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Review of process and performance monitoring techniques applicable to large and small scale wastewater recycling systems

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Water for a Healthy Country Flagship Report
February 2010

www.csiro.au

Smart Water Fund
City West Water
Melbourne Water
South East Water
Yarra Valley Water
Department of Sustainability and Environment
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Water for a Healthy Country Flagship Report series ISSN: 1835-095X

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Citation: Toifl, M. Diaper, C. and O'Halloran, R., 2010. Review of process and performance monitoring techniques applicable to large and small scale wastewater recycling systems. CSIRO: Water for a Healthy Country National Research Flagship

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ACKNOWLEDGMENTS

The authors wish to thank the Smart Water Fund for their financial support for this research. We also wish to thank researchers, water utilities, regulatory authorities and other government bodies with whom we made contact during the course of undertaking this review to discuss research, technologies and regulation in relation to wastewater treatment and monitoring.

EXECUTIVE SUMMARY

This literature review is the deliverable for Milestone 2 of the Smart Water Fund project, Assessment of Best Practice Performance Monitoring Techniques for Small Scale Wastewater Recycling Systems. The aim of the review is to determine the status of technologies and techniques that are currently available for monitoring wastewater and wastewater recycling systems to ensure their ongoing performance. The challenges of best practice performance monitoring of small scale recycling systems have been considered and information from both Australian and international guidelines for wastewater and recycling were used to assist with defining the needs for this review. This review addresses both wastewater and greywater recycling and focuses on monitoring requirements for protection of human health, although environmental monitoring techniques are incorporated where appropriate.

Small scale wastewater recycling systems incorporate a wide range of technology types and scales of application. The variation in scale of application means there will be a greater variability in feed flows and quality compared to a large scale wastewater treatment plant (WWTP). This means that selection of a single sensor or a specific array of sensors or process monitors for all small scale wastewater recycling system is not appropriate, and a methodology needs to be developed which will allow for these uncertainties and variability. This methodology should incorporate the risk management approach of the Australian Guidelines for water recycling: Health and Environmental Risk Management (Phase 1) (2006) and be complementary to the Victorian EPA Code of Practice – Onsite Wastewater Management (EPA 2009).

A number of innovative approaches to monitoring have been identified, including mobile multi-sensor remote monitoring, and monitoring of environmental parameters as opposed to components of the treatment system. New methods for process control of large scale wastewater treatment systems may provide novel approaches to the development of best practice performance monitoring for small scale systems, and include methods such as Bayesian networks, fuzzy logic, neural networks and principal component analysis.

Process control and monitoring techniques play an important role in large scale wastewater treatment, and provide an opportunity for early identification of potential problems within the treatment process. Performance monitoring also plays an important role in wastewater treatment, as this is used to identify any issues with the water quality. In this review, a large

number of process and performance monitoring techniques and technologies have been included for both large and small scale treatment systems, in order to cover the broad range of monitoring options available to the wastewater industry.

During the course of this literature review it became evident that there are many different analysers available to monitor parameters online; including those for organic load indicators, nutrients, physicochemical parameters and inorganic ions. However, it is important to note that some of these analysers are not designed for continuous monitoring, and their performance may be less than satisfactory in treatment plants under continuous monitoring conditions. It was also found that manufacturers' specifications are often set under ideal conditions, and do not always accurately reflect the ongoing performance of analysers in continuous monitoring treatment plant environments.

1. INTRODUCTION

1.1. Background

Water supplies to Australian cities are under increasing pressure, with the impacts of reduced rainfall in water catchments and increasing urban populations prompting water companies to assess alternatives to the current centralised supply approaches. In this context, the current project specifically relates to small scale or decentralised and on-site wastewater treatment plants, which have the potential to make substantial contributions to water recycling. Small scale wastewater treatment and recycling processes are generally based on the same physical, chemical and biological processes used in centralised wastewater and water systems. However, smaller wastewater treatment plants are likely to experience a larger variation in feed water quality and quantity, as they do not have the same buffering capacity as large scale systems. This has lead to uncertainty as to the suitability of using large scale processes and their associated control systems in smaller scale applications, and a different approach to monitoring for small scale wastewater recycling systems is required.

The ongoing monitoring of the system; together with the human, environmental and business risks associated with lack of detection of system failure; has often been identified as a barrier to their widespread adoption. This project aims to address this issue by assessing best practice process and performance monitoring techniques for these systems.

1.2. Project overview

The purpose of this project is to carry out a desktop review and assessment of best practice process and performance monitoring for small scale wastewater recycling systems. The project will identify benefits, limitations, maintenance and calibration requirements of existing and emerging process and performance monitoring techniques. These techniques will not be limited to physical approaches, with feasible management and risk assessment frameworks also being considered where necessary. Capital and ongoing costs, frequency of failure information and comments on the ability to interface with existing control systems will be provided for appropriate performance monitoring techniques where available. However, it is not within the scope of this project to conclude whether the costs are appropriate for a particular end use, which could vary widely from single households to neighbourhood scales.
Throughout this project small scale technologies are defined as any that are not continuously manned and range from single house systems to cluster scale. This scale includes plants above and below the 5 kL/day boundary defined by the Victorian EPA Code of Practice – Onsite Wastewater Management (EPA 2009). The project scope covers wastewater and

greywater recycling only and does not include the treatment of rainwater or stormwater. The project focuses on best practice performance monitoring for human health impacts, although environmental monitoring will be included where appropriate.

The key project deliverables are to:

- Provide a detailed project plan incorporating feedback from the technical steering committee (Milestone 1).
- Carry out a detailed national and international literature survey of existing and new techniques and technologies that may be suitable for process and performance monitoring of small scale recycling systems (Milestone 2).
- Collate and assess the data from the literature survey to determine the practicality of key techniques and technologies, particularly in relation to continuous monitoring (Milestone 3).
- Provide a final report which details the findings of the project (Milestone 4).

This project utilises the Victorian EPA Code of Practice – Onsite Wastewater Management (2009) and the Australian Guidelines for water recycling: Health and Environmental Risk Management (Phase 1) (2006) as key reference documents. The requirements for process and performance monitoring as outlined in these two key references are provided in this review. These documents will be used as reference/baseline requirements when evaluating process and performance monitoring techniques in Milestone 3 of this project. For convenience, these documents will be subsequently referred to in this report as the EPA Wastewater Code of Practice; and the Australian Water Recycling Guidelines or AWRG.

The literature review utilised the following resources: CSIRO library and library staff (to assist with conducting some searches), internet, databases (including but not limited to; ISI Web of Knowledge, Current Contents, Patents database, Derwent Innovations Index, Technology Research Database, and CSIRO Electronic Journal Collection). It is not intended as a stand alone document but will be combined with the assessment of techniques and technologies in Milestone 3 to form the final report (Milestone 4).

Performance monitoring technologies will not be physically tested during this project and this could limit the detection of potential operational issues (e.g. false alarms, interfacing with other operating systems, etc). Whilst every effort will be made to identify any potential problems by communicating with known users of the monitoring systems, there is potential for issues to occur in practice that will not be identified in this desktop review.

1.3. Detailed content of this review

This review is the deliverable for Milestone 2 of the Smart Water Fund project: Assessment of best practice performance monitoring techniques for small scale wastewater recycling plants. The review was undertaken by collating information from an extensive literature search of past and current research publications covering wastewater, decentralised systems, and process and performance monitoring search terms. Grey literature (non ISI listed publications) was included in this search so that information from conference proceedings and industry journals was also included. Information and advice was also sought from other researchers and organisations outside Australia in order to provide information on best practice performance monitoring systems in USA and EU.

The review covers small scale wastewater recycling systems, which each comprise a number of component processes. These processes can be categorised into the collection system, the wastewater treatment process, and tertiary or advanced treatment to produce water of the quality required for recycling. The report provides details of process monitoring and control for wastewater systems (Section 2.1) and wastewater recycling systems (Section 2.2). Section 3 describes candidate performance parameters that have been monitored in wastewater, along with some of the techniques available for performance monitoring. Section 4 summarises the information collected and provides a preliminary assessment of the suitability of the techniques for process and performance monitoring of small scale wastewater recycling systems with respect to human health risks.

1.4. Issues for performance monitoring of small scale wastewater recycling systems

There are a number of factors that need to be considered when assessing best practice performance monitoring techniques and technologies for small scale recycling systems, which can be summarized as:

- Technology type
- Scale of system
- End uses and human and environmental/ecological health risks
- Flow and quality variability

A wide range of decentralised treatment systems are available, ranging from engineered membrane based treatment plants to ecological approaches using natural treatment systems (such as wetlands), which are all designed to provide potable water substitution at a range of scales and water qualities. Treated water from these systems can potentially be used for surface and sub-surface irrigation and other outdoor uses, as well as for toilet flushing, fire protection and in washing machines; in applications ranging from single dwellings to developments of multiple dwellings.

The selection and recommendation of parameters suitable for assessing system performance; e.g. turbidity, conductivity, Total Organic Carbon (TOC), pH, or combinations of these or indicator or surrogate parameters such as *E.coli* counts or Trans Membrane Pressure; also needs to be considered.

The Australian Water Recycling Guidelines (EPHC. 2006) identify pathogenic micro-organisms in recycled water as the main risk to human health as opposed to the chemical components. The pathogenic microorganisms can be bacteria, viruses, protozoa or helminths. These have different physical, chemical and biological characteristics, which require different removal mechanisms in wastewater recycling treatment processes. The direct analysis of microorganisms is usually complex, time intensive and costly, so surrogate parameters are often used. These surrogates may be more easily measured water quality parameters, such as turbidity, particle count or Ultra Violet Transmissivity (UVT). Alternatively the surrogate may relate to the performance of a critical control point (CCP) in the treatment train, such as trans-membrane pressure (TMP) or UV lamp operational status. The Australian Recycled Water Guidelines recommend increased frequency of monitoring for higher risk situations, with continuous monitoring recommended for high risk end uses.

Chemical components present a higher risk to the environment, with B (boron), Cl^- (chloride), Na (sodium), Cd (cadmium), chlorine (Cl_2), salinity, and nutrients (nitrogen and phosphorus) having been identified as eight of the nine key hazards to the environment, in addition to high water flows. The guidelines also state that the assessment of risks to human health is often simpler than assessment of risks to the environment, because with human health risks there is only one end point (humans), whereas there may be multiple environmental end points, i.e. plants, soil, groundwater and air.

The range of environmental end points required suggests that monitoring techniques should not be limited to the treated recycled water stream only, and might also incorporate soil, plant, groundwater or air monitoring techniques. This is an approach suggested by (Bidwell 2000), where soil water quality in the vadose zone was monitored. Groundwater monitoring was also considered, but the time lag before poor quality effluent caused groundwater contamination was considered too large to trigger effective remedial action.

As the environmental and human health risks associated with the different end uses and scales of operation are variable, it is likely that different best practice performance or process monitoring techniques will be applicable at these different scales and end uses.

