote the paper as principal author.

iii. **Methodology and related innovations:** This was the first time the KABP (knowledge, attitudes, beliefs and practices) survey approach had been used for assessment of a water recycling scheme. It was developed by WHO for the assessment of community perceptions of contentious or emotive topics such as
AIDS and smoking (Beltzer et al., 2013; Campbell et al, 1999). The method was found to have good capacity to identify aesthetic components which tend to distort responses relating to acceptability of food irrigation using recycled sewage, opening the way for an innovative method to be used when assessing user-acceptance of future schemes.

iv. **Findings and contribution to scientific knowledge:** An important finding was that the acceptability of irrigation with recycled effluent increases with the perceived number of physical barriers between the irrigation point and the exposed individual. This supports the need for a multiple-barrier approach, with communication to the public and other stakeholders that such a system is in place. The paper also reported that stakeholders are more trusting of communications generated by local scheme monitoring than they are of blanket assurances from water authorities. This highlights the need for stakeholder engagement and ownership in schemes, adding materially to scientific knowledge relating to the community role in successful scheme operation and management.

v. **Place in an integrated portfolio of work:** The paper included the important community dimension in risk assessment and management of agricultural irrigation schemes.

**Paper 3**

i. **Content:** This paper discusses changes in the microbial and physicochemical quality of recycled water with passage through the typical irrigation-scheme reticulation of pipes, pumps and storage dams. Change with storage was recognised early in the research as a very important factor in determining final irrigation water quality. The research was facilitated by the upgrade of the STP in 2005 with low quality effluent being available in the first three years of the research, and high quality water in the following three years. Changes in water quality could therefore be observed for the two water types, with passage
through the same infrastructure over a three year period for each type. Improvement in a number of parameters for low quality effluent, and deterioration for high quality effluent are recorded.

ii. Relevance, impact and applicant's contribution: Study of changes in low and high quality effluents widened the applicability of the research reported in the paper to a wide range of scheme types. The research showed that recycled water storages form a continuation of the STP treatment train in which treated effluent, as a biochemically active product, can undergo marked improvement or deterioration. This emphasises the futility of trying to rely solely on one set of monitoring data from one control point (the STP outlet) to characterise irrigation water, as is the practice for most schemes in Australia and elsewhere.

The local, Scopus-searchable AWA journal Water was chosen for the publication (SNIP 0.145), given contemporary debate regarding the upgrading of STPs to IDAL plants in securing sustainable environmental flows. The paper was only cited once but the author received 13 communications, predominantly from engineers in the water recycling and irrigation sector. It should be noted that Jane Aiken, Scheme technician, was named as primary author in recognition of her dedication in carrying out monitoring to establish the HWRS data base over an eight year period. The PhD candidate, however, remained the corresponding author, having conceptualised and written the paper, developed the methodology, and carried out the analysis and interpretation (Appendix C, page 90, paragraph “The Authors” indicates the candidate’s role).

iii. Methodology and related innovations: The paper was innovative in identifying the need for a series of control points as sequential monitoring points and multiple barriers, based on the outlets of a scheme’s main storage dams. This control point should offer a sampling tap and facilities for diverting flow to other storages, either for further stabilisation, or immediate use on high-value, contaminable crops where the water quality meets a guideline requirement. In this way simultaneous risk control and value adding is enabled through judicious use of each control point, potentially offsetting monitoring costs (economic implications will be assessed in postdoctoral work). Using this approach it was found that a mere seven key performance indicators would
suffice for typical medium-scale schemes, monitored at between two and three control points.

iv. **Findings and contribution to scientific knowledge:** The paper contributed to scientific knowledge by clearly identifying on-site storage as a continuation of the treatment train, with potential to cause improvement or deterioration in the effluent. The need for multiple control points which could also act as multiple barriers to effluent flow was also identified. The potential for regrowth of indicator organisms (faecal coliform, FC) was suggested in this paper.

v. **Place in an integrated portfolio of work:** The potential for indicator regrowth was subject to further research investigation as reported in paper 5. In this regard preliminary findings in paper 3 led to the capstone findings in paper 5, which have international significance.

**Paper 4**

**Derry, C., 2011** Considerations in establishing a health risk management system for effluent irrigation in modern agriculture, *Israel Journal of Plant Sciences*, 59, 125-137.

i. **Content:** The paper consolidates risk management aspects of the project, highlighting the need for transdisciplinary engagement across a range of stakeholders to secure effective risk communication. Areas such as hazard identification, risk analysis, strategy development and implementation, and intervention assessment are discussed from a risk management perspective, using examples from the HWRS.

ii. **Relevance, impact and applicant’s contribution:** This was an invited paper in the Israel Journal of Plant Sciences suggesting a level of international recognition of the candidate’s previous three papers by a country responsible for the highest per capita wastewater reuse internationally (Chen et al., 2013). The journal’s IF is 0.260, 5-year IF: 0.420, Scopus SJR: 0.178, Scopus SNIP: 0.354. The paper received 1 citation and 12 written communications, some of which
were from the Israel Department of Agriculture, suggesting a level of interest in
generated by the work in draft and final form. The applicant was sole author of
this invited paper, having developed the management model which was
presented in other papers including a book chapter on climate change and
agrometeorological risks (Huda, et al., 2007).

iii. **Methodology and related innovations:** The paper proposes an innovative
cyclic health risk management model with capacity to tie together approaches
for effective risk assessment as discussed in the three previous papers (see Fig.
3, page 129 of Appendix D). In the model risk communication subsists at the
centre of the hub encouraging multilateral risk communication between all
relevant monitoring, assessment and intervention activities.

iv. **Findings and contribution to scientific knowledge:** When the risk management
model was trialled in terms of the HWRS setting, it was found that out of 24
recommended amelioration strategies, 10 were successfully actioned by the
scheme within six months, and a further 10 within the following 18 months.
Partly as a result of the information presented in this paper and subsequent
related presentations the candidate was asked to sit on the scientific advisory
committee of the Macarthur Centre for Sustainable Living, and to develop a
framework for the monitoring of water quality improvement bioretention units
by the City of Sydney and subsequently the Cooks River Alliance.

v. **Place in an integrated portfolio of work:** The paper is highly relevant to the
other four papers in the portfolio in that it draws together information on
monitoring and risk assessment under a feasible risk management umbrella,
consolidating the work into a unified whole, offering a clear intervention
strategy and making the portfolio a useful, functional and integrated body of
work as would be expected of a formal thesis at doctoral level.
Paper 5


i. *Content*: The paper examined the environmental stability of enterococci indicator (ENT) which is increasingly being used as the main indicator for monitoring recycled water irrigation schemes because of its assumed stability in ecologically competitive environments (Lleò et al., 2005; Wu et al., 2011).

ii. *Relevance, impact and applicant's contribution*: The paper challenged the advice of the WHO that ENT does not undergo regrowth in environmentally stored water, suggesting that a level of correction may be needed when monitoring with this indicator (WHO, 2011). As the WHO advice is echoed in four prominent monitoring texts, the result presented in the paper is of considerable international importance to those who wish to accurately monitor recycled water usage for irrigation (Bartram & Rees, 1999; Hurst et al., 2007; Mara & Horan, 2003; Nollet, 2007). The journal in which paper 5 was accepted for publication, *Science of the Total Environment*, is the leading international journal for papers integrating the areas environment, health and ecology. This reflects the value of paper 5 and the underpinning research to the scientific community. The journal’s IF is 3.258, 5-year IF 3.789, Scopus SJR 1.749 and Scopus SNIP of 1.505. While only 1 citation of the paper has occurred so far, over 1000 downloads occurred in the first 5 months following hard copy publication, suggesting strong potential for future citation. The findings will have an impact on the revision of future water reuse guidelines. The author devised the complex study design, carried out the analysis, and was principal author of this paper.

iii. *Methodology and related innovations*: An innovative and advanced mixed methodology based on combined linear and multiple regression analysis was used to produce the results. Modelling of the relationship between climate (temperature) and water temperature using a sophisticated regression analysis design was also published by the journal as a special addendum. A large amount of innovative data transformation was required to facilitate the analysis.
iv. **Findings and contribution to scientific knowledge:** The paper presented the important and original finding that, contrary to advice of the WHO and a number of authoritative water analysis texts, ENT indicator can regrow in environmentally-stored water. This indicator instability is potentially leading to rejection or over-chlorination of recycled water internationally, impacting on ecosystems and potentially human health in terms of trihalomethane generation in water receiving irrigation runoff. It is likely that a number of scientific monitoring texts and guidelines will be modified as a result of the findings, and the author has already received interest from Australian government departments. An equation was provided in the paper to enable correction for temperature in future food production and climate change modelling, providing material for ongoing work by other scientists. The paper showed total organic carbon in recycled water to be a more important nutrient than nitrate or phosphate for indicator growth in the Australian setting, providing a starting point for ongoing work into biomass growth. Bird life, often blamed for excess nutrient in storage dams was found to have little or no impact in this study, opening a further research avenue into the origin of nitrogen fluctuations in open water impoundments (Kingsford et al., 1999).

v. **Place in an integrated portfolio of work:** The paper is important in the overall portfolio as it contextualises the use of faecal indicator bacteria (FIB) relied upon throughout the study and as referred to in all five papers, and identifies potential threats to the traditionally-assumed stability of one of these in increasing use. the publication of the final paper in the series in a high-ranking (ARC-ERA “A” rated) journal suggests that the publication series had reached a stage of maturity expected at doctoral level.
7. References


Carr, R., 2005. WHO guidelines for safe wastewater use – more than just numbers. *Irrigation and Drainage*, 54, s103-s111.


DHS (Department of Human Services) Victoria, 2008. Guide for the completion of a recycled water quality management plan. Rural and Regional Health and Aged Care Services Division, Melbourne, Australia.


Appendices A to E:

Thesis papers in published format
Appendix A:

Paper 1: Rapid health risk assessment of effluent irrigation on an Australian university campus
Rapid health-risk assessment of effluent irrigation on an Australian university campus

Chris Derry\textsuperscript{a,},\textsuperscript{*} , Roger Attwater\textsuperscript{b}, Sandy Booth\textsuperscript{b}

\textsuperscript{a}College of Health and Science, University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 1797, Australia
\textsuperscript{b}Blue Mountains World Heritage Trust

Received 14 March 2005; received in revised form 7 September 2005; accepted 14 September 2005

Abstract

Rapid health-risk assessment of chlorinated sewage-effluent irrigation of lawns, fields and crops adjacent to populated areas at the University of Western Sydney was carried out in response to warnings from the supplying authority of deteriorating bacteriological quality of the water. Irrigation with low-quality effluent offered potential for the contamination of a range of foodstuffs and the exposure of staff, students and visitors. The need for early investigation was emphasised by eutrophication presenting as sudden algal bloom in one of the campus dams and an odour suggestive of anaerobic proteolysis on irrigation. No baseline data existed regarding improvement or deterioration in water quality with passage through the dams, or relating to potential for direct or indirect exposure. The assessment design incorporated three methodologies to generate biophysical, environmental and social data. Environmental and social data were used to augment short-term data for biophysical indicators in the estimation of risk. Where required qualitative information was converted to quantitative data using categorical ranking tables, and risk evaluation was carried out using ranked risk and uncertainty values. Results for biophysical indicators showed a steady improvement in water quality with passage through campus dams, emphasising a need to regard the impoundments as part of a treatment chain, rather than as passive storage units. Effluent quality at most irrigation sites marginally exceeded regional action thresholds for relevant crop types, suggesting a need for risk management through revised irrigation practice, system design, distribution management and risk communication. Problems requiring urgent intervention included the concentration of contaminants of bovine faecal origin in one dam as the result of a closed loop within the reticulation. Also of concern was the exposure of certain most susceptible individuals including crèche children who visited pastureland and orchards where irrigated oranges were collected, and potentially immunocompromised or mentally challenged adults in a work-opportunity gardening scheme. Despite its limitations, rapid risk assessment enabled identification and proactive management of major risk factors, promoted risk communication and awareness, and laid the foundation for ongoing risk surveillance.

© 2005 Elsevier GmbH. All rights reserved.

Keywords: Irrigation; Recycled water; Water reuse; Health-risk assessment; Health-risk management; Risk surveillance

\textsuperscript{*}Corresponding author. Tel.: +61 2 45701731; fax: +61 2 45701383.
\textit{E-mail address:} c.derry@uws.edu.au (C. Derry).

1438-4639/S - see front matter © 2005 Elsevier GmbH. All rights reserved.
Introduction

For over 30 years the Hawkesbury campus of the University of Western Sydney (UWS), with its strong agricultural and environmental ethos, has had an agreement with the Sydney Water Corporation to accept tertiary-treated (chlorinated but unfiltered) effluent from the Richmond sewage treatment plant (STP) for irrigation. Currently lawns, sportsfields, fruit orchards, vegetable beds and pasture for horses, deer, sheep and dairy cattle are irrigated with this valuable resource (Booth et al., 2003). While this long-term water reuse has been without recorded health incident, in late 2002 analytical laboratory reports from the STP suggested deterioration in microbial quality of the effluent being supplied to the campus. The STP was a trickling-filter type nearing the end of its service life with limited capacity to cope with increased flows from the burgeoning population in the North-Western Sydney Metropolitan Area. While Sydney Water advised that a large-capacity intermittently decanted aerated lagoon (1DAL) plant would replace the old STP in 2005, the continued use of low-quality effluent for irrigation during the interim phase, with minimal information on associated health risks, was of concern.

The imperative for risk assessment was reinforced when algal bloom suddenly occurred in one of the campus effluent dams and complaints of an odour suggestive of anaerobic proteolysis were received on irrigation. Investigation of a case of dermatitis in a contractor who was allegedly heavily exposed to eutrophied dam water was inconclusive, but emphasised the need to examine the potential for exposure of students, staff and visitors to effluent or its residue, and to predict likely outcomes. There was also a risk of indirect exposure thorough milk, which was sold to a dairy for pasteurisation and distribution, and spray-irrigated fruit and vegetables which were not sold but which were removed from the campus by certain staff, students and work-opportunity scheme participants for consumption.

The simple solution of diverting the effluent away from the campus to a tributary of the Hawkesbury–Nepean (H–N) River was not viable given the prohibitive cost of replacing it with potable water, and the prolonged regional drought with heightened restrictions on the use of potable water for irrigation. In addition, high levels of nitrates and phosphates in the effluent would have aggravated eutrophication in the deteriorating H–N River system which is Sydney’s most important water resource with aquacultural, agricultural, recreational and potable water-abstraction uses. In 1998, a substantial part of Metropolitan population was advised by Sydney Water to boil drinking water or to purchase bottled water following the discovery of potentially pathogenic cryptosporidia and giardia in chlorinated but unfiltered sectors of the water supply, as sourced from the upper-reaches of the H–N system. Earlier occurrence of cyanobacterial bloom in the middle-reaches had presented a threat to public health through the consumption of fish, shellfish and crustaceans contaminated with alkaloid toxins (Derry et al., 2003).

Given the tension between the imperative for sustainable water reuse and the need to protect health, university management commissioned its Integrated Catchment and Environmental Management (ICEM) research group to carry out assessment with a view to identifying risks and developing strategies for proactive intervention. In the process, a methodology for ongoing surveillance would be piloted.

Materials and methods

A multidisciplinary task team with collective expertise in risk analysis, water analysis, epidemiology, toxicology, catchment management and social research was formed to develop an assessment design within an existing environmental health management framework for the broader Richmond regional water reuse scheme (Derry et al., 2002). Results of the assessment were to be reported to a university irrigation risk management committee consisting of representatives from university management, university communities and the risk management team.

The risk analysis design included three methodologies run in parallel to generate biophysical, environmental and social data, the latter two data sets subsequently being used to contextualise and augment the small data set for biophysical indicators resulting from the relatively short monitoring period. During risk estimation qualitative environmental and social data were converted to quantitative data where necessary using categorical ranking tables developed for this purpose.

Biophysical indicator monitoring

This was carried out in terms of regional water quality and health guidelines (ANZECC/ARMCANZ, 2000; ARMCANZ/ANZECC/NHMRC, 2000; SA/SNZ, 2000), which conform with the ISO 14000 Series of Standards, to which Australia is co-signatory. To facilitate monitoring, functional components of the reticulation were identified, as shown in Fig. 1, with seven control points (shown as CP, on the diagram) to monitor change in quality after passage through storage dams or long runs of pipe. To facilitate sampling keyed taps were inserted into mains downstream of impoundments. The buffer pond receiving water from the STP was sampled by direct abstraction.
Review of the international literature revealed that a wide range of chemical and bacteriological parameters had been used for previous recycled effluent monitoring. The Australian/New Zealand guidelines, however, emphasise the need for local relevance in sampling profiles based on toxicological, epidemiological, social and demographic considerations. Local maps showed little major secondary industrial development in the effluent catchment and STP data recorded extremely low levels of toxic or carcinogenic substances, such as metals, metalloids, pesticides and trihalomethanes. This suggested little need for the inclusion of specific chemical substances in the monitoring profile. The same record, however, showed relatively high levels of faecal indicators (total coliforms, thermotolerant coliforms (TC) and Enterococci) in terms of guideline thresholds, although the local epidemiological record showed extremely low prevalence of gastrointestinal disease in the catchment (Department of Health and Ageing, 2004). The possibility of periodic “spikes” of human pathogens, however, remained of concern, given the large number of visitors to the catchment which is adjacent to the Blue Mountains World Heritage Site, and periodic failure of the STP treatment train during storm events when surface runoff gained unwanted access to the sewerage system through wastewater gullies, inundating the STP.

