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An Ghníomhaireacht um Chaomhnú Comhshaoil

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National Centre for Water and Wastewater Research and Demonstration

STRIVE

Environmental Protection Agency Programme

2007-2013

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

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EPA STRIVE Programme 2007–2013

National Centre for Water and Wastewater Research and Demonstration

Treatment and Monitoring of Nutrients, Odour and Sludge at a Small-Town Demonstration Wastewater Treatment System

(2006-ET-LS-12-M3)

STRIVE Report

Prepared for the Environmental Protection Agency

by

National University of Ireland, Galway

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Executive Summary

The treatment of wastewater from small towns with population equivalents (PEs) in the range 200–5,000 PE gives rise to problems different to those encountered in the treatment of wastewater from larger conurbations. While the physical, chemical and biological processes can be similar for small and large population systems, it may be necessary, due to, for example, large flow and concentration variations, to design small-town systems differently to ensure that they work efficiently, economically and with minimum supervision. In order to develop design guidelines for sustainable small-town treatment systems, it was considered necessary to construct a facility capable of examining proprietary and novel technologies that:

- Are simple, robust and cheap to build and operate;
- Can remove organic carbon, nutrients (nitrogen and phosphorus), solids, odours, micro-organisms, fats, oils, greases, and recalcitrant compounds (slowly or non-biodegradable compounds such as antibiotics, pesticides and hydrocarbons) from typical Irish wastewater streams to high standards;
- Treat resultant sludges on-site or locally; and
- Can be monitored and controlled remotely.

Such a facility was proposed, designed, constructed, commissioned and operated by researchers in Civil Engineering, National University of Ireland (NUI), Galway – at Galway County Council's Tuam Wastewater Treatment Plant (TWWTP) – and is known as the NUI Galway/Environmental Protection Agency (EPA) Water Research Facility (WRF).

In this study, the WRF treated a controllable portion of the municipal wastewater entering the TWWTP. The Pumped Flow Biofilm Reactor (PFBR) system – a wastewater technology previously invented and developed by the project team – was installed and operated at the WRF, and was tested under a series of biological and hydraulic loading rates to establish optimum operating conditions for achieving high-quality secondary treatment. Maximum 5-day biochemical oxygen demand (BOD_5), suspended solids (SS) and ammonium-nitrogen (NH_4-N) removals of 96%, 93% and 88%, respectively, were achieved giving average effluent concentrations of 12 mg BOD_5/l, 11 mg SS/l and 4.7 mg NH_4-N/l. A number of other novel waste, water and wastewater treatment technologies were also installed at the WRF. These technologies included a single-house wastewater treatment system, a sludge woodchip filter system, a new small-/medium-scale wastewater treatment system, and a tertiary treatment system. The performances of these technologies are also described in this report. The WRF now has the potential to treat the influent wastewater to non-potable reuse standards.

The WRF is a world-class infrastructure for research and technology development. Some of the main features of the facility include:

- Access to raw wastewater, allowing for technologies to be trialled for primary, secondary and tertiary wastewater treatment. The treatment facility can process up to 50 m^3/day of wastewater;
- That the PFBR can be accessed, monitored and controlled remotely and in real time;
- That this is an ideal site for testing new sensors and analysers for water and gaseous contaminant monitoring. Such sensors can be tested on wastewaters at various stages of treatment;
- That this is an ideal facility for piloting:
  - New SMART (self-monitoring, analysis and reporting technology) monitoring, control and alarm systems;
  - Web-based platforms; and

    - Cost-effective telemetry systems for decentralised water and wastewater treatment facilities;

- That a unique and highly flexible mobile remote monitoring centre (MRMC) can be deployed to technologies on-site or can be leased for use elsewhere. The system can provide real-time, in-situ and remote measurement of water, wastewater and gaseous parameters. The research team has real-time access to data from the MRMC thus allowing instantaneous feedback on process efficiency;

- Access to wastewater sludge allowing new sludge treatment methods to be tested;

- An easily accessible site at Tuam, Co. Galway;

- That samples are regularly taken and monitored and can be tested at the Environmental Engineering Laboratories, NUI Galway; and

- That experienced NUI Galway research staff operate and maintain the research facility.

The NUI Galway/EPA WRF provides a unique research facility with advantages that include:

- Increased opportunities for successful research funding proposals;

- World-class applied and fundamental research;

- Education and training of graduate, postgraduate and postdoctoral researchers;

- Increased collaboration between industries, research and policy institutes, and third-level institutions;

- Public education and technical education and training of stakeholders;

- High-profile dissemination (including via international peer-reviewed journal and conference publications, trade publications and broadcast media) of issues regarding water, wastewater and environmental technologies;

- Policy planning;

- Developing and testing novel indigenous environmental technologies and products; and

- Attracting visiting academics and students from leading international institutions.