1.5. Definitions

- Process control – the task of automatically controlling a process.
- Process monitoring - the Risk assessment of performance of specific components of the process, such as pumps, valves and level sensors, and the diagnosis of faults and errors.
- Performance monitoring - the assessment of water quality delivered from a device/process.

1.6. Current guidelines for monitoring of small scale wastewater recycling systems

1.6.1. Australian guidelines

This project utilises the EPA Wastewater Code of Practice and the Australian Water Recycling Guidelines (EPHC. 2006) for guidance in the assessment of best practice process and performance monitoring techniques.

There are a number of factors that need to be considered when identifying best practice performance monitoring techniques for small scale recycling systems. The Australian Water Recycling Guidelines utilise a risk management approach based on that used in the Australian Drinking Water Guidelines (NHMRC 2004), and outline 12 elements in four main areas as follows:

1. Commitment to drinking (recycled) water quality management
2. System analysis and management
    - Assessment of drinking water quality management
    - Preventative measures for drinking water quality management
    - Operational procedures and process control
    - Verification of drinking water quality
    - Management of incidents and emergencies
3. System review
    - Education and audit
    - Review and continual improvement
4. Other supporting requirements
    - Employee awareness and training
    - Community involvement and awareness
    - Research and development
    - Documentation and reporting.

These four areas provide an ideal categorisation for the different functions of monitoring: compliance or verification testing; process control; operation and maintenance; research and employee or community education. It is important to recognise that best practice monitoring for compliance testing may be very different from that required for research. The function of the monitoring program is related to the timeline of installation of a new technology - for example, research monitoring may be required when a technology is new and untested, and monitoring for compliance commences once a technology is proven and ready for installation in a real world situation.

Whilst it is recognised that all these monitoring functions are required when developing a new water recycling system, this current study will focus on technologies and techniques for system analysis and management and review only, and will not specifically cover research or community and employee awareness and education functions. Some of the technologies identified may be appropriate for these functions, but they will not be assessed in detail for this purpose in Milestone 3 of the project.

The monitoring of small scale recycling systems is a vital component of the four step risk management approach outlined in the Australian Water Recycling Guidelines (Figure 1). In Victoria, the guidelines are applicable to all greywater and wastewater recycling systems > 5kL/day and all multi dwelling greywater recycling systems, regardless of capacity.

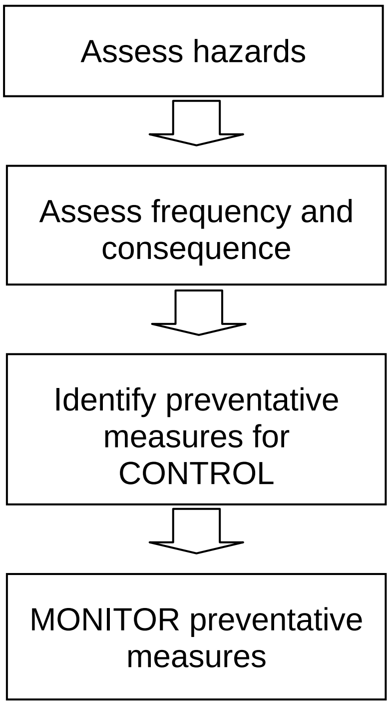


Figure 1: Australian Water Recycling Guidelines Risk management approach

Operational monitoring	***Verification*** monitoring
• Focuses of the performance of all preventative measures, particularly those associated with critical control points • Needs to be of an intensity commensurate with the variability and criticality of the specific preventative measures • Is likely to include a broad range of parameters, with observation, inspection and electrochemical devices being used to demonstrate that the systems is operating as intended • Can be in the form of laboratory microbial and chemical analysis if turnaround tomes are adequate to give warning of non-conformance before recycled water is supplied	• Is independent of operational monitoring • Generally takes place at the point where treatment is considered complete, either at the end of the system or before discharge into open storages • Includes auditing of plant operations and on-site usage controls to test compliance • For health – involves using microbial indicators, and sometimes pathogens, to demonstrate that the scheme is continuing to perform as designed with respect to log reductions

Figure 2: Operational and verification monitoring of a recycled water scheme (EPHC. 2006)

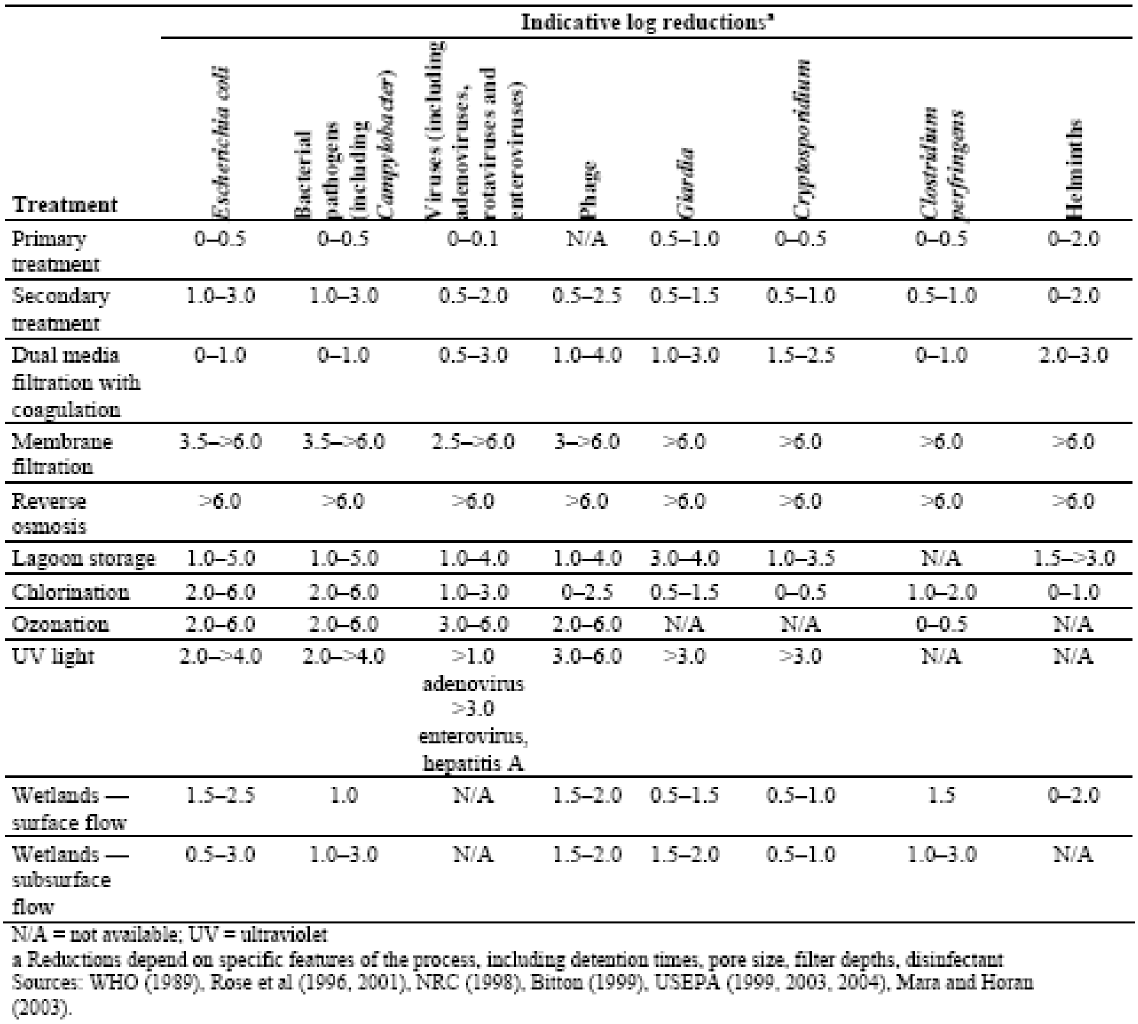
The current study will focus on the Operational and Verification aspects of monitoring, as these describe the performance of a water recycling system during the operational phase, the brief for this project. Baseline and validation monitoring techniques will be included only if appropriate. The requirements for operational and verification monitoring outlined in the guidelines includes a focus on the performance of preventative measures, monitoring frequency and clarification that operational monitoring should occur throughout the process whereas verification monitoring takes place where treatment is considered complete i.e. at the end of the process (Figure 2).

The guidelines also specify log reductions of pathogenic micro-organisms (bacteria, protozoa and viruses) required for different end uses. For a dual reticulation scheme, where recycled water is supplied through a network separate from the drinking water supply, these removals are listed in Table 1. In addition, the guidelines provide indicative log removals for different wastewater recycling unit operations. These removals are different for the various microorganisms of concern in wastewater and range from 0-0.5 log removal for primary treatment processes to >6.0 log removal for reverse osmosis (Table 2). In combination this information can be used to identify appropriate treatment processes for specific recycled wastewater end uses.

Table 1: Log reductions for household uses of recycled water from treated sewage

Activity	Log reduction		
	Cryptosporidium	Rotavirus	*Campylobacter*
Total internal use (no garden watering)	4.7	6.1	4.8
Total residential use (including garden)	4.9	6.3	5.1

Table 2 : Indicative log removal of enteric pathogens and indicator organisms (ARWG, 2006)



	Indicative log reductions[a]							
Treatment	*Escherichia coli*	Bacterial pathogens (including *Campylobacter*)	Viruses (including adenoviruses, rotaviruses and enteroviruses)	Phage	*Giardia*	*Cryptosporidium*	*Clostridium perfringens*	Helminths
Primary treatment	0–0.5	0–0.5	0–0.1	N/A	0.5–1.0	0–0.5	0–0.5	0–2.0
Secondary treatment	1.0–3.0	1.0–3.0	0.5–2.0	0.5–2.5	0.5–1.5	0.5–1.0	0.5–1.0	0–2.0
Dual media filtration with coagulation	0–1.0	0–1.0	0.5–3.0	1.0–4.0	1.0–3.0	1.5–2.5	0–1.0	2.0–3.0
Membrane filtration	3.5–>6.0	3.5–>6.0	2.5–>6.0	3–>6.0	>6.0	>6.0	>6.0	>6.0
Reverse osmosis	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0
Lagoon storage	1.0–5.0	1.0–5.0	1.0–4.0	1.0–4.0	3.0–4.0	1.0–3.5	N/A	1.5–>3.0
Chlorination	2.0–6.0	2.0–6.0	1.0–3.0	0–2.5	0.5–1.5	0–0.5	1.0–2.0	0–1.0
Ozonation	2.0–6.0	2.0–6.0	3.0–6.0	2.0–6.0	N/A	N/A	0–0.5	N/A
UV light	2.0–>4.0	2.0–>4.0	>1.0 adenovirus >3.0 enterovirus, hepatitis A	3.0–6.0	>3.0	>3.0	N/A	N/A
Wetlands — surface flow	1.5–2.5	1.0	N/A	1.5–2.0	0.5–1.5	0.5–1.0	1.5	0–2.0
Wetlands — subsurface flow	0.5–3.0	1.0–3.0	N/A	1.5–2.0	1.5–2.0	0.5–1.0	1.0–3.0	N/A