Based on these considerations a set of seven indicators was selected for monitoring at each control point, as shown with intended uses of each indicator in Table 1. TC was selected as the main faecal-pollution indicator, given the high correlation of results for this indicator and similar faecal indicators shown in STP records. Specific pathogens were excluded owing to the poor likelihood of recovery during the short (3 months) sampling period with a correspondingly low number of total samples (10 for each parameter at each control point). Analysis was carried out by the University’s Environmental Health and Water Laboratory using standard scientific methods (APHA, 1999). Quality assurance was carried out by the submission of two duplicate samples for each parameter to a commercial laboratory during the period. Transient indicators pH, temperature and dissolved oxygen (DO) were analysed in the field using relevant Hach® test kits.

Table 1. Biophysical indicators and related use in study

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermotolerant coliform (TC)</td>
<td>Recent faecal contamination, hence potential for occurrence of pathogens in terms of epidemiological considerations in the catchment.</td>
</tr>
<tr>
<td>Biochemical oxygen demand (BOD)</td>
<td>Indication of carbon and nutrient-pollution load as well as viability of aerobic biomass.</td>
</tr>
<tr>
<td>Dissolved oxygen (DO)</td>
<td>Indication of ecological “health” of water in terms of potential for aerobic activity, hence inverse indicator of nutrient pollution and purification potential. Indication of odour potential from anaerobic proteolysis. Estimation of aerobic stabilisation potential. Indirect indicator for photosynthetic biomass content under given sunlight conditions.</td>
</tr>
<tr>
<td>pH</td>
<td>Correction of BOD and DO results; indicator for chemical pollution or of level of aerobic stabilisation.</td>
</tr>
<tr>
<td>Temperature (Temp.)</td>
<td>Correction of DO results. Risk potential indicator for mesophilic pathogens under natural conditions.</td>
</tr>
<tr>
<td>Conductivity (Cond.)</td>
<td>Indicator for chemical pollution of water. Proxy for total dissolved solids (TDS).</td>
</tr>
<tr>
<td>Suspended solids (SS)</td>
<td>Indicator for settlement, hence purification/stabilisation performance and contextualisation of DO results in terms of photosynthetic biomass activity.</td>
</tr>
</tbody>
</table>
Table 2. Examples of site-specific hazards

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Horticulture dam</th>
<th>Horticulture irrigation area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingestion of wet effluent</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Indirect ingestion via horticultural food products</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Contact with wet effluent</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Contact via irrigation spray drift</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Contact with recently dried effluent (&lt;24 h)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Contact with dried effluent (&gt;24 h)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Abrasion/inoculation with wet or dry residue</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mechanical injury</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Electrocuton</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Dam bursting</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Drowning</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Perception of odour</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Note: + indicates potential existence of hazard.

Table 3. Examples of general hazards

<table>
<thead>
<tr>
<th>Category</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immune status (susceptibility/resistance)</td>
<td>Creche infants (&lt;1 year of age) eating irrigated fruit.</td>
</tr>
<tr>
<td></td>
<td>Creche children (1–5 years of age) eating irrigated fruit.</td>
</tr>
<tr>
<td></td>
<td>Elderly eating irrigated fruit.</td>
</tr>
<tr>
<td></td>
<td>Pregnant women eating irrigated fruit.</td>
</tr>
<tr>
<td></td>
<td>Educationally or immunologically challenged individuals in work-</td>
</tr>
<tr>
<td></td>
<td>opportunity projects eating irrigated fruit and vegetables.</td>
</tr>
<tr>
<td>Communication status</td>
<td>Student general lack of awareness.</td>
</tr>
<tr>
<td></td>
<td>Academic staff general lack of awareness.</td>
</tr>
<tr>
<td></td>
<td>Other staff general lack of awareness.</td>
</tr>
<tr>
<td></td>
<td>Inadequate student safety induction.</td>
</tr>
<tr>
<td></td>
<td>Inadequate academic staff safety induction.</td>
</tr>
<tr>
<td></td>
<td>Inadequate other staff safety induction.</td>
</tr>
<tr>
<td></td>
<td>Inadequate public signage.</td>
</tr>
<tr>
<td></td>
<td>Inadequate notices on taps.</td>
</tr>
<tr>
<td></td>
<td>Inadequate colour coding of taps and pipes (ilac).</td>
</tr>
<tr>
<td></td>
<td>Lack of effective risk communication.</td>
</tr>
<tr>
<td></td>
<td>Poorly identified stakeholder groups.</td>
</tr>
<tr>
<td></td>
<td>Absence of appropriate bulletins for stakeholders.</td>
</tr>
<tr>
<td>Health/safety management status</td>
<td>Over-irrigation resulting in ground water infiltration.</td>
</tr>
<tr>
<td></td>
<td>Opportunities for cross-connection with potable water reticulation.</td>
</tr>
<tr>
<td></td>
<td>Flood inundation of system (emergency planning).</td>
</tr>
<tr>
<td></td>
<td>Major process change (IDAL plant commissioning).</td>
</tr>
</tbody>
</table>

Direct environmental observation

Preliminary identification of hazards (scoping)

The risk assessment team inspected all sites shown in Fig. 1 and held interviews as necessary to produce a comprehensive cross-sectional record of potential physical and practice-related hazards. On-site discussion between team members ensured integration of diverse knowledge and experience and subsequent re-inspections following consultation of the literature ensured that hazards were correctly identified and described. Hazards were recorded as being either site specific or general, examples being shown in Tables 2 and 3.

Risk characterisation

A descriptor was written for each hazard with statements regarding the likelihood of the hazard potentiating, the expected outcome and the certainty (or uncertainty) with which each of those observations was made. Team members were not obliged to record
observations on hazards which lay outside the scope of their knowledge and experience. A summarised statement for each hazard was drafted by a coordinating team member, using standardised nomenclature. This was sent to individual members for comments and suggestions for changes until a “consensus” document had been produced without the rate-reducing step of repetitive meetings and debate. In this way, an informed, written account of hazards and related factors was recorded in the shortest possible time using Delphi methodology. In later stages of this process, team members were informed of preliminary quantitative results for biophysical monitoring and could incorporate this into their qualitative characterisation of risk.

**Action research**

Applied social science research methods were used to gather information from the community on awareness and perception of risks, potential for exposure and the acceptability of a range of intervention strategies. A preliminary step was the identification of communities of practice (COPs), being functional groups with common interests and activities, and therefore consisting of individuals with a similar likelihood of exposure. The use of traditional university groupings, such as staff, students or technicians, was avoided as exposure had potential to vary considerably within such groups.

COPs considered to have the highest exposure risks were those associated with horticultural, dairy, work-opportunity, crèche, farm management and outdoor-laboratory operations. Action research focused on these COPs as they represented important index groups for exposure of the general campus population. At workshops open discussion took place within a topical framework relating to knowledge, attitudes, beliefs and practices. At later meetings proposed intervention strategies based on earlier deliberations were presented to test acceptability and undergo modification to ensure relevant and accountable management practice. To facilitate integration of ideas across groups, summary findings of each group were made available to all other groups.

Final results were presented to the risk management committee meeting, at which all COPs were represented. Details of this process, by which consensus was reached in the shortest possible time, are presented elsewhere (Attwater and Derry, 2005).

**Risk estimation**

Estimation of risk was taken to be the assigning of numerical values to individual risk factors to facilitate analysis (Ommen Commission, 1997). At this point some general assumptions behind the approach used in this assessment are briefly discussed.

**General assumptions**

While risk is sometimes associated purely with the likelihood of occurrence of a hazardous event, this concept has been challenged because events with the same likelihood may have outcomes ranging from minor to catastrophic. A need, therefore, exists to model risk in terms of both likelihood (probability) and outcome (consequence) (Faustman and Omenn, 2001; Mandl and Lathrop, 1981).

In this study, a single risk value, $r$, was calculated for each hazard using an assumption that risk represented the simple (unweighted) product of probability ($p$) and consequence ($c$). In the absence of baseline data, simple linear models were assumed for most hazard scenarios.

An alternative approach is the construction of a risk matrix in which probability and consequence are separated by the allocation of alphabetical characters for probability, and numerical characters for consequence. This approach avoids further manipulation of $p$ and $c$, which may have different intervals and units. In the opinion of the authors, however, there exists a problem in that such matrices must ultimately be interpreted by “eyeballing”, with potential for ambiguity and error. Given this problem and the need for risk ranking to support the decision-making process, the calculation of a single summary value for each risk factor was preferred.

**Uncertainty value estimation**

An important consideration was the need to estimate the level of confidence attached to each risk value, as implied in the action tree risk management framework.

---

**Fig. 2.** Part of a decision-tree risk management framework (adapted from ANZEC/ARMCANZ, 2000, guidelines).
Table 4. Example of a categorical ranking table for the estimation of uncertainty values (u)

<table>
<thead>
<tr>
<th>Value (u)</th>
<th>Descriptor</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extremely certain</td>
<td>( p ) or ( c ) was estimated on the basis of biophysical indicators or other scientific process, with adequate quality assurance.</td>
</tr>
<tr>
<td>3</td>
<td>Highly certain</td>
<td>( p ) or ( c ) was estimated by biophysical monitoring in conjunction with direct environmental observation using established criteria, with a high level of consensus between task team members and COPs.</td>
</tr>
<tr>
<td>5</td>
<td>Moderately certain</td>
<td>( p ) or ( c ) was estimated by direct environmental observation using established criteria, with some consensus between task team members and COPs.</td>
</tr>
<tr>
<td>7</td>
<td>Fairly uncertain</td>
<td>( p ) or ( c ) was estimated by direct environmental observation without established criteria, or with little consensus between team members and COPs.</td>
</tr>
<tr>
<td>9</td>
<td>Highly uncertain</td>
<td>( p ) or ( c ) was estimated with minimal supportive biophysical, observational or action research data.</td>
</tr>
</tbody>
</table>

Table 5. Guideline criteria (action threshold values) for thermotolerant coliforms (TC) in irrigation water (adapted from ANZECC/ARMCANZ, 2000)

<table>
<thead>
<tr>
<th>Recommended irrigation use for water</th>
<th>TC (CFU/100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silviculture, turf, cotton, etc. (with restricted public access).</td>
<td>&lt;10,000</td>
</tr>
<tr>
<td>Pasture and fodder (grazing animals except pigs and dairy).</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Pasture and fodder (dairy animals, with five day withholding period).</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Human-food crops, indirect contact with water (trickle or subsoil irrigation, or items peeled before use); or sold cooked or processed.</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Pasture and fodder (dairy animals, no withholding period).</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Human-food crops (eaten raw, direct contact with water).</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Adopted from the guidelines (ANZECC/ARMCANZ, 2000). An adapted version of the framework as used in the assessment is shown in Fig. 2.

While accurate estimates of confidence (or conversely significance) are possible in epidemiological studies involving substantial data sets, this was precluded in the assessment owing to the "thinness" of the short-term data. To address this problem "categorical ranking tables" were developed for the conversion of quantitative and some qualitative data, to ranked quantitative data, an example being shown in Table 4. The approach is not dissimilar to that used in epidemiological meta-analysis, where data from different sources are divided into qualified categories for comparison (Clayton and Hills, 1996). Ranking is a common procedure in statistical analysis where tests such as Spearman's rank correlation are used to generate categorical numerical data from limited data sets.

The ordinal-scale used allowed allocation of continuous values greater than zero and less than 10 on the basis of the particular mix of qualitative and quantitative characteristics relating to each uncertainty factor. Following determination of uncertainty values for \( p \) and \( c \) using the tables, the mean uncertainty value (u) was calculated for each risk factor, which was multiplied by 10 to bring it into a 1–100 range for ease of interpretation.

**Risk value estimation**

The first step in estimating \( c \) was the comparison of each median result for biophysical indicator monitoring with guideline values for action thresholds, such as those shown in Table 5 for TC. Medians were used in compliance with guideline recommendations relating to actual frequency of observations.

The number of powers by which the measured value exceeded the guideline value was used to determine a preliminary location in categorical ranking tables, such as that shown in Table 6. Fine adjustment was then made to the location, using additional information acquired through direct environmental observation and action research. To maintain objectivity, protocols were established for each ranking table and records of past hazardous occurrences were used to guide table construction where possible.

Probability \( p \) was similarly estimated using categorical ranking tables such as that shown in Table 7. Again, fine adjustment was carried out in the light of information from direct environmental observation and action research. The frequencies of past events (e.g., flood
Table 6. Example of a categorical ranking table for the estimation of consequence (impact) values (c)

<table>
<thead>
<tr>
<th>Value (c)</th>
<th>Descriptor</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insignificant</td>
<td>Results of biophysical monitoring within action threshold value (ATV) for specified use. If exposure event occurred, no health impact would be expected.</td>
</tr>
<tr>
<td>3</td>
<td>Minor</td>
<td>Results of biophysical monitoring marginally exceeding ATV for a specific use. If exposure event occurred, short-term minor health impact possible, requiring advice, minor hygiene or first aid.</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
<td>Results of biophysical monitoring showing at least a 10-fold exceedance of ATV for a specific use. If exposure event occurred, short term, moderate health/safety impact expected, potentially requiring urgent first aid or minor medical treatment.</td>
</tr>
<tr>
<td>7</td>
<td>Major</td>
<td>Results of biophysical monitoring showing a $10^2$–$10^3$ exceedance of guideline values for a specific use. If exposure event occurred, medium or appreciable health impact expected, potentially requiring general medical or specialist treatment, hospitalisation or statutory notification.</td>
</tr>
<tr>
<td>9</td>
<td>Extreme</td>
<td>Results of biophysical monitoring showing $&gt;10^4$ exceedance of guideline values for a specific use. If the event occurred, very high risk or widespread impact, possible chronic health effects, epidemic impact or death.</td>
</tr>
</tbody>
</table>

Table 7. Example of a categorical ranking table for the estimation of probability (likelihood) values (p)

<table>
<thead>
<tr>
<th>Value (p)</th>
<th>Descriptor</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rare</td>
<td>Event just conceivable, but rare. Circumstances exceptional (e.g., 100-year flood).</td>
</tr>
<tr>
<td>3</td>
<td>Unlikely</td>
<td>Event possible but not expected in short term. An unusual occurrence (e.g., person falling into a recycled water dam).</td>
</tr>
<tr>
<td>5</td>
<td>Likely</td>
<td>Event expected in near future. Has occurred fairly recently (e.g., farm staff making skin contact with recycled water).</td>
</tr>
<tr>
<td>7</td>
<td>Highly likely</td>
<td>Event will probably occur soon. Has occurred often (e.g., farm staff making skin contact with dried recycled water residues).</td>
</tr>
<tr>
<td>9</td>
<td>Inevitable</td>
<td>Event will definitely occur soon, or is always observed (e.g., dried residue on crops spray-irrigated with recycled water).</td>
</tr>
</tbody>
</table>

Risk evaluation

The estimated values for risk factors were ranked and presented with associated uncertainty values on a scale of 1–100. These were accompanied by contextualising notes and recommendations for intervention or further data collection. This was included in a comprehensive report to the risk management committee (Derry, 2002). From ranked risk values, management could determine intervention priority, and from accompanying uncertainty values, the need for further assessment or research. Qualitative comments contextualised risk in terms of physical location and community at risk.

Results and discussion

A total of 58 risk factors was identified. Fourteen of these (the upper quartile) were found by the risk management committee to require high priority intervention (Table 8). The highest recorded risk value on a scale of 1–100 was 49, indicating capacity of the model to accommodate more serious hazards. More than half of total risk factors had uncertainty values exceeding 50, indicating a need for further data collection or research in many cases. These results suggest that while rapid risk assessment can be useful in pinpointing areas requiring priority intervention, it can only be regarded as preliminary in the comprehensive assessment of risk.