1 Introduction

1.1 Background

The treatment of wastewater from small towns in the population equivalent (PE) range of 200–5,000 PE generates different problems to those encountered in larger conurbations. While the physical, chemical and biological processes may be similar, it is sometimes necessary to approach the design of the small-town facility differently to ensure that the system works efficiently, economically and with minimum supervision. Some of the problems with, and approaches to, small-town wastewater treatment systems are discussed below.

1. Small treatment systems can receive widely fluctuating flows, which can decrease the residence time in the system and reduce performance. The introduction of a balancing tank in the system with a controlled dosing arrangement to the biological reactors can eliminate any shock loading and improve the performance of the plant. A large balancing tank can also double as a primary settlement tank and aid in the hydrolysis of solids, leading to a possible reduction in final sludge amounts and a more useful and treatable substrate. The primary solids should be moved periodically to a covered sludge holding tank.

2. Fats, oils and grease (FOG) cause problems in biological reactors, and in clogging pipes and fittings in small treatment systems. These materials can be separated simply by mechanical devices at the inlet and biologically broken down in a separate small biofilm treatment system. Other technologies break down FOG either at source, in the sewer system or in the wastewater treatment system itself. Other large solids could be shredded.

3. Organic carbon and nitrogen can be removed in biofilm or suspended growth biological systems. Biofilm technologies include sand and soil filters, trickling filters, rotating biological contactors, biological aerated filters and moving bed filters (EPA, 1999). New biofilm technologies include the pumped flow biofilm reactor (PFBR), horizontal flow biofilm reactor (HFBR), air-suction flow biofilm reactor (ASF-BR) and the vertically moving biofilm reactor (VMBR); the PFBR, HFBR, ASF-BR and VMBR systems were developed at NUI Galway by the project team of researchers. Suspended growth systems comprise reactor variants of the activated sludge process and include extended aeration, oxidation ditches, sequencing batch reactors (SBRs) and constructed wetlands. Advantages cited for biofilm systems over other systems include:

   - Compactness of the treatment plant;
   - The degree of treatment is less dependent on final sludge separation;
   - Waste sludge production can be reduced; and
   - The biofilms can be used in more specialised ways (Odegaard et al., 1994).

   However, biofilm wastewater treatment systems operated in batch mode require the provision of a balance volume upstream of the reactors.

4. A typical biological method of removing organic carbon and nitrogen (N) is to have an anoxic phase or reactor followed by aerobic phases or reactors (Metcalf and Eddy, 2001). The system should have enough capacity for full organic carbon removal by heterotrophic bacteria followed by complete autotrophic nitrification of ammonium-nitrogen (NH_4-N) to nitrate-nitrogen (NO_3-N). The NO_3-N wastewater in the most downstream reactor or phase is returned to the most upstream reactor – the anoxic reactor – which also receives the influent wastewater from the primary settlement tank. Heterotrophs use the oxygen in the returned NO_3-N and organic carbon in the influent for new cell growth. Nitrogen gas is released to the atmosphere during the process.

Membrane technology can also be used to reduce organic carbon, nitrogen, solids and other constituents depending on the composition of the wastewater and type of filtration system used (Stephenson et al., 2000).

5. Phosphorus (P) removal can be achieved biologically or chemically (Henze et al., 2002). Biological phosphorus removal requires a combination of anaerobic and aerobic phases or reactors. During the anaerobic phase, in the presence of readily biodegradable organic carbon, phosphorus is released from the cells of phosphorus accumulating organisms (PAOs) into solution in the reactor bulk fluid. If this anaerobic phase is followed by an aerobic phase, the PAOs perform a luxury uptake of phosphorus into their cells. These cells, with the high concentrations of phosphorus, should be removed from the system, thus reducing the amount of phosphorus in the final effluent. The biological phosphorus-removal process requires more process control and careful removal of waste sludge than the organic carbon and nitrogen removal processes. Chemical phosphorus removal can be also achieved by dosing a suitable metal precipitant, e.g. iron, into the wastewater stream. This is costly and generates additional sludge, which can be difficult to handle. Phosphorus can be readily removed by passing the final effluent through a suitable sand or soil filter that contains a high ion exchange capacity (EPA, 1999). Adsorption capacities vary from 20 mg P/kg soil in sandy soil to 500 mg P/kg in clay. Sand filters can be enhanced by blending with wood chips (Healy et al., 2005) or laterites. The use of soil filters offers a low-cost sustainable solution for removing phosphorus. It must be recognised that soil filters have a finite adsorption capacity and care should be taken to prevent nutrient bypass. Saturated soils can be sent for specialist treatment to recover the nutrients (particularly phosphorus) for reuse in agricultural and industry.