N/A = not available; UV = ultraviolet

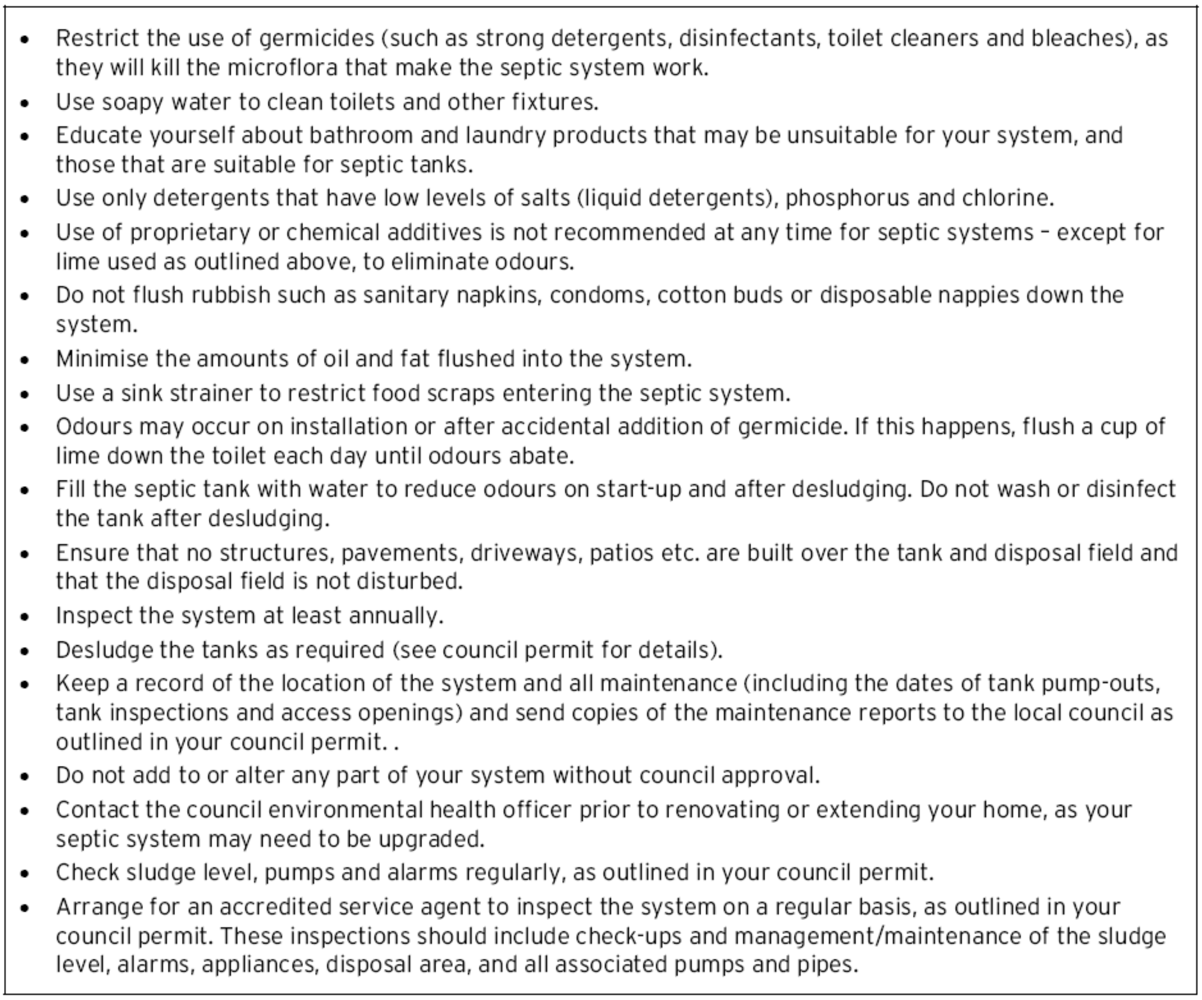
a Reductions depend on specific features of the process, including detention times, pore size, filter depths, disinfectant

Sources: WHO (1989), Rose et al (1996, 2001), NRC (1998), Bitton (1999), USEPA (1999, 2003, 2004), Mara and Horan (2003).

The EPA Wastewater Code of Practice has been developed to provide directions for the management of small onsite wastewater treatment systems of capacity < 5 kL/day, except multi dwelling greywater systems. The Code is presently under extensive review, but the current version identifies four ways to manage onsite domestic wastewater and three main treatment types for all waste systems: primary and secondary water-based systems, and dry composting. A fourth treatment type is identified for greywater treatment systems: tertiary treatment. Four end use options are identified: surface and subsurface irrigation for both wastewater and greywater systems, and indoor uses of toilet flushing and cold water to washing machines for greywater only.

The Code does not specifically detail performance and process monitoring requirements for these different types of technologies and end uses, but describes various water quality and operational needs that are related to monitoring. Table 3 and Table 4 provide examples of these requirements, and describe a wide range of potential monitoring needs for the different processes and end uses. For primary wastewater treatment there is a range of source control operational strategies recommended, including restrictions on the use of germicides, high salt detergents and disposal of fats and oils in the system. There are also a number of requirements for assessing disposal area failure, including surface seepage, high water levels or water logging, sewage overflow or a blocked outflow.

Table 3 : Operation and maintenance of septic tanks, from EPA Code of Practice,



- Restrict the use of germicides (such as strong detergents, disinfectants, toilet cleaners and bleaches), as they will kill the microflora that make the septic system work.
- Use soapy water to clean toilets and other fixtures.
- Educate yourself about bathroom and laundry products that may be unsuitable for your system, and those that are suitable for septic tanks.
- Use only detergents that have low levels of salts (liquid detergents), phosphorus and chlorine.
- Use of proprietary or chemical additives is not recommended at any time for septic systems – except for lime used as outlined above, to eliminate odours.
- Do not flush rubbish such as sanitary napkins, condoms, cotton buds or disposable nappies down the system.
- Minimise the amounts of oil and fat flushed into the system.
- Use a sink strainer to restrict food scraps entering the septic system.
- Odours may occur on installation or after accidental addition of germicide. If this happens, flush a cup of lime down the toilet each day until odours abate.
- Fill the septic tank with water to reduce odours on start-up and after desludging. Do not wash or disinfect the tank after desludging.
- Ensure that no structures, pavements, driveways, patios etc. are built over the tank and disposal field and that the disposal field is not disturbed.
- Inspect the system at least annually.
- Desludge the tanks as required (see council permit for details).
- Keep a record of the location of the system and all maintenance (including the dates of tank pump-outs, tank inspections and access openings) and send copies of the maintenance reports to the local council as outlined in your council permit. .
- Do not add to or alter any part of your system without council approval.
- Contact the council environmental health officer prior to renovating or extending your home, as your septic system may need to be upgraded.
- Check sludge level, pumps and alarms regularly, as outlined in your council permit.
- Arrange for an accredited service agent to inspect the system on a regular basis, as outlined in your council permit. These inspections should include check-ups and management/maintenance of the sludge level, alarms, appliances, disposal area, and all associated pumps and pipes.

Other potential monitoring requirements for all irrigation systems include the use of soil moisture or rainwater sensors, monitoring of irrigation rates and volumes, and a failsafe diversion to the sewer. In addition to these potential monitoring needs, tertiary treated greywater for indoor uses may require measures to ensure that no inappropriate or unintended cross connections of pipe work occur. Many of these needs may be met through appropriate design of the wastewater or greywater system, but some will require monitoring and control throughout the operational life of the system.

All proposed wastewater treatment system installations require a Land Capability Assessment (LCA) as a critical element of the design and approval process. However, this is not a requirement for greywater treatment systems in sewered areas. Although the LCA is critical prior to installation of an on-site system, the Code of Practice does not identify any review of this procedure during the operational phase of a system, although some of the components of the LCA are incorporated in the maintenance and operational requirements.

Table 4: Victorian EPA Code of Practice requirements for wastewater and greywater systems servicing single domestic premises

Treatment type and end use	***Water quality requirements***	***Other potential monitoring requirements***
Primary wastewater – sub surface dispersal	None	Sludge accumulation and scum Source control Pumps Alarms Disposal area failure
Secondary wastewater – sub and surface irrigation	As per Certificate of Approval (includes BOD, SS and potentially N and P in the future)	Irrigation rate and volume Soil saturation Plant and soil type and soil profile Soil moisture or rain sensors Solids carry over Effluent contained in boundary of property Failsafe diversion to sewer
Primary greywater – sub surface irrigation		As secondary wastewater
Secondary greywater – subsurface irrigation	20 mg/L BOD_5 30 mg/L Suspended solids	As secondary wastewater
Secondary greywater and disinfection – surface and subsurface irrigation	20 mg/L BOD_5 30 mg/L Suspended solids < 10 cfu/100mL E.coli	As secondary wastewater
Advanced secondary greywater and disinfection – indoor uses and surface and subsurface irrigation	10 mg/L BOD_5 10 mg/L Suspended solids < 10 cfu/100mL E.coli 0.2 to 2.0 mg/L free chlorine	Treated effluent not used for unintended or inappropriate end uses As secondary wastewater

As previously stated the EPA Code of Practice is currently under extensive review and it is likely that the requirements for monitoring in the new version will be identified more clearly. The expected completion date for review is June 2010.

In addition to the EPA Code of Practice, monitoring requirements are also included in the Certificate of Approvals issued to individual manufacturers of greywater and wastewater treatment processes for less than 5000 L/day. Certificates currently request verification monitoring for Biological Oxygen Demand (BOD), Suspended Solids (SS), E.coli and Residual Chlorine where appropriate, in addition to total nitrogen and phosphorus for some newer approvals. Annual monitoring of BOD, SS and E.coli is required for systems that recycle water to surface irrigation or for indoor uses.

1.6.2. International guidelines

In the USA, the management of small scale wastewater systems is described in the USEPA Voluntary National Guidelines for Management of Onsite and Clustered (Decentralized) Wastewater Treatment Systems (USEPA 2003). This guideline is accompanied by the Handbook for Managing Onsite and Clustered (Decentralized) Wastewater Systems (USEPA 2005b). The management guidelines were developed in recognition of the need for a comprehensive plan covering public education, planning, performance, site evaluation, design construction, operation and maintenance, residuals management, training and certification, inspections and monitoring, corrective actions, record keeping, financial assistance and funding for the large number of small scale wastewater systems in the US (decentralized systems are used in 25% of homes in the USA). Five management models are proposed in the guidelines, ranging from a ‘Homeowner Awareness’ model that describes appropriate activities for treatment systems owned and operated by individual property owners, to a ‘Responsible Management Entity (RME) Ownership’ model for systems owned, operated and maintained by an RME (Table 5).