Biophysical indicators

The results for seven biophysical indicators monitored at seven control points are shown in Table 9. A progressive decrease in TC was seen with passage through campus dams, indicating that the impoundments needed to be regarded as an extension of the treatment train, rather than as mere water storages (see control points 1–6 in Fig. 3). The most marked decrease was seen in the Turkey Nest dam with an approximately 1-log reduction in TC and simultaneous decrease in turbidity, from 38 to 10 NTU. The relative contributions of settlement and ecological activity to purification, however, require further research. Of interest was the increase of BOD from 27 to 71 mg/l, suggesting an
Table 8. Ranked risk factors with associated uncertainty indices

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Risk value (r)</th>
<th>Uncertainty value (u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of recycled water by mentally challenged or immunocompromised participants in the work-opportunity scheme, with potential for ingestion.</td>
<td>49</td>
<td>60</td>
</tr>
<tr>
<td>Backwash of residue from the horticulture micro-irrigation sand filters, into a stormwater harvesting system assumed to supply safe irrigation water.</td>
<td>48</td>
<td>40</td>
</tr>
<tr>
<td>Generation of irrigation spray and spray drift onto a public road adjacent to the campus, involving recycled water heavily contaminated with bovine faecal matter, as the result of a closed wash-down loop incorporating a cowstall and a campus dam (Hillside).</td>
<td>48</td>
<td>30</td>
</tr>
<tr>
<td>Ingestion of fruit, nuts and some vegetables irrigated with recycled water, by students, campus staff and work-opportunity participants.</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Lack of formal information for contractors regarding personal risks of working on the recycled water system.</td>
<td>42</td>
<td>55</td>
</tr>
<tr>
<td>Potential breeding of vector mosquitoes capable of transmitting Ross River viral haemorrhagic fever, in storage dams.</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td>Irrigation of pasture for dairy animals with recycled water heavily contaminated with bovine faecal matter (indirect human health impact through milk).</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Potential ingestion by children at the campus creche of fruit irrigated with recycled water which marginally exceeds the action-trigger value.</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Potential contact of recycled water or its residue with cuts and abrasions of possibly educationally challenged or immunocompromised participants in the work-opportunity scheme.</td>
<td>36</td>
<td>60</td>
</tr>
<tr>
<td>General lack of awareness of risks of using recycled water and of necessary precautions among students and academic staff.</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>Potential inoculation of residual material during the playing of contact sports on fields previously irrigated with recycled water.</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>Potential contact of recycled water or residue, heavily contaminated with bovine faecal matter, with cuts and abrasions of staff of the dairy and horse units.</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Potential cross-connection between recycled water and town-water reticulation systems by contractors.</td>
<td>32</td>
<td>45</td>
</tr>
<tr>
<td>Reliance on suspect detail in some of the engineering drawings relating to underground pipework for recycled and potable water.</td>
<td>30</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 9. Results of biophysical indicator monitoring (medians; N = 10)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermotolerant coliforms (CFU/100ml)</td>
<td>700</td>
<td>90</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>650,000</td>
<td></td>
</tr>
<tr>
<td>BOD₇ (mg/l)</td>
<td>27</td>
<td>71</td>
<td>39</td>
<td>45</td>
<td>21</td>
<td>7</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>38</td>
<td>10</td>
<td>957</td>
<td>12</td>
<td>19</td>
<td>72</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>0.84</td>
<td>0.77</td>
<td>0.67</td>
<td>0.59</td>
<td>0.63</td>
<td>0.71</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>DO (mg/l)</td>
<td>8.87</td>
<td>6.17</td>
<td>5.50</td>
<td>8.45</td>
<td>5.90</td>
<td>8.40</td>
<td>6.47</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>7.7</td>
<td>7.8</td>
<td>9.3</td>
<td>9.0</td>
<td>8.5</td>
<td>7.5</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>15.1</td>
<td>16.0</td>
<td>16.4</td>
<td>16.4</td>
<td>16.5</td>
<td>15.3</td>
<td>14.2</td>
<td></td>
</tr>
</tbody>
</table>

Unlocking of nutrients such as nitrogen, phosphorus, and carbon. The algal bloom observed in the subsequent impoundment (Horticulture dam), which supported the original motivation for risk assessment, may have arisen as an outcome of this nutrient-releasing process.

Given the preliminary results, management were advised that the Turkey Nest dam should be regarded as a bastion against the introduction of pathogens from the failing STP, and that as such it should be a critical control point in ongoing monitoring. In this regard, the
practice of allowing wide volume excursions here and in other dams through excessive pumping, as an outcome of poor water distribution management, needed attention.

It was noted that odour complaints occurred 48–72 h after excessive bloom had occurred in Horticulture dam, suggesting the possibility of using indicators such as turbidity, chlorophyll A or BOD in anticipating and managing odour events. The high pH recorded for the dam in comparison to other dams may have resulted from the photosynthetic removal of carbon dioxide by algal bloom, suggesting the possibility of including pH changes in an odour-anticipating profile. Management was advised that Horticulture dam should be regarded as a critical control point in odour management and that further research was required to enable development of a relevant set of indicators.

DO did not correlate well with other parameters but was found to be influenced mainly by sunlight intensity, suggesting an ecological value but limited use in ongoing health monitoring.

On the basis of biophysical indicators alone, the water in most of the campus impoundments was found to be satisfactory in terms of guideline threshold values for irrigation of food crops to be peeled, cooked or processed prior to use, but not for irrigation of those eaten raw (Fig. 3). The water was also unsuitable for direct human contact, although “contact” was seen to require qualification in terms of exposure level, type and duration, individual susceptibility.

One impoundment (Hillside dam, control point 7, Fig. 3) had TC levels far in excess of those for the effluent entering the system, suggesting a need for investigation by direct environmental observation, as discussed in the following section.

**Direct environmental observation**

When results for biophysical indicators were contextualised in terms of those for direct observation, it became apparent that two broad problem categories existed:

**System design problems**

The system had a low storage capacity necessitating rejection of part of the STP water during wet periods and the supplementation of recycled water with treated water during dry periods. This simultaneous use of effluent and potable water involved a number of above-ground hose connections which increased the possibility of cross-connection between the two supplies. A long-term solution was the reinstatement of disused dams to provide a greater storage volume to buffer demand variations. This would simultaneously increase retention times for the effluent, resulting in improved quality.

The shallow slope of some dam walls was observed to allow the growth of vegetation with potential for mosquito breeding. It was recommended that re-grading of dam walls be carried out with 2.5 cm gravel chip to the correct angle to prevent further erosion and deter vegetation growth and survival of immature forms of the mosquito.

Of particular concern was the poor design of the recirculation serving Hillside dam adjacent to the dairy, where a closed loop resulted in a TC indicator level 10,000 times higher than that found in other parts of the recirculation (control point 7, Fig. 3). This concentration resulted from the practice of abstracting dam water to flush feeders from a cowshed, with return of wastewater to the dam. A sedimentation trap in the return arm of this circuit was found to be ineffective.

The TC results exceeded guideline values by a factor of 100 for even the least demanding irrigation uses, such as silviculture or turf farming with restricted human access. This water was nevertheless in extensive daily use for dairy pasture irrigation using high-pressure irrigation sprayers, giving rise to spray drift which was said to have wet farm staff and students and which reached an adjacent public road. Inspection showed that no provision had been made for a 50 m distance-barrier between the road and the field as recommended in the guidelines, or for additional exposure barriers such as hedges and automatic shutdown based on wind velocity and direction.

While it could be argued that the high TC indicator level resulted from organisms of bovine and not human origin, transmission of diseases from animals to humans by the faecal-oral route is of increasing importance as a contributor to the global burden of ill health (Gajadhar and Allen, 2004). Bovine organisms giving rise to waterborne zoonotic diseases include varieties of streptococci, staphylococci, salmonella and clostridia, parasitic helminths and protozoa, as well as certain viruses
(APHA, 2000). The tragic *Escherichia coli* O157:H7 outbreak at Walkerton, Ontario in which seven people died and 2000 fell ill through consumption of well-water contaminated with bovine faecal runoff, highlights the need to closely monitor operations on pastoral land adjacent to water resources serving public use (Ali, 2004).

With this in mind it was recommended to university management that urgent attention be given to the manual removal and spreading of manure from the cowshed and that quality of the water in the dam be restored to at least that of the incoming water through dilution and storage, prior to the continuation of irrigation. Given its proximity to grazing land with potential for runoff, the dam was designated as a critical control point for ongoing monitoring.

Another example of poor system design was found in the Horticulture precinct, where backwash water containing residue from pressure filters serving micro-jet irrigators was being directed to the stormwater drain. This was regarded as a hazardous practice as campus stormwater was harvested for high-quality irrigation use. Backwash water is known to contain accumulated biofilm with adsorbed micro-organisms and non-polar chemicals and the filters were likely to have concentrated any pathogens present in the effluent (El-Masry et al., 1995). For this reason, management were advised that the backwash water should be redirected to the sewer.

**Operational problems**

Apart from the need for improved water distribution, a need for improved record keeping regarding operation and maintenance of the system was identified. With minimal maintenance staff, the university regularly outsourced work on the reticulation without having an open-trench inspection system with sign-off for completed work. In addition, much of the pipework was not coloured lilac, as is international convention.

At Sydney Water’s flagship Rouse Hill recycling scheme in Western Sydney, even with ample colour coding, contractors nevertheless made four cross-connections between recycled and potable supplies in a 4-year period, compromising the drinking water supply to 82 households (Murray, 2005). This emphasised the need for a multiple-barrier approach to exposure in the campus irrigation scheme. Following unsuccessful attempts by engineering consultants to identify all pipework in the campus reticulation, management were advised that open-trench inspection should be instituted and that in addition the potable water supply should be tested for conductivity and TC at critical control points during routine surveillance in order to detect cross-connections.

Other recommendations based on direct environmental observations were that:

- all surface pipework carrying wastewater be coloured lilac,
- “keyed” taps be fitted to limit access, with cautionary notices at each tap,
- buffer zones (50 m) between irrigated and populated areas be provided,
- soil or subsoil irrigation be used in preference to overhead irrigation,
- irrigation schedules be changed from daytime to nighttime, when campus occupation was relatively low,
- sufficient soak-in time be allowed after irrigation to establish a soil barrier,
- over-irrigation resulting in pooling, high residue levels and potentially long bacterial survival times be avoided,
- operational and environmental records be archived.

**Action research**

Through working with COPs a number of complex contributors to risk were identified. One of these was the existence within COPs of clusters of most susceptible individuals (MSIs), two of which are discussed below.

**Most susceptible individuals**

Infants and young children in the crèche COP were of particular concern, representing a cohort highly susceptible to waterborne infections. While crèche premises were found to be sufficiently far from irrigation operations to avoid spray-drift exposure, young children were taken on visits to see livestock, such as deer and sheep, in areas irrigated with effluent marginally exceeding action thresholds. In addition, micro-spray-irrigated orchards in the horticulture precinct were visited, where oranges were collected and taken back to the crèche for consumption. This posed a potential hazard through the carrying of water or mud back to the crèche on footwear and through the sucking of oranges, which required peeling prior to consumption in terms guideline values for TC. Through action research workshops combined with environmental ground truthing it was found, however, that risk had already been considerably reduced through the teaching of basic hygiene practices to children by crèche supervisors, including:

- hand washing before eating, after visiting the toilet and following outdoor activities and visits,
- eating only at mealtimes, using utensils,
- the avoidance of pica,
- the washing and peeling of all fruit prior to consumption,
the wearing of gumboots during field visits with subsequent removal and washing by the children, under adult supervision, on return to the crèche.

To further their efforts in protecting the children the crèche community requested information, based on the results of ongoing monitoring, as to times when it would be advisable to conduct excursions. In response, a basic risk communication system was developed giving crèche staff access to information in a suitable format. The system took into account a number of factors including monitored water quality and the time-barrier between irrigation and the intended visit.

Using multiple environmental and social risk barriers it was therefore possible to reach a point where the risk management committee and specific COP representatives felt confident that the social, educational and recreational benefits of a “day out” would outweigh the minimal risk posed by occasional, controlled exposure to irrigated areas and foodstuffs.

An additional group of MSIs was identified in the work-opportunity COP where unemployed and mentally and physically challenged participants carried out ornamental and horticultural gardening using effluent of the same quality as that used in the Horticulture precinct. Here there was anecdotal evidence of immunocompromise in terms of chemotherapy and possible HIV positivity, with poor hygiene practice among some mentally challenged participants. Detailed collection of information at individual level was, however, not possible in terms of Australian privacy law, without first going through a lengthy approval process.

Given these circumstances it was suggested that:

- safety induction be given at an appropriate level for all participants (or where relevant, custodians), backed up by written information explaining risks and precautions,
- existing information regarding hand washing after gardening and before eating should be reinforced, as should the need for showering and changing of clothing following exposure,
- hose watering should be carried out only by responsible and physically healthy participants,
- overhead irrigation should be carried out at least 12 h before the arrival of participants,
- keyed taps should be installed,
- fruit or vegetables should be washed in potable water under supervision prior to removal and advice regarding suitable preparation should be given.

Workshops held with the work-opportunity COP again led to a conclusion that the benefits of the scheme should be carefully weighed against the low level of risk which could be achieved through the application of multiple environmental and social barriers to exposure. Produce from the garden taken home by keen participants represented a tangible sign of training and rehabilitation progress, and the well-designed gardens with supportive layout and structures for challenged participants offered an alternative to a sedentary existence.

The risk information system was extended to the work-opportunity COP with information in a suitable format to meet their needs.

Risk communication problems

A need for multilateral risk communication between community, management and monitoring agencies has been identified as crucial to effective and accountable risk management (Freer, 2004; Renn, 2004). Action research workshops involving COPs revealed a number of issues and concerns and resulted in the identification of acceptable risk intervention strategies including:

- The need for a risk management forum with the authority to make changes, the forum to include informed representatives from all stakeholder groups sharing information in a jargon-free, equitable environment. In this study, the risk management committee was found to serve this purpose.
- The placement of signage at entrances to the campus advising the public and visitors that recycled water was in use for irrigation in the interests of sustainability, and that certain precautions could reduce risk.
- The desirability of an information system to advise stakeholders on the water quality, its potential uses and precautions to be taken, in an acceptable, non-technical language.
- The need to identify existing perceptions relating to water reuse on the campus in the interests of improving risk communication. To achieve this, the risk assessment committee suggested that a knowledge, attitudes, beliefs and practices survey be carried out of larger groupings within the university population, and of residents adjacent to the campus, to yield data suitable for analysis. With strong support of the COPs a university grant was secured for this purpose.

Conclusions

International experience has shown that with sound risk management the terrestrial application of tertiary-treated effluent offers a safe irrigation option for a wide range of crops, including foodstuffs, and that by diverting effluent away from water bodies an ultimate improvement in regional water quality may result
promotes a culture of risk-awareness, management and communication in both institution and community.

Acknowledgements

The authors wish to thank the UWS Environmental Health Laboratory for the analysis of samples, the UWS Department of Works and Facilities for sponsoring the assessment, and Communities of Practice for their participation in the assessment and support of the application for additional funding.

References


Appendix B

Paper 2: Risk perception relating to effluent irrigation on a University campus
RISK PERCEPTION RELATING TO EFFLUENT REUSE ON A UNIVERSITY CAMPUS

C. Derry, R. Attwater

Abstract
An assessment of risk perception and communication relating to existing irrigation with tertiary-treated effluent was carried out at the Hawkesbury campus of the University of Western Sydney. This involved a 'knowledge, attitudes, beliefs and practices' (KABP) survey of staff, students and residents of properties adjacent to the campus, and was part of a health-risk assessment aimed at upgrading risk management. In order to assess acceptance of risk relating to potential additional uses, respondents were asked to comment on a range of hypothetical recycling options. The majority of respondents considered the irrigation of grass, trees and shrubs to be acceptable, with approximately half of the staff and residents saying that they already used grey water for this purpose at home. Also acceptable was the irrigation of sports fields, vehicle cleansing, paved surface wash-down, flushing of toilets, and the filling of ornamental ponds and wetlands. While there was only limited acceptance of effluent irrigation for food production, acceptability increased with the introduction of physical or conceptual exposure barriers, such as the peeling or cooking of vegetables, or the production of milk from irrigated pasture. Respondents perceived local risk monitoring as essential to securing safety, even if assurances regarding the original effluent quality had been given by the supplying authority. The survey revealed a need to improve formal communication of risk information to staff and students.

Introduction
For over 30 years the Hawkesbury campus of the University of Western Sydney (UWS), formerly Hawkesbury Agricultural College, has had an agreement with Sydney Water to receive dry-weather flow of effluent from its Richmond sewage treatment plant (STP) for the irrigation of lawns, sports fields, fruit orchards, vegetable beds, and pasture for horses, sheep and dairy cattle. This is a mutually-beneficial agreement by which the University receives a free supply of irrigation water while Sydney Water minimises load-licence payments to the Department of Environment and Conservation (DEC) for effluent discharge into Rickaby's Creek, a tributary of Sydney's main river system, the Hawkesbury-Nepean (Booth et al. 2003, Derry, Booth, Attwater 2003).

A schematic of the on-campus reticulation system and irrigation sites, with relevant data to indicate its extent, is shown in Figure 1.