Table 5: USEPA (2003) summary of management models for onsite and clustered wastewater systems

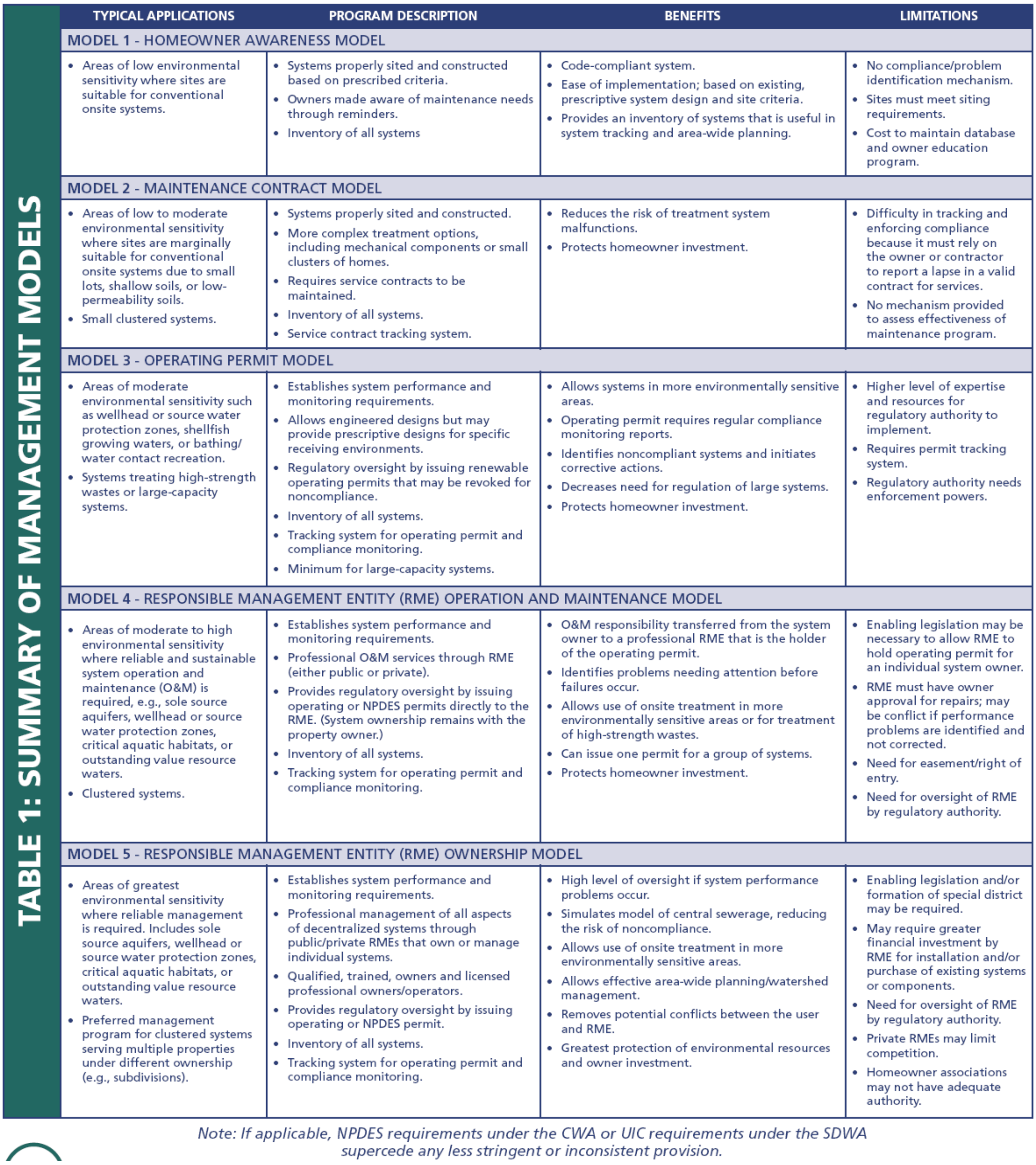


TABLE 1: SUMMARY OF MANAGEMENT MODELS

TYPICAL APPLICATIONS	PROGRAM DESCRIPTION	BENEFITS	LIMITATIONS
MODEL 1 - HOMEOWNER AWARENESS MODEL			
• Areas of low environmental sensitivity where sites are suitable for conventional onsite systems.	• Systems properly sited and constructed based on prescribed criteria. • Owners made aware of maintenance needs through reminders. • Inventory of all systems	• Code-compliant system. • Ease of implementation; based on existing, prescriptive system design and site criteria. • Provides an inventory of systems that is useful in system tracking and area-wide planning.	• No compliance/problem identification mechanism. • Sites must meet siting requirements. • Cost to maintain database and owner education program.
MODEL 2 - MAINTENANCE CONTRACT MODEL			
• Areas of low to moderate environmental sensitivity where sites are marginally suitable for conventional onsite systems due to small lots, shallow soils, or low-permeability soils. • Small clustered systems.	• Systems properly sited and constructed. • More complex treatment options, including mechanical components or small clusters of homes. • Requires service contracts to be maintained. • Inventory of all systems. • Service contract tracking system.	• Reduces the risk of treatment system malfunctions. • Protects homeowner investment.	• Difficulty in tracking and enforcing compliance because it must rely on the owner or contractor to report a lapse in a valid contract for services. • No mechanism provided to assess effectiveness of maintenance program.
MODEL 3 - OPERATING PERMIT MODEL			
• Areas of moderate environmental sensitivity such as wellhead or source water protection zones, shellfish growing waters, or bathing/water contact recreation. • Systems treating high-strength wastes or large-capacity systems.	• Establishes system performance and monitoring requirements. • Allows engineered designs but may provide prescriptive designs for specific receiving environments. • Regulatory oversight by issuing renewable operating permits that may be revoked for noncompliance. • Inventory of all systems. • Tracking system for operating permit and compliance monitoring. • Minimum for large-capacity systems.	• Allows systems in more environmentally sensitive areas. • Operating permit requires regular compliance monitoring reports. • Identifies noncompliant systems and initiates corrective actions. • Decreases need for regulation of large systems. • Protects homeowner investment.	• Higher level of expertise and resources for regulatory authority to implement. • Requires permit tracking system. • Regulatory authority needs enforcement powers.
MODEL 4 - RESPONSIBLE MANAGEMENT ENTITY (RME) OPERATION AND MAINTENANCE MODEL			
• Areas of moderate to high environmental sensitivity where reliable and sustainable system operation and maintenance (O&M) is required, e.g., sole source aquifers, wellhead or source water protection zones, critical aquatic habitats, or outstanding value resource waters. • Clustered systems.	• Establishes system performance and monitoring requirements. • Professional O&M services through RME (either public or private). • Provides regulatory oversight by issuing operating or NPDES permits directly to the RME. (System ownership remains with the property owner.) • Inventory of all systems. • Tracking system for operating permit and compliance monitoring.	• O&M responsibility transferred from the system owner to a professional RME that is the holder of the operating permit. • Identifies problems needing attention before failures occur. • Allows use of onsite treatment in more environmentally sensitive areas or for treatment of high-strength wastes. • Can issue one permit for a group of systems. • Protects homeowner investment.	• Enabling legislation may be necessary to allow RME to hold operating permit for an individual system owner. • RME must have owner approval for repairs; may be conflict if performance problems are identified and not corrected. • Need for easement/right of entry. • Need for oversight of RME by regulatory authority.
MODEL 5 - RESPONSIBLE MANAGEMENT ENTITY (RME) OWNERSHIP MODEL			
• Areas of greatest environmental sensitivity where reliable management is required. Includes sole source aquifers, wellhead or source water protection zones, critical aquatic habitats, or outstanding value resource waters. • Preferred management program for clustered systems serving multiple properties under different ownership (e.g., subdivisions).	• Establishes system performance and monitoring requirements. • Professional management of all aspects of decentralized systems through public/private RMEs that own or manage individual systems. • Qualified, trained, owners and licensed professional owners/operators. • Provides regulatory oversight by issuing operating or NPDES permit. • Inventory of all systems. • Tracking system for operating permit and compliance monitoring.	• High level of oversight if system performance problems occur. • Simulates model of central sewerage, reducing the risk of noncompliance. • Allows use of onsite treatment in more environmentally sensitive areas. • Allows effective area-wide planning/watershed management. • Removes potential conflicts between the user and RME. • Greatest protection of environmental resources and owner investment.	• Enabling legislation and/or formation of special district may be required. • May require greater financial investment by RME for installation and/or purchase of existing systems or components. • Need for oversight of RME by regulatory authority. • Private RMEs may limit competition. • Homeowner associations may not have adequate authority.

Note: If applicable, NPDES requirements under the CWA or UIC requirements under the SDWA supercede any less stringent or inconsistent provision.

These are conceptual approaches and each consists of thirteen critical elements which describe activities required to reach the management goal. The ‘best’ model for a particular community is not necessarily the one which describes the highest level of management, but the one that provides the most appropriate management for the potential risk. The models are flexible and modular so that activities from higher level models can be incorporated into lower level programs in order to achieve specific objectives for a particular site.

The management guidelines include a number of key concepts that are described as the foundation of changes needed to improve the performance of decentralized systems (Figure 3). The first concept is related to the technology type challenge identified in Section 1.4, so that as the complexity increases so also do the operational and maintenance requirements; and a higher level of management is required. Another key concept is the practice of issuing operating permits to the system owner that stipulate specific and measurable performance criteria for the treatment system. These criteria are based on risks to public health and to surface or groundwater sources. These and other compliance criteria suggested in the guidelines are developed by the local regulatory authority.

Key Concepts

- **An increase in the level of management as the level of risk and technical complexity increase**
- **Inventorying** existing systems and their level of performance as a minimum
- **Operating permits** for large systems and clusters of onsite systems
- **Discharge permits** for systems that discharge to surface waters
- Increased requirements for **certification and licensing** of practitioners
- Elimination of **illicit discharges** to storm drains or sewers

Figure 3: USEPA key concepts for improved performance of decentralized wastewater systems

To aid customers seeking information on the regulatory structures in the different states, the National Small Flows Clearinghouse's Regulations Database has been established (http://www.nesc.wvu.edu/nsfc/nsfc_regulations.htm). This resource was formed to educate and assist in the development and management of onsite and cluster wastewater systems.

As this review focuses on monitoring for human health risk, there are other US EPA documents that can provide relevant information on the monitoring of the specific components of a recycled water treatment train. The Ultraviolet Disinfection Guidance Manual for the final Long term 2 enhanced surface water treatment rule (USEPA 2006) provides guidance for public water system operators and designers on the selection, design, operation and compliance (verification) for UV disinfection systems for drinking water treatment. The document also provides guidance for state departments on the necessary tools to assess UV installations and guidance for manufacturers on the testing and performance standards for UV reactors. In Chapter 6 of the document the monitoring requirements for start-up and operation of UV systems are described. The Membrane Filtration Guidance Manual (USEPA 2005a) provides similar information for membrane systems that are used for drinking water treatment and comply with the Long term 2 enhanced surface water treatment rule.

Our review of management and monitoring small scale and decentralised wastewater and greywater systems in Europe has not identified any specific literature on this topic. The European Commission Urban Wastewater Treatment Directive (91/271/EEC) describes requirements for existing large wastewater treatment plants but not for new decentralised systems. The Directive did not allow use of online water quality measurements for compliance testing in 1999 (Jacobsen 1999), but this may have changed in light of subsequent improvements in on-line monitoring technology. Discussions with water company representatives and university researchers in the UK have not provided any additional European literature on this topic.