In 2003 Sydney Water notified the deteriorating quality of effluent from the Richmond STP, an ageing trickling-filter plant where the tertiary process involved alum precipitation, chlorination and lagooning, but not filtration. While Sydney Water data for STP effluent were available, the University had not carried out monitoring for effluent quality change with passage through its reticulation, or for potential human exposure. (It should be noted that since the assessment, Sydney...
Water has replaced the trickling filter plant with an intermittently decanted aerated lagoon (IDAL) plant.

To investigate these aspects with a view to upgrading barriers to exposure, the University commissioned a health risk assessment by a team of University researchers with relevant local and international experience. The assessment involved performance- and health-indicator monitoring at critical control points, with subsequent value-adding to the small, short-term data sets through environmental observation (inspection), and social surveying. Full results of this assessment have been reported elsewhere (Derry, Atwater, Booth 2006).

Risk assessment was carried out within the framework of an existing risk management plan (Derry et al. 2002) which included a cyclic health risk management model (Figure 2) based on the report of the USA Congressional Commission on risk management practice (Omenn Commission, 1997).

In terms of this model, multilateral risk communication was seen to be central to effective and accountable risk management, necessitating an understanding of risk perception in participating stakeholder groups (Amendola 2001; Driedger, Eyles 2003; Frewer 2004; Renn 2004). Risk communication was seen to include the multilateral flow of risk information between the different disciplines engaged in risk assessment, the different members of the risk management team, and the representatives of community stakeholder groups.

To explore risk tolerance and perception, two separate studies were conducted. One focused on larger generic stakeholder groups such as staff, students and residents of properties adjacent to the University, while the other focused on University “communities of practice” (COPs), being clusters of heterogeneous individuals with common function, and therefore potentially-similar exposure experience. These included a horticulture group, dairy farm group, outdoor laboratory unit, University crèche and work opportunity unit.

The COP study, which relied on action research methods, has been reported elsewhere (Atwater, Derry 2005), while the study of larger generic groups, which yielded sufficient data for descriptive analysis, is the topic of the current report.

**Method**

Knowledge, attitudes, beliefs and practices (KABP) assessment was used, being a method frequently adopted by the World Health Organization (WHO) to gather opinion on controversial areas, such as lifestyle and HIV-AIDS exposure (Campbell et al. 1999).

The survey included a sample of 72 staff, 189 students and 72 residents, minimum sample sizes having been estimated in terms of relevant statistical constructs (Clayton, Hills 1996; Herold, Peavy 2002). Level of accuracy (sampling error) was set at p=0.05 with a standard normal deviate of 1.96. Maximum acceptable variance based on the potentially-rarest response was set at 0.05, an assumption based on the results of an earlier pilot study. Statistical correction of sample size for populations of less than 10 000 was applied. Population and sample details are shown in Table 1.

Three separate but analogous questionnaires were developed to collect information from staff, students, and residents relating to:

- awareness of the existing irrigation operation;
- current sources of information;
- exposure opportunities through unprotected contact;
- precautions taken to minimise exposure;
- acceptance of additional reuse options;
- relevant domestic reuse practice.

The questionnaires were pilot-tested then amended as necessary, the final version consisting of 16 closed-response questions, some with open-response sub-sections, with a final open-ended section for recording comments of a general nature. The use of ever-popular Likert response scales was avoided as these tend to introduce marginal response categories, necessitating an increase in sample size.

---

**Table 1. Population and sample sizes.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Population</th>
<th>Minimum sample size at p=0.05</th>
<th>Achieved sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students</td>
<td>4,523</td>
<td>72</td>
<td>189(^1)</td>
</tr>
<tr>
<td>Staff</td>
<td>242</td>
<td>57</td>
<td>72</td>
</tr>
<tr>
<td>Index Residents(^2)</td>
<td>156</td>
<td>50</td>
<td>72</td>
</tr>
</tbody>
</table>

Legend:

1: Effective sample size following standardisation for disciplinary group.

2: An “Index Resident” was the first adult presenting for interview at each dwelling.
Questionnaires were returned anonymously, although students were asked to state their program of study as proxy for disciplinary field to allow statistical adjustment for over-representation from specific fields to take place.

**Student survey**

The sampling frame (delineated population) included all full-time undergraduates attending the campus. The preferred method of random sampling from enrolment lists was not possible in terms of University confidentiality rules, therefore a time-based, systematic sample was drawn at the time of surveying. This involved peer-interviewers approaching one student every 15-minutes at three rearranged nodes of major on-campus pedestrian flow to request participation in the survey. The times at which interviewers occupied these sites were randomly selected.

To reduce selection bias resulting from potential over-sampling of specific disciplinary fields, standardisation was applied during analysis by the adjustment of the observed ratio of students in the sample to match the actual ratio of students in the University population. This yielded a standardised student sample of 189 from the original 204 interviewed. Being well above the estimated minimum sample size of 72, this offered insurance against a potentially-optimistic estimate of variance.

The questionnaire was interviewer-administered by volunteer student peers. Only four of the original 208 students who were approached declined to be interviewed giving an impressive response rate of 98%.

Interviewers were second year environmental health students with knowledge and skills in epidemiology, survey planning, questionnaire design and interviewing. They attended a one-hour orientation session and were paid for each questionnaire completed. They were aware that “under cover” students would be visiting survey nodes for quality assurance purposes.

The questionnaire form included clear “pathways” to be followed by interviewers, to limit incorrect completion. Criteria for interpreting the questions and for recording information accompanied each questionnaire to reduce ambiguity and provide a means of standardising the recording process.

**Staff survey**

Core questions were the same as those in the student survey, with additional questions to capture information relating to the supervisory or middle-management role of staff. The sampling frame consisted of all permanent academic, laboratory and field staff.

Random sampling was carried out using staff lists, the estimated minimum sample size being increased by 100% to account for non-responders, with questionnaires being distributed through the internal mail for self-completion. While the initial response rate was poor (27%), a greatly improved rate (63%) was recorded after a letter was sent to all staff urging participation by those who had received the survey, in the interests of duty of care to students.

**Residents survey**

156 domestic properties immediately adjacent to the campus which might have been effected by spray drift or other nuisance were included. Pilot interviews by three postgraduate students who administered the survey indicated that there was a high level of duplication of information given by different residents in any one household. It was therefore decided that information from only one “index resident” would be included for each household, an index resident being the first adult present for interview. A sample size of 50 was estimated in terms of statistical requirements, and this was increased to 100 to compensate for potential non-response. The sample was randomly selected by application-based random number generation.

Where no one was at home letters were left advising that a follow-up visit would be carried out that evening, followed by a weekend visit if this was unproductive. This approach resulted in a 72% response rate.

**Analysis and Presentation**

Data were manually extracted from the questionnaires, recorded in spreadsheet format and analysed with commercially available statistical software. Data are presented in this report as the percentage of affirmative responses received for each question, although where more than 5% of responses fell into “other” or “unknown” categories, alternative presentation methods have been used. The convention of stating the numerator (n) with each percentage has been replaced by the statement of sample size in Table 1. In cases where sub-groups are discussed the relevant numerator has been stated. Being a descriptive study, the data have been presented mainly as percentages, with corresponding tables and graphs. Percentages have been rounded to whole units in terms of the estimated level of accuracy.

In some instances the classification of qualitative responses to open-ended questions was possible and here rates for the commonest clusters of responses have been given as percentages.

**Results and Discussion**

**Reuse knowledge**

An appreciable percentage of staff and students were aware of regional imperatives for water reuse (86% and 52% respectively) (Table 2). Many were also aware that treated effluent was in use for campus irrigation (81%, 57%), although only a small percentage had undergone formal safety training (safety induction) or had received written information relating to exposure risks and prevention (7%, 9%).

Appreciable opportunity for exposure existed, however, with 46% of staff and 29% of students having come into contact with wet effluent (Table 5 refers), and 33% of index residents observing spray-drift reaching surrounding roads. Only 17% of staff had passed information on to others by formal means. Recorded comments suggested that this reluctance to communicate information was based on the lack of quantitative monitoring data for risk and exposure. This emphasised the need for
ongoing monitoring of health-related indicators at control points, not only to enable risk assessment to be carried out, but also to encourage a process of informed risk communication.

While many staff and students were aware of the existing water reuse management committee (78%, 47%), less than 2% identified it as the relevant contact node for reporting hazards. This emphasised a need for extended stakeholder participation on the committee to raise the level of awareness of its function and to open effective communication channels between relevant campus communities and management.

It was of interest that while only 20% of students were aware of the University’s recently established stormwater reuse wetlands, 31% of local residents were aware of their existence. Most of these residents gave their source of information as signage on the main road adjacent to the wetlands and informal conversations with University staff, while relatively few named articles in the printed media as their source of information. Only 15% of residents were aware of Sydney Water’s current water recycling proposal, despite media coverage. This suggested a need to explore locally-relevant methods of informing communities of regional reuse schemes, such as signage, talks at meetings or displays at sustainability centres.

In response to open-ended questions, residents said they wanted more information on campus water reuse, a process for reporting observed hazards such as spray-drift, and literature on household grey water reuse.

Reuse attitudes

Respondents were presented with a range of hypothetical recycling options using tertiary treated effluent “which complied fully with national guidelines for safe use”, and were asked to comment which of these they would feel “comfortable” with. This encouraged comment in terms of aesthetic values (innate feelings of acceptance or possibly revulsion), rather than health risk, although logic suggests that these factors may be conceptually interrelated (Table 3).

A large majority of University respondents (staff plus students) accepted effluent for toilet flushing and for the irrigation of grass, trees and shrubs, while 100% of the index residents supported this option. This is understandable given that 46% of index residents said they were already practising informal water reuse at home (see Table 5), the majority using grey water for general garden irrigation (open-ended responses). A test for non-parametric data revealed a statistically significant association (p<0.05) between the use of grey water at home, and the acceptance in principle of effluent-irrigation of vegetables if cooked prior to consumption.

When irrigation categories were ranked by potential health risk, as shown in Table 3, a stepped increase in acceptability with decreasing risk was noted across the three respondent groups (ANZECC/ARMCANZ/NHMRC 2000; FAO/WHO 2003; Mara, Cairncross 1989). This permitted graphs for acceptability relating to irrigation and non-irrigation use to be produced using pooled data (Figures 3 and 4).

While there was relatively low acceptance of irrigation of foodstuffs compared to other uses, it should be noted that a high percentage of “unsure” responses were recorded for each proposed food irrigation use (range 20% to 22%). This suggests that variables other than food type may be involved in community assessment of aesthetic acceptability, and that additional research is indicated to identify these potentially important modifiers of risk tolerance.

Reuse beliefs

Most University respondents believed that scientific monitoring and control by a risk management committee was necessary to secure safe irrigation with disinfected effluent, even if assurances were to be given by the water provider regarding the quality of the original supply (Table 4). In contrast, about half of the index residents believed that supply by Sydney Water would alone be a sufficient guarantee of quality. Almost 80% of staff and 50% of students said they would like to have regular updates on effluent quality via the University Web site. Some contextualising comments as relating to water reuse beliefs included:

“Hopefully there will be more recycled water reuse programs in this State; it would certainly ease our water problem. I guess the cost of these programs is an issue”

“Environmental management aspects also need attention; environmental flows, not over-harvesting water, protection of deep aquifer recharge, prevention of shallow aquifer recharge with salination, monitoring of salt levels and high pH”

“There is more we would like to know: Can you drink reused effluent? How safe is it? Will it be passed through animals, e.g. milk, meat? How will it affect native wildlife and fish?”

“When the treated effluent was used on the rugby oval, cuts would take longer to heal; the waste water used on the Oval

<table>
<thead>
<tr>
<th>Table 3. Acceptability of suggested effluent reuse options.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Suggested use</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
</tr>
<tr>
<td>Grass, trees and shrubs</td>
</tr>
<tr>
<td>Sports fields</td>
</tr>
<tr>
<td>Dairy posture</td>
</tr>
<tr>
<td>Vegetables eaten cooked</td>
</tr>
<tr>
<td>Vegetables eaten peeled only</td>
</tr>
<tr>
<td>Salad vegetables eaten raw</td>
</tr>
<tr>
<td>Other use</td>
</tr>
<tr>
<td>Washing down of paved surfaces</td>
</tr>
<tr>
<td>Flushing of toilets</td>
</tr>
<tr>
<td>Washing down of vehicles</td>
</tr>
<tr>
<td>Filling of ornamental ponds</td>
</tr>
<tr>
<td>Filling of wetlands</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4. Beliefs relating to local effluent reuse.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Belief</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Monitoring and control by a University risk management committee can secure safe irrigation</td>
</tr>
<tr>
<td>Supply from Sydney Water without University monitoring can secure safe irrigation</td>
</tr>
<tr>
<td>Regular updates on effluent quality should be provided via the University Web site</td>
</tr>
</tbody>
</table>
should be treated to a higher level.”
“Everyone should have a rain tank. If
correct tests have been performed, I
consider it safe except for edible plants”
“The water has been used for 60 years on
the golf course in Richmond with no
problems”
“It’s too late to start. It should have been
done earlier”

**Reuse practices**

A substantial percentage of staff, students
and index residents had come into contact
with effluent either directly or through the
consumption of fruit, vegetables and nuts
from experimental horticultural areas
(Table 5).

Of the exposed University group, 40%
(n=30) had made indirect contact through
spray drift, 33% (n=25) had eaten irrigated
produce, and 16% (n=12) had made direct
contact with wet residue on lawns, pasture
or plants. Less common exposure
evidence included direct contact with
irrigation spray, dried residue on plants, or
wet materials handled during laboratory
work.

Of those aware of campus effluent reuse,
57% (n=33) of staff and 24% (n=26) of
students said they had taken personal
precautions to reduce exposure. Of this
student and staff sub-group, 52% of had
practised avoidance and 34% hand-washing
after contact. There was minimal use of
personal protective equipment (PPE), such
as gloves or raincoats, suggesting a need for
PPE, and for advice regarding its use.

Collective data for staff and residents
showed the most popular use for grey water
at home to be lawn, shrub, flower and tree
irrigation (93%, n=82), the preferred
sources of grey water being shown in table
6. In terms of the survey, source was not
matched to use. It should be noted that
aerated wastewater treatment systems
(AWTSSs) represented a relatively minor
source of recycled water in comparison to
grey-water generating equipment, with
washing machines, baths, showers and spas
being responsible for 53% of all reused
water.

**Conclusions**

The survey revealed an appreciation among
respondents of the regional imperative for
water reuse, and a similar level of awareness
that reuse was being practiced on campus.
Communication of relevant health risk
information to staff and students was,
however, inadequate and this appeared to
relate to a lack of local water-quality
monitoring data for inclusion in safety
induction sessions and bulletins. The need
for ongoing monitoring was therefore
identified as important in facilitating both
the assessment and communication of risk.
University respondents identified
University risk monitoring as necessary
even if the water provider was able to give
assurances of safety regarding the original
supply. This may suggest an appreciation
that safety depends not only on the supply
but also on the way in which it is
subsequently stored and applied.

The process of communicating information
to staff and students through safety
inductions, bulletins and signage also had
potential to inform the local community.
The effectiveness of different communication pathways, however, required further research.

A large majority of participants accepted in
principle the concept of irrigating grass,
trees and shrubs with treated effluent, as

**Table 5. Water reuse practices.**

<table>
<thead>
<tr>
<th>Practice</th>
<th>Affirmative responses (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact with wet effluent or irrigation of effluent-irrigated fruit, vegetables or nuts</td>
<td>46</td>
</tr>
<tr>
<td>Use of personal protective equipment, hand washing, or avoidance</td>
<td>57</td>
</tr>
<tr>
<td>Water reuse practiced <em>at home</em></td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 3. Acceptability of irrigation uses: all respondents.

Figure 4. Acceptability of non-irrigation uses: all respondents.
well as toilet flushing. A lower percentage accepted foodstuff irrigation, although this varied with the type of foodstuff to be irrigated. Acceptance also varied with attenuation of the link between effluent and consumer through the use of barriers such as peeling, cooking and the conversion of irrigated pasture to milk. These observations suggested that consumer acceptance of food irrigation is negotiable in terms of the type of food irrigated, and the existence of exposure barriers.

The survey contributed to the understanding of stakeholder perceptions of risk, and indicated the type of monitoring needed to generate information for effective risk communication as central component in health-risk management for sustainable reuse.

Acknowledgments

The researchers wish to thank the Regional and Community Grants Scheme of the University of Western Sydney for funding the research, and the UWS and Richmond communities, for their participation and support.

The Authors

**Chris Derry** is senior lecturer in environmental epidemiology in the School of Natural Sciences, UWS, and researcher with the CRC (Irrigation Futures).

**Dr Roger Atwater** is Manager, Hawkesbury Water Recycling Scheme.

**Table 6. Sources of water reused at home by residents and staff (n=96).**

<table>
<thead>
<tr>
<th>Source</th>
<th>% response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing machine</td>
<td>33</td>
</tr>
<tr>
<td>Rainwater harvesting (eg: dam, tank)</td>
<td>23</td>
</tr>
<tr>
<td>Bath, shower, spa</td>
<td>20</td>
</tr>
<tr>
<td>Dish washer, sink</td>
<td>9</td>
</tr>
<tr>
<td>On-site aerated sewage treatment systems</td>
<td>8</td>
</tr>
<tr>
<td>Others</td>
<td>7</td>
</tr>
</tbody>
</table>

**References**


Appendix C:

Paper 3: Impact of recycled water quality on a Sydney irrigation scheme
IMPACT OF IMPROVED RECYCLED WATER QUALITY ON A SYDNEY IRRIGATION SCHEME

J T Aiken, C Derry, R Attwater

Abstract
Treated effluent has been used for irrigation, including for some food crops, by the Hawkesbury Water Recycling Scheme at the University of Western Sydney, Hawkesbury Campus, for some years. In recent years the STP concerned was upgraded from trickling filter to IDAL. The impact of improved effluent was compared with previous observations, in all, over a four year period.

Monitoring of water quality in on-site storages suggested that recycled water impoundments should be regarded not merely as storage buffers but as a continuation of the treatment train in which improvement or deterioration of water quality can occur with time, under the action of physical, chemical and biological factors and is an important area requiring further research.

End-user interests also need to be studied with agriculturalists preferring high nutrient irrigation water and environmental and health managers preferring low nutrient levels.

Introduction
The Hawkesbury Water Recycling Scheme (HWRSS), situated at the Hawkesbury Campus of the University of Western Sydney on the urban-rural fringe of the Sydney Metropolitan Area, receives treated effluent from Sydney Water's Richmond STP. The water flows into a network of open storage impoundments from which it is pumped to sports fields, lawns, experimental fruit and vegetable crops, and pasture for cattle, sheep, fowl and horses. On average, about 1.5 ML per day of recycled water is supplied through an agreement based on a 30-year partnership between UWS and SWC. Treated environmental flows are discharged into Rickaby's Creek, a tributary of Sydney's main river system, the Hawkesbury Nepean (Booth et al. 2003).

Up to late 2005 the supply was essentially secondary, involving a trickling filter (TF) process with pond stabilisation. In response to the ageing and overloaded nature of the plant preliminary health-risk assessment was carried out by the University to monitor changes in effluent quality in terms of a limited range of parameters measured at sequential control points in the reticulation. Following the assessment a multiple-barrier approach for managing water quality and human exposure was put in place to reduce direct and indirect exposure risk, the methodology and results of which have been published elsewhere (Derry et al. 2006, Attwater et al. 2006).

In 2005 Sydney water carried out extensive alterations to the STP, replacing the old TF process by intermittently decanted aerated lagoon (IDAL) process with tertiary treatment involving sand filtration and chlorination/dechlorination. The process was designed with a high capacity to anticipate population increase in Sydney's rapidly growing North Western sector, and high wet-weather flow events. The literature shows that IDAL treatment has an impressive ability to remove nitrogen from effluent by a process of nitrification/denitrification in a carbon-rich environment, resulting in the harmless discharge of nitrogen gas to the atmosphere (Weiner and Matthews 2003). Potential for IDAL process optimisation under relevant local conditions has been described (Rajanayagam et al. 1999).

Commissioning of the unit enabled reduction of health risk in terms of crop irrigation and direct human exposure, and simultaneously reduced the risk of eutrophication which had in the past been responsible for blooms of algae and, occasionally, toxin-producing Microcystis ("blue-green algae") (Derry et al. 2003). In addition the removal of chlorine prevented the formation of possibly-teratogenic disinfection by-products (Hruddy 2009).

Following the preliminary health-risk assessment in 2005 using the limited range of parameters mentioned in the abstract, data collection continued for a further two years yielding four years of data for equal periods before and after the STP upgrade. During this data collection period the mean annual throughput remained relatively constant owing to unchanging irrigation demand during a time of almost continuous drought. The paper discusses the changes in effluent quality observed with passage through the Scheme's storage dams both before and after the introduction of IDAL process/tertiary treatment, with implications for open dam storage of high and low quality effluents in general.
Method

Monitoring points were fitted proximate to control points in the supply line leading to the horticulture precinct where experimental food crops demanding high quality water were under irrigation (Figure 1). These coincided with valved or pumped critical control points, allowing for cessation of supply should a water quality problem be identified. The indicated dams are basin-shaped, clay-walled open impoundments with a maximum depth of about 4.5 m, which have been in use for about 30 years with minimal maintenance. They offer good opportunities for sunlight exposure and aeration through wavelet action, and minimal wall erosion has been noted. It was estimated that there was a mean retention time of about 73 days in the first dam and 58 days in the second.

A minimal set of seven parameters (FC, TP, TN, BOD5, pH and SS) relevant to performance, health and ecological impact was selected for sampling. Samples were analysed by the Environmental Health Laboratory of the University of Western Sydney in compliance with standard methods (APHA 2005), field collection being consistent for method, day and time. Quality control involved submission of random samples to an external NATA accredited laboratory. Transient indicators pH and EC were monitored on-site using a monthly-calibrated Yeo-Kal 611® water quality analyser.

Median values were calculated and compared to the intervention action-threshold values adopted for the Scheme as shown in Table 1. In the absence of integrated agricultural and health action-threshold values for irrigation reuse schemes in Australia a consolidated set of values was established based on local and international guidelines and publications (ANZECC/ARMCANZ 2000; ARMCANZ/ANZECC/NHMRC 2000; Asano 1998; DEC NSW 2004; EPA Victoria 1993; Lazarova, Bahri 2005; NSW RWCC 1993; USEPA 1992; WHO 1989). This ensured that the experimental production of fruit and vegetables in the horticulture precinct complied with standards for safe salad crop production relevant to an equivalent commercial setting. Issues associated with intervention values in Australia will be discussed in a later paper.

Table 1. Received effluent quality before and after the STP upgrade.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STP effluent quality before dam storage (median value)</th>
<th>STP effluent quality after IDAL upgrade (median value)</th>
<th>Action-threshold value for most critical irrigation use (salad-crop irrigation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>240 cfu 100 mL⁻¹</td>
<td>0 cfu 100 mL⁻¹</td>
<td>10 cfu 100 mL⁻¹</td>
</tr>
<tr>
<td>TP</td>
<td>8.62 mg L⁻¹</td>
<td>0.02 mg L⁻¹</td>
<td>2 mg L⁻¹</td>
</tr>
<tr>
<td>TN</td>
<td>32.0 mg L⁻¹</td>
<td>4.1 mg L⁻¹</td>
<td>15 mg L⁻¹</td>
</tr>
<tr>
<td>BOD5</td>
<td>13.0 mg L⁻¹</td>
<td>2.0 mg L⁻¹</td>
<td>20 mg L⁻¹</td>
</tr>
<tr>
<td>pH</td>
<td>7.8</td>
<td>7.7</td>
<td>6.0 – 9.0</td>
</tr>
<tr>
<td>SS (TSS)</td>
<td>15.5 mg L⁻¹</td>
<td>2.0 mg L⁻¹</td>
<td>30.0 mg L⁻¹</td>
</tr>
<tr>
<td>EC</td>
<td>0.973 dS m⁻¹</td>
<td>0.930 dS m⁻¹</td>
<td>1.6 dS m⁻¹</td>
</tr>
</tbody>
</table>

Table 2. Changes in TF effluent quality prior to upgrade, with dam storage alone.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STP effluent quality before dam storage (median value)</th>
<th>STP effluent quality after IDAL upgrade (median value)</th>
<th>Action-threshold value for most critical irrigation use (salad-crop irrigation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>240 cfu 100 mL⁻¹</td>
<td>14.0 cfu 100 mL⁻¹</td>
<td>10 cfu 100 mL⁻¹</td>
</tr>
<tr>
<td>TP</td>
<td>8.62 mg L⁻¹</td>
<td>4.25 mg L⁻¹</td>
<td>2 mg L⁻¹</td>
</tr>
<tr>
<td>TN</td>
<td>32.0 mg L⁻¹</td>
<td>6.05 mg L⁻¹</td>
<td>15 mg L⁻¹</td>
</tr>
<tr>
<td>BOD5</td>
<td>13.0 mg L⁻¹</td>
<td>4.1 mg L⁻¹</td>
<td>20 mg L⁻¹</td>
</tr>
<tr>
<td>pH</td>
<td>7.8</td>
<td>8.5</td>
<td>6.0 – 9.0</td>
</tr>
<tr>
<td>SS (TSS)</td>
<td>15.5 mg L⁻¹</td>
<td>6.0 mg L⁻¹</td>
<td>30.0 mg L⁻¹</td>
</tr>
<tr>
<td>EC</td>
<td>0.973 dS cm⁻¹</td>
<td>0.837 dS cm⁻¹</td>
<td>1.6 dS cm⁻¹</td>
</tr>
</tbody>
</table>

Non-parametric of the data was determined and relevant tests applied to for significance in terms of the assumed statistical level (p=0.05), followed by box-and-whisker plotting using the same statistical application (SPSS®).

Results and Discussion

STP effluent quality changes following IDAL upgrade

Following the commissioning of the IDAL-process unit, significant improvements in median quality for effluent received by the Scheme occurred as shown in Table 1.

TF effluent quality changes with storage, prior to upgrade

Storage of the original TF effluent in the Scheme’s dams resulted in some improvement in median values for all parameters, with TN, an important indicator of eutrophication potential, removed to the point of compliance with the action-threshold limit. A 1 log (90%) removal of FC also occurred, approaching the limit for the most critical irrigation use, salad crop irrigation (Table 2).

Stored water quality changes by parameter

While median values for FC suggested low health risk, relatively high inter-quartile and total ranges showed that there were times when FC “peaks” occurred, suggesting a corresponding increased risk of pathogen passage through the system. For timely risk identification and intervention, including communication with stakeholders, a relatively high frequency of routine monitoring (weekly) was thus required (Attwater, Derry 2005; Derry, Attwater 2006).

Figure 2. FC (log) by control point, before and after upgrade. (Note: In this semi-log graph the y-axis zero point indicates the arithmetic zero).
Faecal coliform
The Australian Water Quality Guidelines establish an action-threshold value of 10 CFU (thermotolerants) per 100 ml in irrigation waters used for salad-crop irrigation via direct application, such as overhead irrigation (ANZEC/GAFMC/ANZ 2000). At the time of the study WHO recommended a far less stringent standard (1000 CFU/100 ml). The lower value was, however, adopted to account for the observed wide inter-quartile and total ranges in the local effluent (WHO 1999).

Median values (horizontals within each coloured box) indicated a better-than 1 log reduction with passage of the TF effluent through the Campus system. The wide inter-quartile and total ranges, however, showed that there were times when a “pathogen spike” could pass through the reticulation suggesting the accepted practice of using median values for small potable supplies to be inadequate for biologically active effluents (NHMRC 2004).

Following risk assessment, surface micro-jet irrigation was replaced by subsoil irrigation which introduced a 10-15 cm soil barrier, 70 cm barriers are known to achieve 2 - 3 log reductions (99.9% removal) of FC (Kadam et al. 2008).

While the IDAL upgrade resulted in the supply of a very high quality, stable effluent, FC increase occurred with passage through the Scheme’s dams. This was possibly due to flocks of birds, including duck, introducing faecal matter to the dams (Graczzyk et al. 2008). The possibility of natural increases in FC was unlikely but is undergoing further research.

Total phosphorus, total nitrogen and pH
Following the upgrade the nitrogen and phosphorus content of the effluent was considerably reduced (Figures 3 and 4). This has implications for irrigation runoff which might enter the Hawkesbury Nepean River contributing to eutrophication (Asano 1998).

The graded removal of phosphate from the TF effluent with passage through the dam and subsequent addition of phosphate to the IDAL effluent in the same dams is of interest suggesting that phosphate precipitated from the old effluent might have been stored in sediments to be later released on contact with the softer IDAL effluent. This led to the persistence of algal blooms in the final dam, despite the upgrade. It was found that pH increase was a useful indicator for anticipating this bloom in irrigation use and odour control (Weiner, Matthews 2003). While similar decrease in TN occurred with passage of the TF effluent, a corresponding increase with subsequent passage of the IDAL effluent was not observed. This suggests that while phosphates were removed from the old effluent by sedimentation, nitrates were probably removed by nitrification/denitrification in the presence of excess dissolved carbon.

An interesting paradox was associated with the improvement of effluent through IDAL process to result in very low nutrient levels. One pasture manager had estimated a saving of about $10,000 per annum in fertiliser costs when using the old, high nutrient effluent. Health and ecological advantages of a low nutrient water supply may have, however, offset this disadvantage suggesting a need for triple bottom line assessment of agricultural irrigation reuse schemes.

Biochemical oxygen demand, suspended solids and electrical conductivity
BOD₅, SS and EC (Figures 6-8) are frequently used to provide basic information on general operating performance and
threats in sewage treatment and storage systems (APHA 2005).

BOD results for both TF and IDAL effluents were within the action-threshold emphasising the limitations of using this indicator alone. In the relatively low-BOD TF effluent, the storage dams still exhibited some capacity for removal for BOD. Increase in BOD seen in the very stable IDAL effluent again suggests the introduction of extrinsic organic pollution.

Some removal of SS by physical settlement was taking place in the relatively turbid old effluent, but increases again occurred with passage of the new effluent through the same storage dams, possibly from sediment leaching with biomass increase or bird life contamination. Results for EC were consistently low, as expected from a non-industrial effluent. This also confirmed that the clay dam walls were relatively intact and an effective barrier to soil salinity which is known to occur in the region (Bowler 1976).

Conclusions
The research showed that recycled water impoundments should be regarded not merely as buffer storages, but as a continuation of the treatment train in which improvement or deterioration of water quality can occur with time, under the action of physical, chemical and biological factors. While storage in the Scheme’s dams had capacity to improve low quality effluent to the point where it met some recycling requirements, high quality effluent conversely underwent degradation when introduced into the same impoundments. This probably involved leaching of phosphates from old sediments and the addition of nutrient faecal matter from bird life, with accompanying algal growth.

The study suggested that basic operation and safety of recycled water storages can be monitored using a few well-established water industry indicators at a limited number of control points. Median data often accepted for small-scale potable impoundments are, however, inadequate for stored effluent and the analysis of measures of spread for all parameters is indicated. To detect short-term indicator excursions suggesting opportunities for pathogen transmission through systems, frequent monitoring is needed, again pointing to the need for small, economical indicator sets with potential for local analysis.

Health risk management associated with quality fluctuations in low quality effluent should be based on a multiple-barrier approach including the ability to divert water at strategic control points in the reticulation for reflux or additional stabilisation in buffer storage. Measures such as soil-irrigation barriers also need consideration. Ultimately food production hygiene and human exposure limitation will rely on good risk communication with stakeholders to provide effective information feedback systems.

While the study focused on surveillance (ongoing, routine monitoring), special monitoring is required if xenobiotics, pesticides, heavy metals and other persistent pollutants are to be detected and controlled in water intended for food-crop irrigation or for direct addition to water supplies (Echols et al. 2009). Specific bacterial, viral or protozoal monitoring is also needed where epidemiology suggests that local waterborne infections may exist. Other areas requiring special monitoring are algal blooms and their causes, odour problems, leaching of substances from sediments, nitrification-denitrification opportunities, and potential for wildlife contamination.
End-user interests also need to be studied with agriculturalists preferring high nutrient irrigation water and environmental and health managers preferring low nutrient levels. Removal of health indicators such as FC and Enterococci to a zero point is, however, unjustified and a range of intervention action-threshold limits should be established with a view to matching recycled water purity, and hence cost, to intended use.

While guidelines have recently been produced dealing with the direct addition of treated effluent to drinking water supplies (EPHC 2006), irrigation is likely to remain an important option, with food-crop irrigation allowing the water to reach its highest economic potential. Optimising the use of accessible treated effluent and stormwater resources will depend largely on the capacity of recycling schemes to safely store water, particularly largely untapped wet weather flows. In this regard the changes occurring in recycled water quality with storage remains an important area requiring further research.

Acknowledgments

The authors wish to thank Capital Works and Facilities and the Environmental Health Laboratory, UWS for sampling and analysis, and the Sydney Water Corporation for the provision of STP data.

The Authors

At the time of the study Dr Jane Aiken was a field technical officer for the Hawkesbury Water Recycling Scheme, University of Western Sydney. Currently she is environmental team leader with Billfinger Berger Services (Australia) Pty Ltd, and a private consultant specialising in soil science.

Chris Derry is Principal Researcher and Health Risk Analyst with CRC Irrigation Futures and WHO Collaborating Centre for Environmental Health Development, University of Western Sydney, specialising in safe water recycling and food crop irrigation. Email: c.derry@uws.edu.au (corresponding author).