2. PROCESS CONTROL AND MONITORING OF WASTEWATER AND WASTEWATER RECYCLING SYSTEMS

Process control and process monitoring are closely linked, as monitoring is required to provide the data for process control. It is essential that the validity of data from monitoring equipment is checked to ensure sensor or actuator faults are diagnosed and remedied. The degree of process control and monitoring is somewhat dependent on the timeline of technology development and the innovative nature of the technology.

Process control strategies for current large scale biological wastewater systems are often based on a benchmark simulation model of the process that incorporates modelling of activated sludge and settling processes i.e. COST/IWA (Rosen *et al.* 2004). The development of these control strategies requires a detailed understanding of the process and development of algorithms describing the process. New strategies for process control of these primarily biological systems are continually being developed. A summary of some of these newer approaches is given in Section 2.1.

Wastewater recycling systems incorporate additional tertiary, advanced and disinfection treatment processes. Relevant process control strategies are reviewed in Section 2.2, in addition to the requirements of these processes in terms of removal of pathogenic microorganisms, which are the primary human health hazard.

2.1. Wastewater systems

The majority of wastewater treatment processes are biologically based, utilising the naturally occurring bacterial communities in the wastewater. Process control of biological systems is recognised as being fundamentally different from that of chemical processes, for which the majority of methods and techniques have been developed. The mathematical models required for process control of complex biological systems are difficult to formulate, or they may require additional experimentation in order to provide the data required to formulate accurate models.

While the aim of this review is to provide details of current practices and innovations in process and performance monitoring of wastewater technologies, the links between process control and monitoring mean that it is difficult to separate the two strategies. For this reason recent research innovations in process control are also included in the review. In addition, there have also been advances in integrated modelling and control of wastewater systems which are relevant to the development of best practice monitoring for small scale recycling systems, so a review of these research advances is also incorporated.

2.1.1. Process control strategies

Statistical Process Control (SPC) has long been used in the manufacturing and chemical industries, and uses statistical tools to monitor the production process in order to predict significant deviations that may later result in rejected product. This technique has also been applied in the wastewater treatment industry, but the complex nature of biological processes suggests that other techniques are more appropriate for this application. In recent years a number of different approaches to process control, and the associated monitoring systems, have been applied to a variety of wastewater treatment processes and systems (Table 6).

Table 6: Recent process control techniques for wastewater treatment

Technique	***Wastewater treatment process***	***Comments***	***Reference***
Bayesian networks	Laboratory scale wastewater system	Abnormal operation and faults detected	(Cheon *et al.* 2007)
Bayesian networks and automatic learning	Activated sludge plant in Spain (35,000 m^3/day)	Approach deals with uncertainty and allows prediction and diagnosis	(Sangüesa and Burrell 2000)
Decision support system	Activated sludge model	Improved plant performance, reduced costs and aided decision making	(Xu *et al.* 2006)
Knowledge based expert system	Pilot scale three stage wastewater treatment process	Allowed set point modification and fault detection	(Baeza *et al.* 2000)
Fuzzy modelling	Simulation model	False alarms identified	(Skrjanc 2007)
Multivariate SPC and multidimensional visualisation Principal Component Analysis (PCA)	Wastewater treatment plant in Spain	Both methods identified same period of abnormal operation. PCA identified likely abnormal operation.	(Wang *et al.* 2004)
Neural network (Artificial)	Lab scale reactor for chlorination and dechlorination	Potential to reduce chemical costs	(Yu *et al.* 2008)
Neural network (artificial) and fuzzy control	Wastewater treatment plant in China	Operational decision making and forecasting achieved	(Qing *et al.* 2005)
Neural network and Multivariate SPC	Activated sludge plant in Korea	Mobile multi sensor remote monitoring system used	(Lee *et al.* 2008)
Neural networks	Wastewater treatment plant in Israel	Allowed fault detection and diagnosis, and extraction of expert rules	(Boger 1992)
Distributed Computer Control system (with mixed architecture)	Three stage wastewater treatment process	New architecture for control system proposed	(Katebi *et al.* 1998)
SCADA and Superior Tuning and Reporting system (STAR)	Ten wastewater treatment plants in Denmark	Improved nitrogen and phosphorous removal and reduced energy	(Nielsen and Onnerth 2000)

A Bayesian network is a mathematical object which combines qualitative information about the structure of a network with quantitative information about the relationships between variables in that network. A Bayesian network can model probabilities and identify variables with the most impact and can also model expert or subjective knowledge and can automatically learn from raw data. Bayesian networks have been applied to wastewater treatment processes as they can combine background knowledge and data from sensors, and deal with uncertainties. This approach has been successfully applied to an activated sludge plant, and has allowed the identification of process faults and abnormal operation.

A decision support system (DSS) is an interactive software-based system intended to help decision makers compile useful information from a combination of raw data, documents, personal knowledge, or business models to identify and solve problems and make decisions. Three fundamental components of a DSS architecture are the database (or knowledge base), the model (i.e., the decision context and user criteria), and the user interface. Decision support and expert systems have been developed for real time control of simulated (Xu *et al.* 2006) and pilot scale (Baeza *et al.* 2000) wastewater treatment plants. These systems provided help with fault detection and maintenance, modified setpoints to allow for different influent conditions, improved plant performance and reduced treatment costs. Other authors have also suggested that different set points are required at different times, for example weekday versus weekend operation (Guerrero *et al.* 2009), and this may be a process control strategy particularly applicable to small scale recycling systems.

Fuzzy logic is a mathematical technique for dealing with imprecise data and problems that have many solutions rather than one. Fuzzy logic works with ranges of values, rather than the yes/no on/off values of classical logic and solves problems in a way that more resembles human logic. The approach is often used in conjunction with expert systems, neural networks and real-time systems that must react to an imperfect environment of highly variable, volatile or unpredictable conditions. Fuzzy logic and fuzzy causal network approaches have been applied to simulation model data for identification of false alarms (Skrjanc 2007). The approach has also been used in combination with neural networks (Qing *et al.* 2005) for operation and control of a wastewater treatment plant in China.

An (artificial) neural network is generally a non-linear data modeling tool that tries to simulate the structure and/or functional aspects of biological neural networks. It consists of an interconnected group of artificial neurons, and processes information using a connectionist approach to computation. Neural networks are adaptive and change structure based on external or internal information that flows through the network during the learning phase. They can be used to model complex relationships between inputs and outputs or to find patterns in data. The neural network approach has been applied to various wastewater treatment processes in China, Korea and Israel, and has been found to aid operational decision making, forecasting, fault detection and diagnosis, and to reduce chemical costs. One particularly novel method used for data collection in one of these studies utilised a mobile multi-sensor remote monitoring system (Lee *et al.* 2008)

SCADA (Supervisory Control and Data Acquisition) systems are utilised in the process industry to monitor and control the process. One new development is the STAR system, which adapts the control to the currently measured conditions rather than to fixed setpoints as in the SCADA system (Nielsen and Onnerth 2000). The system has achieved reduced costs of energy and chemicals, and improved discharge quality for ten wastewater treatment plants in Denmark.

2.1.2. Process monitoring for fault detection

Process monitoring for fault detection is utilised to identify failures of system components such as actuators or sensors, for abnormal or crisis situations, and for operational or maintenance requirements. Techniques have been applied to a variety of wastewater treatment systems, from laboratory scale simulations (Cheon et al. 2007; Choi and Lee 2004); to large scale industrial processes (Albazzaz et al. 2005). A recent review by WERF on non traditional indicators of system performance for decentralized systems (Maclennan and Nutt 2010) also provides an overview of traditional and non-traditional methods that can be useful for fault detection.

There are a range of techniques used for process monitoring assessment and fault detection and diagnosis in wastewater treatment processes, including multidimensional visualisation, fault detection and isolation (FDI), partial least squares (PLS), fuzzy logic, and principal component analysis (PCA) and associated derivatives (Table 7). Newer PCA methods of statistical process monitoring allow application to non-linear processes, such as wastewater treatment, for fault detection and diagnosis. These new methods have shown superior fault detection (Zhang 2008) when compared to traditional PCA methods.

All these techniques provide different methods for identifying faults, failures and abnormal events from large datasets. Multidimensional visualisation is a way of expressing multivariate data in a graphical form that allows visual detection of outliers or data clusters and abnormal events. The tool can be used to aid plant operators in identifying abnormal operations, although training and some expert knowledge of the technique would be required and the method is not suitable for online fault detection at present.

Table 7: Current techniques for fault detection in wastewater treatment processes

Technique	***Wastewater treatment process***	***Advantages/Disadvantages***	***Reference***
Multidimensional visualisation	Industrial WWTP	Not automated and not suitable for online fault detection at present	(Albazzaz *et al.* 2005)
Multivariate SPC	Industrial WWTP		(Albazzaz *et al.* 2005)
Multiblock partial least squares for FDI	Industrial WWTP in steel mill	Deconstructive approach	(Choi and Lee 2005)
Dynamic kernel PCA	Laboratory scale system	Setup allowed comparison of approaches	(Choi and Lee 2004)
Kernel PCA		Kernel PCA combined with linear determinant analysis (LDA) provided best results	(Jun *et al.* 2006)
Improved PCA	Simulated process	New method better for identifying faults than traditional approach	(Lee *et al.* 2004)
Adaptive multiway PCA	Pilot scale sequencing batch reactor	New method gave improved results	(Lee *et al.* 2005)
Multiway PCA and Case Based Reasoning	Pilot scale sequencing batch reactor	Used to solve problems based on past experiences	(Ruiz *et al.* 2009)
Independent component analysis	Simulated process	New method gave improved results	(Lee *et al.* 2006)
PCA	Full scale sequencing batch reactor	Improved diagnosis with combined sensor outputs	(Park *et al.* 2005)
Kernel independent component analysis	Simulated activated sludge and settling	Compared to support vector machine method	(Zhang 2008)
Fuzzy logic		Three months data required. Utilises input quality data	(Grieu *et al.* 2001)
Fuzzy logic		Deals with uncertainties. Used in chemical processes and HAZOP	(Huang and Wang 1999)
Fuzzy logic and evidence theory	Anaerobic wastewater treatment	Allowed fault detection and diagnosis	(Lardon *et al.* 2004)
Integrated computer control system (IC^{2}S)	Wastewater treatment plant in Canada	Three types of sensor faults diagnosed	(Schraa *et al.* 2005)

Principal component analysis is a multivariate statistical technique which is used to find patterns in data and to express the data to highlight the similarities and differences between variables. The technique allows the data to be compressed by reducing the number of dimensions, without loss of information. This method and its derivatives is the most commonly applied to wastewater treatment processes, although the majority are laboratory or simulated batch processes.

The multi block partial least squares method for fault detection and isolation (FDI) breaks up a process into meaningful unit processes which helps to reduce the complexity of the partial least squares method. The PLS method combines features from PCA and traditional multiple regression analysis and is useful in predicting a set of dependent variables from a very large set of independent variables. The application to wastewater treatment processes of this method is relatively new, with only one application to an industrial WWTP (Choi and Lee, 2005).

The fuzzy logic approach has been described in the previous section and has been applied with some success in fault detection and diagnosis for an anaerobic WWTP (Lardon *et al*., 2004).

The integrated computer control system (IC2S by Hydromatics Inc.) discussed by Schraa et *al*. (2005) is an on-line model based control system which integrates modelling knowledge and real time data from sensors in a WWTP. This approach has the potential to reduce failures, reduce energy and chemical requirements and pollutants to the environment, but requires a reliable stream of data from sensors. The detection of sensor errors such as drift, noise, catastrophic failures, power outages and transmission problems becomes a critical component of the monitoring system. Sensor validation is discussed in more detail in Section 3.5.

2.2. Wastewater recycling systems

Wastewater treatment trains for recycling wastewater incorporate additional treatment processes to improve water quality to the required standard. Unit processes include membranes, reverse osmosis, UV, ozonation and chlorine and other physical and chemical processes. As wastewater recycling systems are relatively new features in urban water management, the process control strategies for these systems are not as well developed. Currently there is a paucity of data from which to develop process models as technologies have not been applied to wastewater treatment previously, although generally the technologies are relatively well understood.

2.2.1. Process control strategies

A recent paper describes a process control strategy for a wastewater membrane bioreactor (MBR) (Nopens *et al.* 2009). The paper describes the development of the COST/IWA Benchmark simulation model (BSM) to include filtration models to describe the membrane component of the system. The BSM-MBR has shown promising initial results and work is continuing in developing the model.

Other recent papers from the 10th IWA Instrumentation, Control and Automation Conference describe process control strategies for water system unit processes such as coagulation and membrane filtration and reverse osmosis (Singh *et al.* 2009). Improved process control utilising Trans membrane pressure (TMP) for the coagulation and membrane filtration process led to reduced operational costs of between 1.8 and 47% (Kageyama *et al.* 2009). Fluorescence spectroscopy proved a useful measure of reverse osmosis membrane performance in removal of dissolved organic matter, and a potential alternative to the established methods of Total organic carbon (TOC) and conductivity. Fluorescence spectra can be interpreted using PCA and PLS in addition to Fluorescence Region Integration (FRI), which was the method adopted in this paper. Further development of an on-line method of fluorescence detection is being undertaken.

A design methodology is proposed for the control system of a drinking water treatment plant, which incorporates five design steps which take treatment process characteristics into account (Van Schagen *et al.* 2009). The methodology was adapted from one used in the chemical industry and suggests the following steps:

Step 1: Identify objectives

Step 2: Identify operational constraints

Step 3: Identify important disturbances

Step 4: Determine controlled variable

Step 5: Determine control configuration

This methodology takes into account plant wide objectives and would be applicable to recycled wastewater systems. The authors stress the importance of including operators, technicians and control engineers in the application of the design procedure.

As expected the published literature for the process control of small scale wastewater recycling plants is sparse. Inclusion of water treatment process control in the literature search may identify additional research in this area. Resource restrictions of this project limit this investigation to the more recent publications from the IWA Instrumentation, Control and Automation Conference discussed above.

2.2.2. Operational monitoring

The Australian Recycled Water Guidelines (2006), which are applicable to greywater treatment systems for multi-dwelling indoor use or all greywater and wastewater systems of >5kL/day, provide information on onsite controls, operational monitoring and support programs for recycled water treatment processes. For dual reticulation schemes where treated water is used both indoors and outdoors, strengthened cross connection controls are required including the ongoing education of householders and plumbers. The water quality objectives for this type of system are to be determined on a case by case basis and could include turbidity criteria for filtration, disinfectant contact time (Ct) or UV dose. *E.coli* must be less than 1 per 100mL.

Examples of operational monitoring of recycled water treatment processes to ensure on-going validation (verification) are summarised in Table 8. For all treatment processes supporting programs are instrument calibration and an asset maintenance program. The operational monitoring required for health risks is much the same as for continued validation, except turbidity upstream of the membrane plant is not required and the cleaning frequency of the UV lamp is required. These operational monitoring parameters are surrogates for the measurement of microorganisms in the recycled water. See Table 2 for indicative log removal of enteric pathogens and indicator organisms required by the different treatment processes.

Table 8 : Examples of operational monitoring for continued validation of recycled wastewater systems

Process step	Routine operational monitoring to ensure continued validation
Membrane plant	Turbidity upstream and downstream of system Head loss across system (TMP) Particle counts on outlet Daily membrane integrity test
Ultraviolet plant	Turbidity upstream of disinfection system UV transmissivity UV intensity and or/calculated dose Flow rate to enable calculation of retention times Ballast functionality, lamp power and lamp status, lamp age
Chlorination plant	Turbidity upstream of disinfection system Free chlorine temperature and pH at downstream monitoring point Flow rate to enable calculation of Ct

A typical sampling program for a recycled wastewater treatment train will include the above along with many other parameters, monitored at daily, weekly, monthly, biannual or annual frequencies. More frequent sampling occurs for schemes with higher exposure end uses.

2.3. Integrated modelling and control of wastewater systems

A number of researchers have suggested extending the boundary for assessment of wastewater process control systems to incorporate sewers and stormwater management (Schutze 1999). Using this approach researchers have identified control objectives (criteria) that are located outside the wastewater treatment system boundary, and have used water quality parameters in a receiving water body, rather than treatment plant effluent quality or discharge volume (Fu *et al.* 2008). Schutze (Schutze 1999) used the software package SYNOPSIS to model water quality and quantity in an integrated system as described above.

Hamad *et al* (2003) describe the energy and mass integration used in industrial processes, a combination of the two methods being process integration. Mass integration is basically a water and contaminant balance, and can be used to minimise wastewater discharge. The process described is more suited to the conceptual design of wastewater servicing, and describes five strategies for mass integration, segregation of streams, low cost modifications, mixing and recycling, interception and high cost process modifications. The approach also suggests a functional analysis of system components in order to optimise design. This latter aspect is also incorporated in standard permaculture methods.

2.4. Case studies

Papadopoulos *et al* (2007) describe the development and application of software for recording, assessing and reporting data from the operation of urban wastewater treatment plants in Cyprus. A database was developed to store and archive data on urban wastewater treatment plant samples, and hotel and industrial discharges. This allowed report creation, search facilities, data processing, performance assessment and corrective processes. The database was connected to a GIS platform that incorporated details of cities and their associated wastewater treatment plants, along with protected or sensitive areas, rivers, lakes and other water sources.

Research and development case studies of process monitoring are often limited to water quality parameters and do not encompass energy, materials, aesthetics, or social aspects (e.g. (Atasoy *et al.* 2007). Bradley *et al* (2002) suggest an assessment of onsite wastewater systems based on sustainable development criteria covering social, economic and environmental aspects.

3. PERFORMANCE MONITORING

Performance monitoring refers to the assessment of water quality delivered from a device/process, and it requires analysis of a number of different parameters that are often dependent on the final use of the water. With the ongoing water shortages in many Australian cities, the need has arisen to secure our water supplies using recycling and various new initiatives. This has highlighted local requirements for the availability of appropriate performance monitoring systems. In recent years there has been much research done in the area of performance monitoring. This includes broad reviews of wastewater monitoring (Bourgeois *et al.* 2001; Johnson 2005; Maclennan and Nutt 2010; Olsson *et al.*

1997; Vanrolleghem and Lee 2003) and reviews of current techniques and technologies for specific applications (Maclennan and Nutt 2010; O'Halloran 2009; O’Halloran 2008) as well as the development of new sensors and other technologies. Some of these are discussed in more detail in the following sections.

3.1. Performance parameters

There are a number of parameters of concern in small scale recycling systems, which include excess nutrients, suspended solids, salts, metals and pathogenic micro-organisms. These may be of concern for both environmental and human health reasons.

Whilst nutrients such as phosphorus and nitrogen are required for plant growth, excessive amounts are detrimental to the environment. High levels of suspended solids have the potential to physically block the soil pores or cause blockages in irrigation systems. In addition, high levels of salts will also impact on both soil structure and plant growth. High concentrations of metals such as boron, aluminium and zinc are of concern for plants and soil. Boron is known to be present in some laundry products and is acutely toxic to plants. In previous studies, concentrations of boron found in greywater (Friedler 2004) have been above the recommended maximum levels for irrigation water (EPA 1991). In some cases, zinc concentrations in greywater have been observed to be approaching or above the levels recommended for irrigation water (Christova-Boal D. 1996; Hypes 1974);

Microorganisms can also be of significant concern, particularly for systems where the end use is surface irrigation, toilet flushing or other applications with potential human contact. There are a number of bacteria, viruses and protozoa known to be commonly present in wastewater that could pose risks to human health if they were not removed adequately during the treatment process. The risks are significantly less for systems designed to be used only for sub surface irrigation.

3.2. Indicators or surrogates for parameters of concern

Most parameters of concern are readily measurable within a laboratory environment. For example, relatively simple chemical analysis can determine phosphorus, nitrogen, metals and levels of suspended solids in treated water. Nitrogen and phosphorus levels can be used to provide an indication of the potential for biological regrowth to occur in the treated water. Electrical conductivity is a surrogate measure for total dissolved solids, which provides a measure of the dissolved salt content or salinity. The sodium adsorption ratio (SAR), is a ratio of sodium (Na) to the combination of calcium and magnesium (Ca + Mg) in relation to known effects on soil dispersibility, and is a useful indicator to assess the impacts of treated water on soil infiltration and potentially soil degradation.

Microorganisms remain the major concern for human health. Many of these can also be readily tested in a laboratory environment although some analyses can have a relatively lengthy turn-around time.

A major issue with small scale treatment systems is the requirement for ongoing performance monitoring and detection of faults and failures. Although most parameters of concern can be rapidly analysed within a laboratory environment, it is much more problematic in a treatment plant setting where any delay or error can result in the discharge of potentially unsafe water. Surrogate operational monitoring is possible and parameters such as trans-membrane pressure and UV transmissivity can be used to ensure health risks are minimised (see Table 8).

The other difficulty lies in developing a detection system that does not give a significant number of false alarms. A high level of false alarms may result in potential problems going undetected by home owners who assume it to be just another false alarm, or perhaps they may even disable the detection system to avoid nuisance alarms.

3.3. Performance monitoring techniques

A number of performance monitoring techniques that are commonly used in wastewater treatment plants and some smaller scale wastewater treatment systems are outlined in Table 9. A number of the parameters can be measured continuously inline - conductivity, pH, ORP/DO and turbidity (see Section 3.7), whereas others have been developed into online monitoring systems such as (RA)COD and TOC.