Dr Roger Attwater is Senior Manager, Environment and Risk Management, with Capital Works and Facilities, University of Western Sydney. His background and interests focus on the integrated management and sustainability of environmental assets.

References


Appendix D:

Paper 4: Considerations in establishing a health risk management system for effluent irrigation in modern agriculture
Considerations in establishing a health risk management system for effluent irrigation in modern agriculture

CHRIS DERRY
School of Science and Health, University of Western Sydney, Locked Bag 1797, Penrith NSW 2751, Australia

(Received March 22, 2010; accepted in revised form June 7, 2010)

ABSTRACT

Treated sewage effluent is a valuable and reliable agricultural irrigation resource in areas of low or unpredictable rainfall. Its importance is likely to grow under the influence of global climate change. The use of this resource is not, however, without health risk which is difficult to estimate using data from standard microbial and physicochemical monitoring alone. A health risk management system enables risk reduction through hazard identification, risk characterisation and analysis, strategy development and implementation, intervention assessment and risk communication. In this process data from both risk assessment and routine technological monitoring are integrated to yield synergies. In addition to meaningful information is a need for intersectoral collaboration in making the right decisions. This can be achieved through the establishment of a multidisciplinary risk management team with members drawn from communities of practice. Examples from the University of Western Sydney (UWS) experience are used to support the suggestions made.

Keywords: health risk management, health risk assessment, water recycling, effluent irrigation, safe food production, communities of practice, climate change.

INTRODUCTION

Modern agricultural development in regions with low or unpredictable rainfall in conjunction with rapid adjacent urbanisation and population growth has reinforced the imperative for irrigating with recycled effluent as a water resource largely independent of climatic variability (Asano, 2002; Lazarova and Bahri, 2004). Effluent irrigation is, however, not without health risk but this can be reduced to acceptable levels if suitable management systems are in place (Attwater et al., 2006; Toze, 2006a).

For over 30 years the University of Western Sydney (UWS) has received effluent from the Richmond wastewater treatment plant (WWTP) for irrigation of lawns, sports fields, food crops and pasture for cattle, sheep, deer and horses in terms of an agreement with the Sydney Water Corporation (SWC) (Booth et al., 2003). While this long-term water reuse arrangement had been without recorded health incident, in late 2002 reports suggested deterioration of supply from the ageing and overloaded trickling-filter based WWTP. The SWC advised that a new, high capacity WWTP was to be commissioned in 2005 based on intermittently decanted aerated lagoon (IDAL) technology, but the interim use of an inevitably deteriorating supply was of concern.

In 2003 initial health risk assessment was carried out to determine the level of risk posed by the effluent. An outcome was the establishment of a health risk management system to coordinate effort and to attend to the reduction of risk to an acceptable level through application of a multiple barrier approach. The paper discusses considerations in establishing such systems, drawing on...
the UWS experience to illustrate salient points. Details of the risk assessment method and its outcomes are discussed elsewhere (Derry et al., 2006).

THE CASE FOR HEALTH RISK MANAGEMENT

There is convincing epidemiological evidence of disease transmission attributable to the use of raw sewage for irrigation (Ensink et al., 2006; Shuval and Fattal, 2003; Srinivasan and Reddy, 2009). WHO have set a precautionary ceiling of 1000 fecal (thermotolerant) coliform (FC) health indicator organisms per 100 mL of water for irrigation of crops likely to be eaten uncooked, and for irrigation of sports fields and public parks (Hespanhol and Prost, 1994). This is, however, only likely to be achieved by secondary or tertiary treatment of effluent, with subsequent disinfection using an agent such as chlorine, ozone, or ultraviolet light (Gray, 2005).

Countries such as the United States, Spain, Israel, and Australia have stricter criteria than WHO for crops eaten uncooked, with Australia setting an action ceiling of 10 or fewer FC and Israel having a multiple barrier approach aimed at achieving a similar standard. In the USA requirements vary widely by state, with some requiring no FC to be present (Lazurova and Bahri, 2004). It should be noted that the setting of criteria stricter than those established by the WHO could be seen as representing conservative health policy, given that there is little solid epidemiological evidence in the literature of elevated disease incidence where crop irrigation with properly managed secondary or tertiary treated effluent has been carried out.

On the other hand, there are many reports of disease outbreaks resulting from inadequate storage or management of water generally in agricultural settings where contamination with animal fecal matter has taken place. Recent occurrences have been related to changes in climate resulting in prolonged drought, when animal fecal matter has built up on land, followed by heavy rain with excessive wash-off into water reserves.

A notorious outbreak occurred months into the new millennium in the Canadian town of Walkerton, Ontario, when 2,500 residents developed bloody diarrhea ultimately resulting in seven deaths. The cause was E. coli O157:H7 which had entered the town well as a result of runoff from nearby agricultural land on which cattle manure had been spread. The judicial commission of enquiry found that unusual climatic events had flushed accumulated enterohemorrhagic organisms from fields and rusting pipework into the town water supply. It was reported that if the results of testing had been heeded the tragedy could have been avoided but there was no multidisciplinary management system in place to identify or act on unfavorable analytical reports. There was also no system for communicating risk information in a transparent way to facilitate stakeholder awareness and intervention (Danon-Schaffer, 2001; O’Connor, 2002).

A case closer to home for the writer was the unthinkable "boil water alert" sent out by NSW Health to three-quarters of the four million residents of metropolitan Sydney in 1998, when potentially pathogenic Giardia and Cryptosporidium parasites were found in the city’s main water supply (Loff and Fairley, 1998). Subsequent investigation suggested that the contamination had been caused by the interaction of risk factors, including the large number of farm and wild animals in the catchment, the removal or fire-destruction of natural vegetation, unusually long drought periods interspersed with short, heavy deluge, and lack of water filtration prior to chlorination. Infectious forms of the organisms are chlorine resistant, whereas they are largely removed by the age-old process of sand filtration or by air flotation of suspended matter with subsequent skimming. While transparency and early response by NSW Health and the SWC prevented human cases from being recorded, there was evidence that proactive risk assessment under an established risk management umbrella might have negated the crisis (McClelland, 1998).

At UWS, a case of heavy contamination of treated, stored effluent through bovine fecal runoff was identified during the initial risk assessment of the recycling system. Main components are shown in Fig. 1, with control points comprising shut-off valves and sampling taps strategically situated at the outflows of campus dams (CP). Median results for a series of preliminary samples are shown in Fig. 2. While the quality of the effluent improved with passage through the dams (CPs2), an approximately 4-log increase in FC was noted when relatively clean effluent flowed from the Turkey Nest dam (CP) into the Hillside dam (CP) (Derry et al., 2006).

This heavy on-site contamination of stored effluent was found to be due to the practice of abstracting treated effluent from the Hillside dam for wash-down of a cowshed, with subsequent waste return to the dam through an ineffective sedimentation trap, resulting in concentration of fecal matter in what amounted to a closed loop in the recirculation. The PC level observed for this dam was similar to that of low quality, undisinfected effluent, unsuitable for intended pasture irrigation in the presence of animals, despite the fact that water supplied to the storage dam had met the necessary criterion (ANZECC/ARMCANZ, 2000).

The hypothesis of some farm staff that there was little risk to humans because the fecal matter in the dam was of bovine and not human origin echoed the inac-
curate and dangerous lay sentiment revealed during the inquest into the Walkerton tragedy. Through a short-cut in correct manure disposal (dry spreading on land away from water resources) lactating cows, their milk, staff, students, and the public using an adjacent road had been exposed to both spray drift from overhead irrigators and residual water on soil and grass.

A multiple barrier approach was instituted, including cessation of the wash-down process, introduction to the dam of good-quality effluent with continued pasture irrigation to remove low quality effluent, a 5-day withholding period for cattle, limiting irrigation to 50 m from the road to contain spray drift, erection of signs advising of effluent irrigation, painting of all above-ground effluent pipes lilac, safety induction for all staff, students and contractors working in the area, and inclusion of the dairy farm manager and staff on the health risk management committee.

These three cases illustrate the high potential for contamination of stored water when agricultural or wild animals are in the area, and suggest the existence of a dangerous myth that animal fecal matter entering

Derry / Safe agricultural water recycling
water is somehow a "natural" occurrence and therefore not as much a concern as human fecal matter entering water. The UWS experience built on the myth with the assumption that treated effluent is already a degraded product which does not deserve the same storage care generally afforded to potable water.

A HEALTH RISK MANAGEMENT MODEL

From the cases discussed it is evident that effective health risk management needs to be participative. A good starting point is the development of a risk management model which establishes process and has capacity to bring participants together without bearing the structural stamp of any particular group or discipline. In the UWS example a cyclic model was developed (Fig. 3), based on the USA Ommen Commission report of 1997.

This cyclical model offers several advantages (Derry, 2003):

- It enables the risk management strategy to be regularly upgraded in response to feedback from intervention assessment.
- Being cyclic, the process can start at any stage, building on an existing initiative. For example, the agricultural operation might already have basic risk management strategy documented, and a newly formed risk management group could advance this to implementation, while at the same time carrying out preliminary hazard identification.
- Risk communication sits at the hub of the model, encouraging intersectoral exchange of information at all levels and stages.

KEY RISK MANAGEMENT ACTIVITIES

1. Hazard identification

This initiates risk assessment and involves the recognition of situations, practices, and environments likely to have negative impact on health. Use of an external analyst can circumvent political pressure and entrenched ideas effecting this important, formative stage of the risk management process. It involves field visits by the analyst, accompanied by local staff, and subsequent contextualization of observations and comments using existing reports, publications, and maps. The analyst produces a qualitative description of the hazards, with their locations, reasons for inclusion, and possible contributory factors. To reduce costs it might be possible to offer the assessment with publication rights to a university research department, increasing local transparency of process.

During this phase at UWS 23 preliminary hazards were identified, examples of which are shown in Table 1.

These three examples show that hazard identification...
Fig. 3. Cyclic health risk management model developed at UWS.

- is qualitative and relatively quick to perform;
- demands combined health and engineering knowledge at a substantial level and awareness of local conditions, such as regional disease endemicity and nature of disease vectors;
- yields meaningful results which alone could stimulate discussion, strategy development and intervention.

2. Risk analysis

This is a process in which hazards are awarded numerical values to enable risk ranking for prioritization. Bearing in mind that all human activities carry a certain level of risk, and that blanket intervention is therefore impractical, ranking is important in guiding efficient and accountable intervention. The simplest formula for risk is:

\[ r = p \times c \]

where

- \( r \) = risk
- \( p \) = probability or likelihood that a specific hazardous event will occur in a certain period of time
- \( c \) = consequence or outcome should that hazardous event occur

There are a number of approaches for assigning values to \( p \) and \( c \) in the calculation of \( r \) for each hazard, including the use of ordinal ranking tables, such as Tables 2 and 3 below, relevant to the UWS experience.

Values can be assigned in both tables between medi-
### Table 1
Examples of identified hazards, with reasons for their inclusion

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Reasons for inclusion</th>
<th>Contributory factors</th>
</tr>
</thead>
</table>
| Minor subsidence of dam wall adjacent to dairy causing shallowing, and vegetation growth at the water's edge | - Creation of environmental conditions (vegetation, shallow water, sunlight penetration, low gradient), likely to breed vector mosquito species (*Culex* and *Ochlerotatus*) for Ross River Viral Haemorrhagic Fever (RRVHF), which is becoming established in the area  
  - Indicator of bovine intrusion with potential to contaminate dam water with faecal pathogens (e.g. *Giardia*, *Cryptosporidium*)  
  - Increase in suspended solids (SS) through wall subsidence, and wave action in shallows  
  - Potentially more serious future structural damage to dam | - Presence of cows grazing on or near storage dam wall  
  - Incorrect wall structure (clay without gravel chip or other protective covering)  
  - Inadequate inspection and maintenance |
| Lack of awareness of recycled water risk by contractors working on the system | - Contractors (plumbers, pump service personnel, electricians) may be directly or indirectly exposed to effluent  
  - No sign-off on work performed, presenting potential hazard through cross-connection and contractor exposure opportunities  
  - Public liability issue for the University | - No printed information or safety induction with sign-off for contractors  
  - No inspection system with sign-off for completed work  
  - No inspection system with sign-off before back-filling of trenches  
  - No line pipe work with local and general signage. |
| Surface irrigation of citrus fruit (oranges, typically eaten raw), with potential access | - While oranges are part of experimental cropping, there is possible removal by staff and students, and members of the public over weekends and in evenings  
  - Potential health hazard through direct ingestion of effluent on surface of fruit through sucking of skin, production of zest, decorative use in salads, etc.  
  - Treatment plant effluent is currently low quality  
  - Final quality after passing through storage dams is currently unknown.  
  - Opportunity for barrier creation exists through change to subsoil irrigation | - No prohibition of access to the experimental area by public or students (unfenced area)  
  - No printed information or safety induction for staff and students, with sign-off  
  - Existing effluent supply from treatment plant requires improvement  
  - Stored water quality requires bacteriological/physicochemical assessment  
  - Irrigation system design incorrect  
  - Risk management team is needed to coordinate efforts |

### Table 2
Example of ordinal ranking table for estimation of probability (p) for each risk factor

<table>
<thead>
<tr>
<th>Median Value of p</th>
<th>Descriptors</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare</td>
<td>Exposure event just conceivable but probably rare.</td>
<td></td>
</tr>
<tr>
<td>Unlikely</td>
<td>Exposure event possible but not expected in the short-term.</td>
<td></td>
</tr>
<tr>
<td>Likely</td>
<td>Exposure event will probably happen in the near future.</td>
<td></td>
</tr>
<tr>
<td>Highly likely</td>
<td>Exposure event will occur very soon or has occurred often.</td>
<td></td>
</tr>
<tr>
<td>Inevitable</td>
<td>Exposure event now occurring or occurs with great frequency.</td>
<td></td>
</tr>
</tbody>
</table>
3. Strategy development

The idea of having a risk management model that did not bear the stamp of any particular administrative or disciplinary group was also applied to the structure of the risk management team. To achieve this, representation was called for from "communities of practice" (COPs), which were existing clusters of individuals from mixed disciplinary backgrounds, but sharing a common interest. For example, the horticulture COP consisted of horticultural scientists, students, managers, administrators, and technicians with a common interest in the irrigation of fruit and vegetables for research and teaching projects. The group’s concerns regarding the unauthorized removal of experimental produce impacting on research outcomes overlapped with the Health Risk Management Team's concern that practice might transmit infection, leading to opportunities for collaboration in controlling a high risk activity (Attwater and Derry, 2005).

The Team initially met every other month, with meetings becoming less frequent as implementation of strategy by the University’s Department of Capital Works and Facilities progressed. Identifying field operatives with the will and resources to action the findings of a risk management team is a vital part of the process. An overarching risk management strategy was the adoption of a multiple-barrier approach to risk reduction, functional examples of which are given in the following section.

4. Strategy implementation

Part of the implementation strategy was the development of operational protocols based on the generic model shown in Fig. 4, as adapted from the ANZECC/ARMCANZ guidelines, 2000.

Examples of implemented multiple barrier approaches to prevent human exposure to low quality treated effluent in the horticulture precinct included:

- changing the system from surface irrigation to subsoil irrigation, introducing a soil barrier to the passage of microorganisms;
- fitting of keyed taps to limit access to irrigation effluent;
- displaying cautionary notices at taps and at the entrance to the campus;
- painting of existing surface pipework lilac, and using lilac piping for all above and below ground replacement work;
- emailing cautionary messages to COPs when water quality was low;
- introducing safety induction for all students;
- introducing inspection and sign off on all work performed by contractors;
- prohibition on most susceptible individuals (MSIs), including children from the University crèche, visiting the precinct during weeks when water quality was low.
- weekly monitoring of the recycled water supply for health and operational indicators;

Derry / Safe agricultural water recycling

<table>
<thead>
<tr>
<th>Median Value of $c_0$</th>
<th>Descriptor</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insignificant</td>
<td>No injury or inconvenience to individuals. No treatment of any sort required. No possible impact on groups of people and no further assessment required.</td>
</tr>
<tr>
<td>3</td>
<td>Minor</td>
<td>Short-term health effect or inconvenience requiring health screening or first aid only, or some impact on groups possibly requiring further environmental health (EH) assessment</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
<td>Medium-term health effect requiring visit to clinic for observation, tests or treatment by nurse or GP, or impact on groups requiring mandatory EH or other assessment</td>
</tr>
<tr>
<td>7</td>
<td>Major</td>
<td>Long-term health effect requiring hospital admission or specialist treatment, or mass impact on groups requiring urgent EH or other assessment or statutory notification</td>
</tr>
<tr>
<td>9</td>
<td>Extreme</td>
<td>Permanent health effect or death, or epidemic or catastrophic impact requiring complex, extensive or long-term EH action, clean-up, or removal of people from the area</td>
</tr>
</tbody>
</table>

Table 3
Example of ordinal ranking table for estimation of consequence ($c$) for each risk factor
Define primary management strategy

Determine guideline criteria for relevant risk factors

Test estimated risk factor values against guideline criteria

Decision Framework

Low risk (continue routine monitoring)

Potential risk (Characterise risk, explore/implement corrective actions, conduct further assessment)

High risk (Initiate immediate, best-practice corrective actions)

Low risk (continue routine monitoring)

Fig. 4. Example of a risk management decision-tree used to guide strategy implementation.

- ultimate upgrading of the treatment plant in 2005 to a new IDAL plant which supplied tertiary treated, filtered and disinfected effluent of a consistently high quality.

5. Intervention assessment

Intervention assessment was carried out to ensure that strategy was correctly implemented and to identify and assess new hazards which subsequently came to the fore. Initially this was conducted by a risk management steering group, but as ongoing surveillance structures were put in place the UWS Department of Capital Works and Facilities took over the function. Assessment of large works, such as the installation of lilac pipelines, was carried out visually, while routine monitoring of health and operational parameters was carried out by a technician using field equipment for the physicochemical parameters, with analysis of the health (microbial) samples at the UWS Environmental Health Laboratory.

6. Risk communication

A survey of knowledge, attitudes, beliefs, and practices (KABP) of staff, students, and the public living adjacent to the campus was carried out to assess the type of information and approach needed for effective risk communication (Derry and Attwater, 2006).

To communicate level of exposure risk to workforce COP members on a regular basis, risk management decision-trees were pictorially adapted to provide readily understood information. For example, FC levels were communicated in the form of a traffic light which showed green when FC were within the action threshold, amber when there was a 1 log exceedance, and red when there was a 2 log exceedance.

In risk management meetings, presenters used pictorial slide presentations to communicate information and were asked to present in discipline-neutral (de-jargoned) language as far as possible. Team meetings were
informal events and COP representation went a long way to negating professional status barriers known to have impeded intersectoral achievement elsewhere (Meyer, 2002).

**ROUTINE MONITORING OF WATER PARAMETERS**

The value of quantitative data from scientific analysis in enhancing the risk assessment process has been mentioned. A brief discussion of technological monitoring of parameters at the UWS scheme follows.

**Indicators**

Research was carried out on a wide range of indicators to select an economical subset which would generate sufficient data for routine operation while also giving information for health risk intervention. This subset is shown in Table 4.

Had effluent quality been consistent, monthly monitoring at each of the control points would have been sufficient, but wide interquartile and total ranges in the health indicator data suggested a need for weekly monitoring to detect indicator spikes when pathogens might pass through the system.

Monitoring was carried out by a technician using a Yoo-Kal 611® field water quality analyser for physico-chemical parameters and Hach Drel® field spectrophotometer for phytonutrients nitrate and phosphate. Tests for BOD and FC were carried out in the Environmental Health Laboratory of the University using 5-day dilution and membrane filtration methods (APHA, 2005).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Interpretation (source APHA, 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faecal Coliform (FC)</td>
<td>Indicates level of recent faecal contamination and hence potential for presence of pathogens, requiring interpretation in context of regional disease endemicity. Today E coli (EC) indicator may be used because of the case of the new analytical method. EC is also preferred by some analysts because it is more indicative of human (as opposed to animal) contamination than FC. Where FC monitoring has been changed to EC, higher values can be expected owing some dislocation in monitoring data. <em>Enterococcus</em> should be used for low quality effluents because of the ability of relevant organisms to survive harsh and competitive environments, although they are not as well associated with pathogens as the coliforms (FC and EC).</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (BOD₅)</td>
<td>Indicates level of secondary treatment and hence stability, potential organoleptic offensiveness and chlorine demand</td>
</tr>
<tr>
<td>Suspended Solids (SS)</td>
<td>Indicates level of primary treatment determining clarity, presence of clumped organisms and chlorine demand</td>
</tr>
<tr>
<td>Conductivity (Cond)</td>
<td>Indicates level of chemical pollution of water by industry, and salinity. Proxy for Total Dissolved Solids (TDS)</td>
</tr>
<tr>
<td>Temperature (Temp)</td>
<td>Indicates risk potential for mesophilic pathogen increase in hot climates through growth in storage</td>
</tr>
<tr>
<td>pH</td>
<td>Increase in pH is indicative of carbon dioxide removal by photosynthesis, and therefore indicates algal growth or eutrophication potential in storages, when read at a fixed time of day. Also used for correction of BOD result. May be automatically carried out where electronic field monitoring equipment is used.</td>
</tr>
<tr>
<td>Total nitrogen (TN)</td>
<td>Phytonutrient indicating eutrophication potential in storages.</td>
</tr>
<tr>
<td>Total phosphorus (TP)</td>
<td>Phytonutrient indicating eutrophication potential in storages.</td>
</tr>
</tbody>
</table>

*Derry / Safe agricultural water recycling*
Monitoring criteria

Results for water tests were directly compared with selected criteria for different types of irrigation use, based on a range of local and international guidelines, in the absence of consolidated health guidelines for agricultural irrigation in Australia. The criteria relating to fecal coliform indicator (FC) are shown in Table 5, and are largely based on the existing Australian/New Zealand guidelines for fresh and marine water (ANZECC/ARMCANZ, 2000).

Where the quality of irrigation water underwent short-term deterioration, flow could be arrested at control points and water redirected to areas where a lower quality was acceptable for the intended use in that sector of the agricultural scheme.

Criteria can vary considerably from country to country, largely on the basis of disease endemicity (the entrenched existence of a specific communicable condition in a local area). For example, Israel and Australia, which do not have high endemic worm infestations of human populations, do not have a requirement for helminthic eggs in irrigation water, whereas WHO guidelines, which must address safe irrigation needs in non-industrialised countries with generally heavy worm infestations, set a standard of no more than one worm egg per liter tested (Lazarova and Bahr, 2004).

Local water authorities in most dry countries, in fact, find it difficult to comply with national water criteria at certain places and times and it is for this reason that guidelines, rather than mandatory regulations, are set. Surprisingly, since 1978 Israel has had strict regulations on recycled water used for agricultural irrigation despite the fact that only secondary treatment, with some additional barrier control, is required. Given these provisions it is the author’s opinion that there might be times and places where compliance is not practical, reinforcing the need for universal risk assessment and management as a supportive approach. It is of interest that both the WHO guidelines and Israel’s regulations place some reliance on storage of treated water as a tertiary treatment, and in this regard the following comment is offered based on the HWRS experience.

The dramatic change in effluent quality used in the UWS scheme before and after 2005, when the high performance IDAL WWTP was commissioned, gave opportunities for study of changes in both low- and high-quality effluents with storage (Aiken et al., 2010).

Prior to completion of the new plant, the low-quality effluent underwent some improvement with storage in the UWS dams, the FC indicator showing a better than 1 log median reduction, as shown by the three left hand box-and-whisker plots in Fig. 5. For interpretation of this result it must be noted that storage involved a 131-day mean retention time in two well-aerated and sunlit, basin-shaped dams, with a maximum depth of 4.5 m and some wavelet action. There was low rainfall during the total monitoring period because of an eight-year drought.

Following the treatment-plant upgrade FC in the effluent consistently approached zero, but subsequent storage in the irrigation scheme’s dams resulted in an FC increase, thought to be due to fecal contamination by wild birds frequenting the dams. This topic, and the possibility of FC growth with temperature in storage, is undergoing further research.

Pathogen testing

The question of whether to test for pathogens in recycled irrigation water often arises. The commonly used bacterial indicators FC (TC), E. coli, and to some extent Enterococci, however, give an excellent indication of pathogenic presence in water (Horan, 2003) and costly testing for pathogenic intestinal bacteria is probably unnecessary in routine crop irrigation monitoring. In a comprehensive study within the agricultural setting where a range of pathogenic bacteria and protozoa were matched against a number of health indicators, “in-

<table>
<thead>
<tr>
<th>Recommended use</th>
<th>FC (colony forming units/100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silviculture, turf, cotton, etc. (with restricted public access)</td>
<td>&lt;10,000</td>
</tr>
<tr>
<td>Pasture and fodder (grazing animals except pigs and dairy)</td>
<td>&lt;1,000</td>
</tr>
<tr>
<td>Pasture and fodder (dairy animals, with five day withholding period)</td>
<td>&lt;1,000</td>
</tr>
<tr>
<td>Human-food crops, indirect contact with water (trickle or subsoil irrigation, or items peeled before use, or sold cooked or processed)</td>
<td>&lt;1,000</td>
</tr>
<tr>
<td>Pasture and fodder (dairy animals, no withholding period)</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Human food crops (eaten raw), and direct human contact with water</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>
stances where a pathogen was detected in the absence of detectable bacterial indicator were extremely infrequent and the fecal indicators were also found to be good surrogates for protozoa (Wilkes et al., 2009).

Two protozoal (single-celled animal) parasites of particular concern in treated effluents virtually internationally are *Giardia lamblia* and *Cryptosporidium parvum*, which are secreted in large numbers by infected humans and animals, often as symptomless carriers. While settlement and thorough sand filtration during water treatment removes most of the infectious cysts/oocysts, they are resistant to chlorination (Gray, 2005). With regard to these parasites, chlorination of effluent therefore becomes academic, whereas storage in dams that reduce suspended solids (SS) and organic matter could be regarded as an important part of a multiple barrier approach. Contamination of dams with animal fecal runoff or wild animal feces, however, could dramatically increase levels of the parasites. In the case of both parasites, monitoring of SS, BOD, and FC is more practical than the costly and sometimes inconclusive monitoring for the parasites themselves.

The relationship between coliform indicators and enteric viruses is not always a reliable one. Enteroviruses are many orders of magnitude smaller than bacteria and some survive tertiary wastewater treatment including chlorination. Norwalk virus, for example, which causes severe epidemic diarrhea and vomiting with little induced immunity, requires a massive 5–6 mg L\(^{-1}\) chlorine for 30 minutes for inactivation, a level seldom achieved in potable water or wastewater treatment (Gray, 2005). Despite all precautions, the virus can therefore be found in treated town supplies during epidemics, and costly testing for it in irrigation water, particularly at sites where multiple barrier precautions are already in place, appears both academic and unnecessary.

**Advanced chemical monitoring**

There is much international debate about the hazard of chemicals in effluent used to irrigate crops, where exposure through ingestion would occur at low levels but for prolonged periods.

Heavy metals are a real concern, but are associated more with industrial than residential wastewater and tend to be precipitated and removed in sludges by primary and secondary treatment. Studies of crop irrigation with effluents containing heavy metals have, in any event, shown low plant uptake (Toze, 2006b), suggesting no need for routine on-site monitoring, particularly where WWTPs data already includes information on these substances.

The presence of persistent pollutants in effluent, such as endocrine-disrupting chemicals and pharmacologically-active compounds, is sometimes dismissed as unimportant because levels are lower than those generally used to treat humans (Toze, 2006b). Caution is needed, however, because of the potential for chronic exposure in consumed food and water, and the fact that pregnant
women and children are inadvertently exposed. While this remains an important area for research, it probably lies outside the scope of routine monitoring for daily risk management of crop irrigation schemes.

CONCLUSIONS

Recycled urban effluent is a valuable and reliable agricultural irrigation resource in areas of low or unpredictable rainfall, and its strategic importance is likely to grow under the influence of global climate change. The use of the resource is not without health risk, but this can be addressed through the implementation of a local health risk management system.

Effluent quality will depend largely on the level of treatment it receives prior to its delivery at the irrigation site. While raw effluent is a high-risk product transmitting a wide range of human pathogens and parasites, treatment to secondary level without chlorination will provide some protection against a range of diseases. Criteria set for agricultural irrigation in many countries, however, require chlorination or other disinfection to achieve consistent compliance.

Even high-quality effluent has considerable capacity for re-contamination once delivered to the agricultural site. This is particularly so where the water is stored in open impoundments and has potential to receive fecal runoff from land occupied by farm or wild animals, or where the water is frequented by wild birds. These and a range of other problems cannot be proactively identified through routine technological monitoring alone, but may be easily identified through qualitative hazard assessment as a starting point for quantitative risk assessment. Data from technological monitoring can be fed into the risk assessment process resulting in synergies which enhance intervention strategies and outcomes.

In risk assessment, interdisciplinary collaboration by a number of disciplinary and functional sectors is usually needed to make sense of a complex array of mixed data. At UWS this was achieved through the establishment of a multidisciplinary and multi-levelled risk management committee involving the identification and participation of local communities of practice. An indication of the success of this committee was that out of the 24 amelioration strategies identified in preliminary risk assessment, 10 were actioned within six months, with a further 10 actioned within the next 18 months. Following this the new WWTP was commissioned, resulting in a high-quality disinfected tertiary effluent suitable for safe application to all crop types, including high-value salad crops.

Establishing a risk management system at UWS was an important part of ensuring duty of care towards staff, students, contractors, and the public, and facilitated the development and transfer of technology to effluent irrigation schemes operating elsewhere.

REFERENCES

Derry, C. 2003. Risk assessment of wastewater reuse on Hawkesbury Campus, University of Western Sydney Phase 1: hazard identification, risk analysis, unsafe practices, priority actions, general safeguards and controls. ICEM Research Group, Sydney, Australia.
Lazarova, V., Bahri, A. 2004. Water reuse for irrigation: agric-
culture, lands, and turf grass. CRC Press, New York.
Appendix E:

Paper 5: Regrowth of enterococci indicator in an open recycled-water impoundment
Regrowth of enterococci indicator in an open recycled-water impoundment

Chris Derry a,⁎, Roger Attwater b

a School of Science and Health, University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 2751, Australia
b Capital Works and Facilities, University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 2751, Australia

HIGHLIGHTS
• The supposition that enterococci faecal-indicator organisms do not multiply in open water impoundments was challenged.
• The resultant risk of false-positives leading to downgrading or over-chlorination of stored recycled water was identified.
• Ambient temperature and total dissolved carbon were identified as primary growth factors for the indicator.
• Nitrate and phosphate were not found to be growth-limiting. Rainfall and duck presence also did impact on numbers.
• A formula for the indicator-temperature relationship was derived for food-production and climate-change modelling.

ARTICLE INFO
Article history:
Received 21 June 2013
Received in revised form 27 July 2013
Accepted 27 July 2013
Available online 2 September 2013

Editor: Damien Barcelo

Keywords:
Health risk assessment
Indicator regrowth
Enterococci indicator
Water recycling
Climate change
Sustainable agriculture

ABSTRACT
The purpose of the research was to assess the potential for enterococci faecal-indicator to regrow in recycled water while under environmentally-open storage. Regrowth would result in false-positive indicator results with possible downgrading, rejection or over-chlorination of recycled water. The research setting was the main 93-megalitre storage impoundment of the Hawkesbury Water Recycling Scheme in Sydney’s North West, receiving tertiary treated (chlorinated) effluent from the Richmond sewage treatment plant. The water is used to irrigate horticultural food crops, pasture for dairy cattle, sheep, deer and horses, and for the maintenance of lawns and sports fields. Highly significant positive relationships were noted in multivariate analysis between indicator counts and the growth factors atmospheric temperature and UV254 adenosine (p = 0.001 and 0.003 respectively). Nitrate and phosphate did not show significant relationships suggesting that these nutrients may not be growth-limiting at levels found in recycled water. Rainfall and wild duck presence did not appear to have an impact on enterococcal growth in the study. The overall predictive power of the regression model was shown to be highly significant (p = 0.001). These findings will assist in recycled water monitoring and the revision of guidelines, with potential for the reduction of the chlorination by-product burden on the environment. A formula derived for the relationship between the indicator and atmospheric temperature could be used in food-production and climate-change modelling.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Enterococci indicator (ENT) is increasingly being used to assess water quality in complex environmental settings because of its resistance to inactivation when exposed to micro-ecological and chemical challenges, and its ability to accurately reflect the presence of pathogens (Llubé et al., 2005; Wu et al., 2011). It is already in widespread use as an indicator of the quality of marine and other recreational waters internationally, and in recent years has become an important indicator in water recycling where safe irrigation of food and fodder crops is to be ensured (Benami et al., 2013; Chevermont et al., 2013; Poma et al., 2012).

A required property of faecal indicator bacteria (FIB), such as total coliform (TC), faecal coliform (FC) Escherichia coli (EC) and ENT, is that they do not give false negative or positive results. To avoid false negative results, it is important that FIB remain viable in recycled water so that the original water quality or subsequent contamination event is accurately reflected. This is problematic in environmentally-open water storages, such as large recycled-water storage dams, because microbiological and biochemical competition continues following treatment, which is aimed primarily at the removal of pathogens. Exposure to environmental factors such as low temperature, sunlight, wave action, oxidation and settlement further threatens indicator organism survival (Asano, 1998).