Table 9: Current parameters used for performance monitoring in wastewater treatment processes

Parameter	***Wastewater treatment process***	***Comments***	***Reference***
Conductivity (inline measurement)	Often used in wastewater treatment	Simple manual or online measurement, however dependent on expected conductivity levels in the treated water to begin with	(Howard *et al.* 2004)
COD (Chemical oxygen demand) (online measurement)	Commonly used in wastewater measurements	Provides a measure of oxidisable material in the water. Standard test takes a few hours to complete although quicker and online versions are now available (PeCOD).	(Bourgeois *et al.* 2001); (Zhao *et al.* 2004)

Parameter	***Wastewater treatment process***	***Comments***	***Reference***
BOD (Biochemical oxygen demand) (online measurement)	Often a regulation requirement for wastewater treatment plants	Provides a measure of oxygen consumed by microorganisms in the water, but has a 5 day turn-around time.	(Bourgeois *et al.* 2001)
pH (inline measurement)	Wastewater treatment plants	Used in most aspects of water supply and wastewater treatment.	APHA, Standard Methods for Water and Wastewater, 2005; (Kishida *et al.* 2003)
Microbiological indicators (currently mostly laboratory measurements but new more rapid methods may become online)	Wastewater treatment plants/small scale systems	Commonly used to monitor the quality of the waste/recycled water, however traditional methods require long incubation times. New, more rapid methods are becoming available.	(Elad *et al.* 2008); (Servais *et al.* 2005); (Spano *et al.* 2005); (Howard *et al.* 2004); (Blinova 2000); (Hayes *et al.* 1997); (Belkin *et al.* 1996); (Apte *et al.* 1995)
Chlorine (inline measurement)	Disinfection control in many small scale systems.	Good source of disinfection, however monitoring required ensuring no system failure resulting in unsafe recycled water production.	APHA, Standard Methods for Water and Wastewater, 2005; (Hach 2005).
ORP / DO (Oxidation reduction potential / Dissolved oxygen) (Inline measurement)	Small scale wastewater treatment plant/ sequencing batch reactors	Intelligent diagnosis using commonly measured on-line parameters such as ORP and DO. Possible to use ORP and pH as parameters for real-time control processes	(Strandberg 2007); (Park *et al.* 2005), (Kishida *et al.* 2003)
SS (Suspended solids)	Wastewater treatment plants	Useful indicator in how well treatments are working	
Turbidity (Inline/online measurements)	Wastewater treatment plants	Useful for determining the quality of water. Often used in wastewater regulation.	
TOC (Total organic carbon) (Online Measurement)		Provides a measure of organic carbon in a sample. Provides information about water quality	(Buender 2009); (Warmenhoven and Spanjers 2009); (Bourgeois *et al.* 2001); (Hach 2001)
Soil/groundwater/soil moisture sensors	Environmental monitoring	Ability to monitor the use and effects of recycled water on the soil	(Paige and Keefer 2008); (Konukcu *et al.* 2003); (Hummel *et al.* 2001); (Rudnitskaya *et al.* 2001)

Many of the performance monitoring technologies and techniques listed in the table above work well for large scale systems such as wastewater treatment plants where operators perform regular maintenance and calibration on the equipment. However, several of these parameters (e.g. conductivity) also have potential for monitoring small scale treatment systems as they are robust, reliable, inexpensive and require very little maintenance and calibration. There have also been recent advances in COD analysis with the development of rapid online COD analysers. Advances are also being made with BOD analysis to shorten the 5 day turn-around time. However, both COD and BOD analysers require regular maintenance and calibration. Another reliable sensor is provided by pH, which can give an indication of a system’s performance, even though some calibration and maintenance is required for online units. Analysers for oxidation/reduction potential and dissolved oxygen measurements are robust and produce reliable results, however some maintenance and calibration is still required. Robust instruments are available for turbidity measurements and some of these also require very little maintenance and calibration. Total organic carbon and flow injection analysis typically involve expensive equipment, require ongoing operator input, maintenance and frequent calibration, and in their current state may not be well suited for monitoring the ongoing performance of small scale systems. Soil, groundwater and soil moisture sensors may also be useful in ongoing monitoring. Microbiological indicators have also been used for a number of years, and recent advances can potentially allow rapid microbial assessment of the treated water. Examples of these include: a method for the rapid detection of faecal coliforms using colorimetric assay within one hour (Apte *et al.* 1995) and online monitoring for nitrogen inhibition using immobilised bacteria which could be used to give an early warning of toxicity (Hayes *et al.* 1997).

3.4. New and innovative techniques

This section focuses on some of the new and innovative techniques for performance monitoring in wastewater treatment processes that have been developed or improved in the last decade. Table 10 provides an outline of these techniques along with some information about the targeted wastewater treatment processes, and additional details such as advantages and disadvantages of each technique. Biosensors combine biological reactions and a physicochemical sensor to allow detection of analytes. The biological component may be for example a cell, cell tissue, an enzyme or an antibody. Biosensors do not necessarily measure microorganisms. Flow injection analysis is a laboratory based method in which chemical analysis is performed in-line. Reagents for analysis are added directly to the process stream and any other analysis operations such as heating, cooling, mixing or aerating are also carried out in-line. The method works well in a strictly controlled laboratory environment but is unlikely to be practical in a wastewater treatment process.

Table 10: New and innovative techniques for monitoring performance in wastewater treatment processes

Technique	***Wastewater treatment process***	***Comments***	***Reference***
Biological or biosensors	Small scale treatment systems	Simple, robust and reliable sensors able to detect contamination events quickly.	(Dewettinck *et al.* 2001), (Evans *et al.* 1998); (Melidis *et al.* 2008); (van der Schalie *et al.* 2001); (van der Schalie *et al.* 2002)
BOD sensors	Wastewater treatment	Rapid BOD analysis can measure BOD in minutes rather than days. Some issues with reliability for differing sample compositions	(Rastogi *et al.* 2003); (Trosok *et al.* 2002); (Iranpour and Zermeno 2008); (Stuetz *et al.* 1999); (Yang *et al.* 1996)
Phosphate sensor	Wastewater treatment plant	Different methods (e.g. novel microfluidic lab-on-a-chip, or application of various multivariate techniques to wastewater treatment plant data)	(Slater 2009) (Jansson *et al.* 2002)
Nutrient sensors	Pilot plant scale	Online measurement of nitrate, ammonia, phosphorus for process control	(Gutierrez *et al.* 2009) (Balslev *et al.* 1996)
Microelectrode array	On-line water quality monitoring	Good reliability for monitoring disinfection agents such as free chlorine. Accurate measurements over several months without loss of sensitivity.	(Gobet *et al.* 2003)
Chemical sensor array	Continuous monitoring for sudden changes in wastewater quality	Results show how a chemical sensor array based system can be used for real-time process monitoring.	(Bourgeois *et al.* 2002)
Optical methods	Wastewater	Spectra obtained will vary significantly depending on the contaminants present.	(Sutherland-Stacey *et al.* 2009); (Gutierrez *et al.* 2009); (Mizaikoff 2003) (Danigel *et al.* 1993)
Fluorescence methods	Wastewater samples	Distinct fluorescence spectra are observed for wastewater and treated wastewater. Fluorescence is currently an area of great interest for the wastewater industry.	(Henderson *et al.* 2009) (Baker *et al.* 2004); (Reynolds 2002)
Flow injection analysis	Wastewater treatment plant	System presented still suffers from unsatisfactory long term stability.	(Pedersen *et al.* 1990)
Remote monitoring	Ability to work on any scale	Enables technologies to be monitored without the need for site visits. Allows the use of alarms to indicate system faults and failures.	(Jaiswal and Ius 2009)

There has been significant progress with new and innovative techniques for monitoring wastewater over the last decade. This includes the development of biological and nutrient sensors as well as fluorescence and optical methods. Some of these are still only available for laboratory use, and require further work if they are to become the next generation in performance monitoring technologies. Although there have been significant breakthroughs in the areas of fluorescence and optical methods, the high cost of these instruments will remain a disadvantage for their use in ongoing performance monitoring applications in the short term. Remote monitoring will most likely also play a very important role in ongoing performance monitoring, and it has the potential to substantially reduce monitoring costs. Significant advances in remote monitoring technologies have seen them become more reliable and less costly over the past decade making them a viable option for monitoring small scale wastewater systems. A major advantage of remote monitoring compared to laboratory based analysis is the ability to continuously collect data over long periods of time at various sites without requiring skilled staff to carry out the sampling and analysis. Typically the information being collected on site can be sent via mobile phone networks and downloaded onto a computer so that the data can be accessed. In most cases the system can be set up to send an alarm if the parameters being measured fall outside a preset range. This allows qualified personnel to respond to and assess alarms triggered by individual systems. Automatic reporting to a central base staffed by qualified personnel can provide a level of confidence to regulatory authorities concerning the ongoing performance of small-scale systems.

Another advance in monitoring is the use of molecular techniques to analyse microbial communities in wastewater. Recent advances in polymerase chain reaction (PCR) techniques enable rapid, specific and sensitive detection of many pathogens. The technique also enables the quantification of potential pathogens in source waters that are otherwise difficult to analyse using traditional microbiological techniques. There are two types of PCR analysis, binary PCR which detects the presence/absence of selected microorganisms and quantitative PCR which detects and quantifies potential pathogens.

Two techniques that have found applications in wastewater analysis are; denaturant gradient gel electrophoresis (DGGE), a PCR method; and fluorescent *in situ* hybridization with DNA probes (FISH) (Sanz and Kochling 2007). DGGE is a rapid and simple method that provides characteristic band patterns for different samples, allowing quick sample profiling, and has proved suitable for identifying the microorganisms that form sludge. FISH allows identification of microorganisms at any desired taxonomical level, depending on the specificity of the probe used. FISH is currently being used for elucidation of the composition, quantification and distribution of different bacterial groups in granules and biofilms, as well as their structure and architecture.

The Water Environment Research Foundation (WERF) is investigating a Hand-Held Advanced Nucleic Acid Analyzer (HANAA) for Waterborne Pathogen Detection (Project no: 99-HHE-4-ET), which evaluates the use of a novel hand-held instrument for the rapid detection and identification of pathogens. WERF are also investigating the use of real time PCR for Molecular Detection of Pathogens and Indicators (Project no: 01HHE2A), to provide knowledge of the relationship between quantitative real-time PCR, adenovirus infectivity, and cultured enterococci bacteria in environmental waters and sewage. There are also other projects investigating or developing methods for practical, rapid detection of viruses and cryptosporidium.

In Australia, the Urban Water Security Research Alliance (UWSRA) is undertaking a project investigating the safety and sustainability of purified recycled water, a strategy adopted by the Queensland Government to address water shortage in the region. One component of this project aims to develop improved methods for the detection and study of specific microbial pathogens and trace organic compounds in wastewater and fresh water using bioanalytical monitoring tools (Toze 2010). This research is also investigating viral concentration methods, along with the use of potential surrogate physicochemical parameters such as turbidity.

3.5. Sensor validation

Most of the options presented above have some advantages and disadvantages. For ongoing performance monitoring of small scale wastewater treatment systems, the selected monitoring technology or technique should ideally be robust, reliable and require little maintenance and calibration, which will immediately eliminate some of these methods. It is also important to consider which technologies and techniques will provide the most important information and thus are the best options for ongoing performance monitoring of a range of small scale recycling systems. Sensors and probes are likely to have faults during normal operation such as drift, shift, fixed values, incorrect gain, complete failure, in addition to faults associated with calibration (Schraa *et al*., 2005; Nivert *et al*. 2009). Some methods for detection of sensor faults are given in Section 2.1.2.