With simplified assessment approaches, EC has become the most widely used indicator for drinking water quality but it is readily inactivated when stored in environmental settings. FC provides a
broader monitoring alternative but the group includes varying proportions of EC, introducing a reliability issue (Blaustein et al., 2013; Jamieson et al., 2004). For this reason both EC and FC are regarded only as indicators of recent faecal contamination, then in relatively pure water, with ENF being increasingly incorporated into monitoring schedules for non-potable water types, including recycled water.

While there are a number of publications concerning the inactivation of enterococci in the open environment, few studies have dealt with regrowth, which would lead to false positives being recorded if terms of fixed monitoring criteria (Chowdhury, 2012; Post, 1970). This lack of information appears to have resulted in a false sense of security, with a number of influential texts advising that environmental regrowth is unlikely (Bartram and Rees, 1999; Hurst et al., 2007; Mara and Horan, 2003; Nollet, 2007; World Health Organization, 2011).

The occurrence of false positives could give rise to unnecessary downgrading of recyclable water for less productive agricultural uses, such as turf irrigation instead of food crop or pasture irrigation. An alternative response aimed at sustaining the intended use is hyper-chlorination at the source, resulting in the generation of disinfection by-products, with potential ecological and public health impacts (Ritter et al., 2002; Sun et al., 2009).

The aim of the present study was therefore to investigate the potential for ENF regrowth in recycled water stored in an environmentally-open impoundment, in terms of a range of related growth factors.

2. Data and methods

2.1. Locality and parameters

Water quality data relating to the primary storage dam (Fig. 1) of the Hawkesbury Water Recycling Scheme (HWRS) was retrieved from the relevant data archive for the period March 2003 to December 2008. The scheme receives tertiary-treated (chlorinated) effluent from the Richmond sewage treatment plant (STP) in terms of a long-standing agreement with Sydney Water Corporation, the sewage catchment being primarily residential. The water is used for agricultural and horticultural irrigation including food crops, pasture for dairy cattle, sheep, deer and horses, and for the maintenance of lawns and sports fields. During this period extensive data had been collected for the development of a risk management system, after which data collection was limited to a routine monitoring subset (Derry et al., 2006; Derry, 2011).

The above ground, clay-lined dam is 200 m wide and four metres deep with a 93 megalitre capacity and a 1.35 megalitre median daily through-flow. It is maintained between 80% and 100% capacity under a pumped, automatic control system regulating both input and output. The environmental parameters based on the literature for FIB growth in potable water reticulations included water temperature (Tempwtr), the related mean ambient air temperature (Tempwtr), UV254 filter and unfiltered as proxies for dissolved and total organic carbon, total nitrogen (TN), total phosphorus (TP), dissolved oxygen (DO), biochemical oxygen demand (BOD5), total suspended solids (TSS), electrical conductivity (EC) and rainfall (American Public Health Association (APHA) et al., 2012; Chowdhury, 2012; Gardini et al., 2001).

2.2. Method

Two study designs were considered, the first being cross-sectional, based on the correlation of change in ENF between the dam inlet and outlet with growth factors, the second being longitudinal based on the changes in ENF values under the action of growth factors observed in the region of the dam outlet with time.

![Fig. 1. Hawkesbury Water Recycling Scheme main storage dam (lower left) and Richmond sewage treatment plant (upper right) (Coordinates — 33.610, 150.763) ©2013 Google.](image-url)
Following preliminary assessment, problems relating to the viability of the first design were revealed, with hydrological evaluation indicating a 69-day retention period for a hypothetical water "parcel" passing between the inlet and the outlet. This was too long for the estimation of meaningful summary indices for temperature and rainfall exposure, given the short-term variability of these factors. In addition, no significant correlation was found between FIB indicator counts at the inlet and outlet with applied lag periods of 0 to 69 days, suggesting indicator inactivation to be an important confounder in terms of the first design.

A fundamental assumption of the second design was that despite STP disinfection to a relatively high standard (median FC count 30 CFU/100 ml) and subsequent indicator inactivation, a few enterococci could short-circuit the dam, possibly in wind-driven surface films, to seed the water in the vicinity of the outlet, enabling regrowth. The literature records examples of regrowth of FIB and pathogens at suboptimal temperatures from a minimal number of seeded organisms, given a food-rich medium (Costan-Longares et al., 2008; Van Der Linden and Van Impe, 2012). One environmental study was able to record increase in ENT within 24-h in a lagoned raw sewage, which would have presented a carbon-rich food source (Post, 1970).

Given the challenges to the viability of the first design and the theoretical support for the second, the second design was selected.

2.3. Water sampling and data collection

According to the data archive a total of 267 weekly samples had been taken representing an 89% sampling coverage for the period. The same technician carried out all sampling procedures during the period with analysis by Australian Laboratory Services (ALS), an accredited member of the National Association of Testing Authorities (NATA). Transient indicators EC0nd, DO and Tempwater had been field-monitored using a Yeo-Kal 61® water quality analyser.

Standard methods incorporating quality control procedures had been required by the laboratory for sampling, transportation and analysis, and additional random QC checks on certain ALS results were carried out at the UWS Environmental Health laboratory (American Public Health Association (APHA) et al., 1999).

The samples had been taken from the 160 mm diameter pressurised, 1m3 outlet line from the dam by means of a locked sampling tap 50 m downstream from the dam, the dam take-off being a foot valve suspended 1 m below the surface of the water from a float anchored 13 m from the dam’s Western edge. Sufficient pumping time had been allowed to ensure mixing in the pipeline which was in frequent use for transferring water to the service dams. This encouraged homogeneity of the sample and limited pipe-biofilm capture.

Weekly monitoring results had been consolidated into an annotated electronic data base in Excell® spreadsheet format. Data for rainfall and Temp air (the mean of the daily maximum and minimum air temperatures) were obtained retrospectively from the Australian Government Bureau of Meteorology (BOM) electronic archive for the Royal Australian Air Force weather station, located 2.3 km from the research site.

2.4. Data transformation and statistical approach

The data for ENT were log10 transformed to accommodate numerical values from 1 to 2000 CFU, and a small constant (0.5) added to zero values to facilitate inclusion in logarithmic data for analysis (McDonald, 2008). Cases showing null values were removed and the data cleaned by stripping outliers identified by normality and kurtosis plotting. A final set of 110 matched variables (cases) distributed uniformly over the study period was obtained for regression analysis.

Linear bivariate plotting was performed, with analysis using Pearson’s product moment correlation method to indicate strength of relationship within dependent and independent variable pairs. This was followed by multiple regression analysis for significance of the overall model, and of individual variable pairs with standardisation applied to dependent variables in terms of a constant.

Three of the 11 environmental variables (TN, TP and TSS) were excluded from multivariate analysis because relevant data had been collected on a monthly as opposed to a weekly basis, presenting a different level of data resolution. Matrix inversion instability was reduced by adopting Tempair as analogue for Tempwater, and UV254 untreated as analogue for UV254 filtered. Tempair was selected in preference to Tempwater in multicollinearity control, being the primary environmental variable offering a high level of resolution based on daily data collection by the BOM. This facilitated modelling of thermal lag between air and water for refinement of the regression model, as outlined in Appendix A. A high level of correlation (r = +0.99) was observed between filtered and unfiltered UV254 values, justifying the use of UV254 untreated as proxy.

Out of the 11 environmental variables available for bivariate analysis this produced six representative variables for multiple regression analysis. Excel® was used for all data storage, manipulation and presentation, in keeping with the format of the original data archive, with bivariate and multivariate analyses carried out using Minitab® 16.

3. Results

3.1. Bivariate linear regression analysis

The results of bivariate correlation between ENT and the 11 environmental parameters are shown in Table 1.

Tempair and Tempwater showed moderate positive correlations with ENT, the former correlation being marginally stronger, probably because of adjustment for thermal lag and indicator incubation enabled by the high resolution BOM climate data. The relationship between ENT and Tempair could be represented by the equation:

\[ y = 0.066x - 1.249 \]

This suggests that for each 15.2 °C rise in air temperature a 1-log (tenfold) increase in ENT would occur across the recorded temperature range. Although at a low level, consistent positive correlations with the majority of other environmental factors were also recorded. Scattergrams showing the positive relationship between ENT and Tempair and Tempwater are presented as Figs. 2 and 3. Contributing to the strength of correlation observed with air temperature is the large number of counts of 1 CFU/100 ml in autumn and winter when the median temperature was below 15 °C, with no counts occurring at this level in spring and summer when the median temperature was above 20 °C.

3.2. Multiple regression analysis

The results of multiple regression analysis are shown in Table 2. Two of the individual environmental variables (Tempair and UV254 untreated) predicted changes in ENT with a very high level of statistical significance.

<table>
<thead>
<tr>
<th>Environmental parameter</th>
<th>Pearson’s correlation coefficient (r)</th>
<th>Strength of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>0.55</td>
<td>Moderate</td>
</tr>
<tr>
<td>Water temperature</td>
<td>0.51</td>
<td>Moderate</td>
</tr>
<tr>
<td>UV254 treated</td>
<td>0.38</td>
<td>Low</td>
</tr>
<tr>
<td>UV254 untreated</td>
<td>0.37</td>
<td>Low</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>0.55</td>
<td>Low</td>
</tr>
<tr>
<td>Total suspended solids</td>
<td>0.34</td>
<td>Low</td>
</tr>
<tr>
<td>Rainfall</td>
<td>0.25</td>
<td>Low</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>0.22</td>
<td>Low</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>0.22</td>
<td>Low</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>0.00</td>
<td>Very low</td>
</tr>
<tr>
<td>Biochemical oxygen demand</td>
<td>-0.05</td>
<td>Very low</td>
</tr>
</tbody>
</table>
Fig. 2. Relationship between air temperature and enterococci indicator (ENT).

(p = 0.001 and 0.003 respectively) in regressions standardised for the co-effect of other environmental variables (Table 2).

The overall predictive power of the model incorporating six degrees of freedom (based on correlation of ENT with Temp\textsubscript{air}, UV\textsubscript{254 unfiltered}, rainfall, DO, EC\textsubscript{ond} and BOD\textsubscript{5}) was also highly significant (p = 0.001), with the six environmental variables accounting for a substantial 34.9% of the variation in enterococci counts, in terms of the observed, adjusted R-square value.

4. Discussion

The highly significant relationships identified between ENT indicator and the two environmental variables Temp\textsubscript{air} and UV\textsubscript{254 unfiltered} suggested that indicator regrowth had occurred in the open-environmental body of recycled water under the action of temperature and given the available carbon food source.

A known laboratory growth requisite for FIB including enterococci is a mesophic temperature range (Lebloffe and Pierce, 2010). Growth rate varies markedly at different temperatures within this range, however, with enterococci growing optimally between 37 and 40 °C but undergoing rapid decrease to zero growth with incubation temperature increase up to 50 °C. With temperature decrease below 40 °C, however, a sharp drop in growth occurs far more gradually, with optimal growth rate being only halved at 25 °C and quartered at 14 °C (Gardlini et al., 2001; Van Der Linden and Van Impe, 2012). As dam temperatures in the study ranged between 20 and 28 °C in the summer, and 10 and 17 °C in the winter, there was ample opportunity for temperature-induced growth of enterococci in the warm-temperate area given the presence of a carbon food source. Given this, the findings of the field study, while challenging information found in WHO guidelines and in a considerable body of textbook literature, are not surprising.

Research on organic carbon as a limiting factor for FIB growth in environmentally-open water storages is rare (Chowdhury, 2012), but there are numerous journal reports relating regrowth of FIB, including enterococci, to carbon source in closed potable water systems, lending credibility to the environmental study findings (Carter et al., 2000; Escobar et al., 2001; Jemba et al., 2010; Lechevallier et al., 1991; Zhang and DiGiano, 2002).

It has been suggested that increase in temperature in drinking water reticulation has an effect on FIB growth by increasing biomass and hence available carbon (Niquette et al., 2001). In the present study, however, temperature was shown to act independently of UV\textsubscript{254} as a potential biomass proxy, suggesting that this relationship was not operating.

Growth factors other than temperature and UV\textsubscript{254 unfiltered} did not show statistically significant correlation with ENT in multivariate analysis, but showed a consistently positive relationship in bivariate analysis, suggesting the possible presence of a low-level supportive role.

The lack of a significant relationship of ENT with the important bacterial nutrients nitrate and phosphate suggests that the levels found in the recycled water were sufficiently high for them not to be growth limiting. It is of interest, however, that phosphorus showed a stronger correlation than nitrogen (r = +0.35 and +0.22 respectively), as phosphorus is reported in the scientific literature as being the more important growth limiting substance in closed, potable water reticulation systems (Sathasivan and Ohgali, 1999).

In studies elsewhere rainfall was significantly related with FIB in water distribution systems, presumably because of first-flush events carrying water from faecally-contaminated land into impoundments feeding potable-water treatment works (Chowdhury, 2012; Lechevallier et al., 1991). A significant relationship between ENT and rainfall was not, however, detected in the present study possibly because the rainfall in question is constructed well above ground level, limiting the entry of faecally-contaminated runoff.

While it has often been hypothesised that wild-bird faecal matter contributes to FIB increase in environmental water, there are few hard research results in the literature to support this. One extensive study of a heavily populated waterfowl refuge detected only small increases of faecally-related TN and TP in the water, suggesting a low impact.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>T-statistic</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>4.78</td>
<td>0.001</td>
</tr>
<tr>
<td>UV\textsubscript{254 unfiltered}</td>
<td>3.06</td>
<td>0.003</td>
</tr>
<tr>
<td>Rainfall</td>
<td>1.14</td>
<td>0.265</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>-1.30</td>
<td>0.197</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>-0.49</td>
<td>0.627</td>
</tr>
<tr>
<td>Biochemical oxygen demand</td>
<td>-0.70</td>
<td>0.485</td>
</tr>
<tr>
<td>Constant</td>
<td>0.35</td>
<td>0.724</td>
</tr>
</tbody>
</table>

Table 2: Results of multiple regression analysis of enterococci indicator with environmental factors.
5. Conclusions

The finding that ENT indicator organisms reappear in an open water storage under the action of temperature and given a suitable carbon food supply is of concern in terms of the potential for generation of false-positive indicator results. Further research is indicated under a range of climatic conditions, however, to explore the generality of this phenomenon. The observed regrowth under temperate climatic conditions is of concern as most of the world’s food production takes place in temperate regions, often under reduced effluent irrigation. Researching the phenomenon under tropical and hot-arid climates, where temperatures may optimise mesophilic growth range, would be of particular interest with implications for regional strategic food supply (Food and Agricultural Organisation, 2002).

The formula derived for ENT increase with climatic air temperature needs to be tested under a range of climatic conditions to understand its potential use in food-production and climate change modelling. The observation that nitrogen and phosphorus were not growth limiting at levels occurring in this study also needs further research to determine the point at which they become critical for regrowth in environmentally-stored water.

ENT regrowth leading to false positive results would potentially lead to downgrading, rejection or over-chlorination of recycled water. Chlorination or other forms of disinfection is the likely choice where agricultural production targets have been set and indicator action-thresholds for the water supply pre-determined.

Excess chlorination carries a risk of land-runoff of persistent disinfection-by-products into natural receiving waters, exacerbating reduction in aquatic or marine biodiversity. Risk of increased human health impact could also exist where abstracted water is only subjected to basic treatment aimed at securing potability, impact on human perception of recycled water safety, and therefore acceptability, also needs to be taken into account when considering the existence of false positive results.

Given these factors, the potential for ENT regrowth needs to be taken into account during the revision of water monitoring guidelines and texts, as part of a total strategy aimed at reducing the disinfection-by-product load in the environment.

Conflict of interest statement

The authors report no conflicts of interest relevant to this article.

Acknowledgements

The authors thank Capital Works and Facilities, University of Western Sydney for making data available for this study, and Paul Fahey, School of Computing, Engineering and Mathematics, University of Western Sydney for advising on results of regression analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2013.07.096.
Appendix A. Supplementary material for paper: Regrowth of enterococci indicator in an open recycled-water impoundment (electronically linked to publication)

Identifying the thermal lag relationship between air and water

To achieve this a series of correlations between air and water temperature were performed with lag periods varying between 0 and 7 days. The resultant model indicated an optimal correlation ($r = +0.89$) when applying a 3-day lag period (Fig. S.1), the scattergram of this relationship being shown in Fig S.2. Ultimately a 4-day lag period was applied in regression analysis between ENT and Tempair, incorporating the optimal thermal lag period plus one day minimum incubation period.

![Fig. S.1. Impact of lag period on correlation for air and water temperature](image-url)
Fig. S.2. Scattergram for air and water temperature, with three-day lag period
Appendix F:

Complete list of author’s HWRS research project publications
Reviewed papers, presentations, book chapters and major reports generated through the research project


Society (ANZSYS) International Conference on Water Reuse, Wollongong, Australia, 14-16 February. ANZSYS, Wollongong, Australia.