Reliable monitoring of wastewater and treated effluent raises a number of critical issues. In traditional laboratory analysis, samples are collected and analysed for discrete parameters, and most online wastewater monitoring systems use an extension of this procedure, in which laboratory techniques are modified and ruggedized to make field based instruments.

However, this approach has one severe limitation – the techniques used require carefully controlled conditions to give good performance. This is quite feasible with trained staff in a laboratory environment, but much more difficult in the field, and practically impossible in highly fouling wastewaters.

Some of the technologies presented require frequent calibration or regular replacement of chemical reagents, which may limit their practical use. Others may not provide reliable results if the sample matrix varies greatly, and some sensors require stable environmental conditions such as temperature to provide good results, which may be difficult to control in a treatment plant environment.

An alternative approach has been developed by CSIRO and Griffith University in which a rapidly flowing stream of wastewater is continuously fed through a manifold containing a number of selected physicochemical sensors. The flow keeps the sensors clean, and the sensor responses are analysed both on the time axis and by intercorrelation between sensors. Custom algorithms allow normal system behaviour to be defined, and this is then used as the basis of a reference baseline. This approach enables major events to be detected, and sensor faults to be rapidly identified (Zhao *et al.* 2009).

3.6. Inlet, outlet and process monitoring

Another important consideration is where in the process the monitoring should be performed. The main options are at the outlet of the treatment process (end of pipe) or during the treatment process (process monitoring) or at the inlet of the treatment process. End of pipe monitoring is a requirement for process verification in the Australian Guidelines for Water Recycling.

One of the advantages of inlet compared to end of pipe monitoring is that it can act as an early warning of a failure or fault, which may allow sufficient time for potentially unsafe water to be intercepted and discharged directly to sewer. However, most small scale treatment systems have disinfection as the final step, so end of pipe monitoring may provide a more accurate representation of the quality of the final product water. A potential solution to this would be to monitor both inlet and at end of pipe. This could also be useful for reducing false alarms if the system were set to only trigger an alarm if both the inlet and outlet water quality were out of range.

3.7. Continuous monitoring

Performance monitoring can be performed either online or inline (*in situ*). Inline analysis is typically simpler in design and is often the more cost effective option. It involves a probe being placed directly into the flow of the sample to be analysed. The main issue with inline analysis is that it is essential that the probe is robust and relatively chemically insensitive. However, many available inline sensors are often affected by physical and chemical interferences as the sample matrix (wastewater) is typically subject to significant fouling and background changes. Online analysers usually do not face the same problems of robustness and chemical insensitivity; however they are typically significantly more expensive and require routine maintenance and calibration. Online measurements are usually carried out by extracting some of the sample from the main flow, via peristaltic pumps or similar, and then automatic injection into an analytical instrument for analysis. There have been significant developments in this area in recent years, which will lead to improved *in situ* monitoring as well as improvements in calibration and auto-adjustment of inline instruments (Fogelman *et al.* 2009; Nivert *et al.* 2009),

3.8. Case Studies

There have been a number of case studies where ongoing performance monitoring has been done very successfully, mainly on a large scale. The two examples presented below are unique in that although they are based on large scale wastewater treatment, they have been designed to require very little maintenance and do not require full time personnel present on site. Both of these case studies will be discussed in more detail in Milestone 3.

3.8.1. Sydney Water - Brooklyn STP

In 2007 and 2008 Sydney Water undertook the task of designing and building a remotely and automatically controlled sewage treatment plant to service Brooklyn and surrounding towns (Marvell *et al.* 2009). The automation system for the plant was designed in accordance with Sydney Water's SCADA system standards, which ensure that all control systems are uniform and consistent. The SCADA system developed for Brooklyn includes: local and remote process control and monitoring, alarm trend and report generation, online documentation, and web cameras for both local and remote monitoring. An integrated instrumentation, control, automation and telemetry system allows the instrumentation and critical alarms to be monitored around the clock in Sydney Water's Operations Centre.

3.8.2. AquaPoint Bioclere™ - Piperton, Tennessee – USA

The city of Piperton in the USA has recently chosen a distributed wastewater treatment system instead of a conventional sewerage treatment plant (AquaPoint 2009). The main reason behind this decision was that Piperton is quite small but is expected to grow to a population of 20,000 by 2024. The main issue with building a conventional treatment plant was the high operational costs and how they could be funded in the short term before the population had increased. The AquaPoint Bioclere™ technology has been designed to allow for population growth and for additional modules to be added as more households come on line. Each unit is modular and scalable so that it can be phased in as required on both an individual level and for the entire wastewater infrastructure for the town. The technology can accommodate daily flows in the range of 2000 L to 400,000 L, it is easy to operate and requires very little operator time. In addition, the system has very low life cycle, operation and maintenance costs. The treated water is used for sub surface or drip irrigation; hence it does not require a significant amount of treatment. The individual systems are monitored by customised remote telemetry on one common network for the entire town, allowing an operator to check the condition and status of each unit in real time as well as respond to alarms from any location. The operator can also adjust settings and make changes to the system remotely, which allows a single operator to oversee a large number of plants.

4. CONCLUSIONS AND PRELIMINARY ASSESSMENT OF SUITABILITY FOR SMALL SCALE RECYCLING SYSTEMS

There are numerous factors that need to be considered in developing best practice performance monitoring techniques for small scale water recycling systems. These factors relate to variability and uncertainties associated with:

- Technology type
- System scale
- End uses and risks
- Effluent flow and quality

Best practice performance monitoring for these systems needs to address the main risks associated with the use of these technologies, pathogens in relation to human health risk and chemical components in relation to environmental risks.

The review of Australian guidelines and regulatory requirements for small scale wastewater recycling systems included assessment of the Australian Guidelines for water recycling (EPHC. 2006) and the Victorian EPA Code of Practice (EPA 2009). Currently these documents do not provide clear guidance for process, performance and verification monitoring across all system scales. In Victoria, individual property and systems < 5kL/day have different requirements to those > 5kL/day, except for multi dwelling greywater recycling systems. The local Victorian guidelines for systems <5kL/day are not prescriptive in their requirements for operational monitoring and different needs are recommended for greywater systems compared to wastewater systems. EPA Certificates of Approval provide prescriptive requirements for verification monitoring. The local guidance is currently under extensive review which is due for completion in June 2010. The US has adopted a framework approach to the overall management of onsite and decentralised wastewater treatment systems, which includes performance, operation, maintenance and monitoring. This system allows flexibility in approach and development of site specific and appropriate monitoring systems.

The variability's and uncertainties associated with small scale wastewater recycling systems and the different regulatory requirements suggest that this framework approach may be suitable in Victoria. The development of a methodology for monitoring would be more appropriate than specifying a particular monitoring technique or sensor for all treatment systems.

Many techniques for process control have been developed for larger scale wastewater treatment systems. These approaches deal with the uncertainties associated with biological processes, and so may be applicable to the development of frameworks and approaches for smaller scale systems. The approaches include Bayesian networks, fuzzy logic, neural networks and principal component analysis (PCA). However, Bayesian networks and PCA both require large datasets to identify significant parameters and develop models and so may not be appropriate to the data poor, small scale wastewater recycling systems. Bayesian networks do have the ability to self learn from existing data so may be applicable once some data becomes available.

An approach that may provide benefit to the process control of small scale recycling systems is that of variable setpoints for different operating conditions. Large scale wastewater treatment plants generally operate to single setpoints but new approaches have found improved performance when control is adapted depending of current conditions. This seems a more appropriate method for variable feed stream quality small scale processes.

Limited literature was identified describing process control of small scale wastewater recycling systems, primarily due to the paucity of historic operational data and information to support the mathematical models and statistical approaches used for process control.

Advances in integrated approaches to model and control larger scale wastewater treatment systems are also potentially applicable to the decentralised wastewater treatment approach. Monitoring of parameters outside the boundary of the treatment process may provide an alternative to extensive process monitoring, particularly for assessment of environmental health risks.

The different requirements of operational and verification monitoring likely mean that different monitoring approaches and techniques will be required. Current parameters that may be used for process monitoring are conductivity, COD, BOD, pH, micro biological indicators, chlorine, ORP/DO, SS turbidity, TOC and soil moisture. Not all of these parameters will be appropriate for monitoring in small scale wastewater recycling systems and further assessment will be undertaken in Milestone 3 of this project.

The appropriate use of indicator and surrogate monitoring parameters also requires further investigation. The Australian guidelines for water recycling provide detailed guidance for monitoring surrogate parameters for ongoing human health risk mitigation but an assessment of the validity of these approaches for all small scale wastewater systems is required.

New techniques for process and verification monitoring include biosensors, microelectrode arrays, chemical sensor arrays, optical methods, fluorescence methods, flow injection analysis and remote monitoring. Biosensors have found application in verification monitoring of large scale wastewater recycling systems through PCR techniques. Fluorescence methods have been applied to reverse osmosis operation.

Some of the technologies and techniques that have been presented in this review will have limited potential for use in ongoing performance monitoring due to onerous calibration and maintenance requirements. The reliability and ongoing performance of the various techniques and technologies also needs to be investigated further. Both calibration and maintenance along with reliability issues will be addressed in the next stages of this project, and it is expected that this will narrow the number of technologies and techniques suitable for ongoing performance monitoring.

Compatibility with existing technology is another issue that will be addressed in the next stages of the project. Given that the techniques and technologies will not be physically tested, this will be limited to information that can be obtained from manufacturers and users of these systems. The multidimensionality of the application of small scale recycling systems in time, scale and end uses also needs to be considered.

The resources required for ongoing performance monitoring should also be carefully considered. These include energy requirements, materials and ongoing use of consumables such as reagents, calibration solutions etc, and also user input requirements. These factors will have a direct impact on the costs associated with a monitoring system aside from the initial purchase costs. Resources and cost requirements for suitable systems (including purchase costs) will be included in the next stages of the project.

This literature review has identified numerous process and performance monitoring techniques and technologies that can be used for ongoing monitoring of small and large scale wastewater treatment systems. It is recognised that some of them have significant calibration and maintenance requirements which make them suitable for use in environments such as large scale wastewater treatment plants where there are skilled operators to perform these tasks. However these techniques may not be suitable for small scale treatment systems, even though they will often have similar monitoring requirements to large scale systems so as to ensure public and environmental health. This will only highlight the extent of ongoing costs for various monitoring technologies, and there are likely to be significant issues concerning cost effectiveness and the availability of trained personnel.

During this literature review, it has become evident that some currently available technologies and sensors are not suitable for continuous monitoring. This will be investigated further in the next stage of the project. It is anticipated that of the numerous process and performance monitoring techniques and technologies identified in this review, only a limited number will meet the requirements necessary to make them suitable for ongoing performance monitoring of small scale treatment systems.

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