6. Odour and fly nuisance must be kept to a minimum. These odours may be reduced by the use of covered tanks and can be treated by passing any nuisance gases in combination with fresh air flow through the aerobic biofilm or suspended growth reactors that are used in the removal of organic carbon and nitrogen. Fly problems can be eliminated by keeping biofilms moist.

7. Sludge handling and treatment can be a major source of difficulty in small treatment plants. It is currently not economical to build an anaerobic digester for treating sludge for a 200–1,000 PE and the economics of treating the sludge at a central sludge facility depend on its distance from the wastewater treatment system. Sludge in Ireland is typically transported to a central hub and then treated. Normally it is land-spread or sent to a composting facility. Land-spreading is increasingly being seen as an unsustainable disposal route. Sludge in Sweden is now introduced subsoil in short-rotation willow coppices during the growing season and this offers a solution on-site or near-site with the benefit of producing a biofuel or bedding material. Sufficient sludge storage should be available on-site for the willow dormant season. The project team has developed a novel woodchip filter for the treatment of sludges – a pilot-scale version of this system was trialled at the National University of Ireland (NUI) Galway/Environmental Protection Agency (EPA) Water Research Facility (WRF).

8. All equipment should be robust and readily maintained by local technical people. Complex one-off equipment with moving parts should be avoided. Pump technology is well developed, reliable and relatively cheap, and can be replaced rapidly if required. The performance of pumps can also be readily monitored and controlled through basic programmable logic controllers (PLCs).

9. The treatment facility should be monitored and, ideally, controlled remotely. This reduces the amount of supervision and travel costs. Quality monitoring can be achieved by installing sensors at critical locations in the system and interrogating them remotely through broadband Internet and mobile phone technology. For example, an NH_4-N sensor and an NO_3-N sensor in the biological reactor would not only measure the state of

nitrification but could also indicate that organic carbon removal had occurred based on the biological constraint that nitrification can only take place when organic carbon removal is nearly complete. On-line chemical oxygen demand (COD), biochemical oxygen demand (BOD) and phosphorus analysers are now also available. Pumps could be monitored and controlled remotely. Energy usage should be monitored; employing good process control can significantly reduce the energy requirements. Flow rates through the treatment system can also be measured using flumes, weirs, flow meters and pressure transducers, which can be interrogated remotely. Sludge blanket sensors and turbidimeters can be used to assess effluent quality and to control solids treatment.

10. Wastewater treatment systems should be mathematically modelled and calibrated so that different operating regimes could be simulated and analysed. For example, it would be interesting to examine the effect of reducing the air input (saving costs) or changing pumping regimes in a treatment system. There are a number of computer programs available for modelling wastewater treatment plants in this manner, e.g. GPS-X™, AQUASIM, STOAT™ and EFOR™. They are all based on the International Water Association (IWA) deterministic model for wastewater treatment.

Aachen University, Germany, has a facility for rigorous testing and certifying new small wastewater treatment technologies at its wastewater facility. Some countries have on-site wastewater research facilities where industry, universities and local authorities have collaborated to promote the development of international wastewater treatment technologies and industries; these include the UK, Denmark, France, Australia and Canada. The WRF is comparable to these facilities, ensuring that a world-class research and development centre is available to Irish researchers and industry stakeholders.

1.2 Proposed Solution

For balanced social infrastructure worldwide, the development of sustainable wastewater treatment systems for small towns (200–5,000 PE in Ireland) should:

- Be simple, sustainable, robust and cheap to construct and operate;
- Reduce FOG from wastewater streams to high standards;
- Remove organic carbon, nutrients (nitrogen and phosphorus) and solids from wastewater streams to high standards;
- Decrease micro-organism numbers where required;
- Treat resultant sludges on-site or locally; and
- Be monitored and controlled remotely.

Such a demonstration wastewater treatment system, incorporating the characteristics above, was established by a Civil Engineering research team from NUI Galway under the EPA's Environmental Research Technological Development and Innovation (ERTDI)[1] programme, at an existing wastewater treatment plant (Tuam Wastewater Treatment Plant – TWWTP) in conjunction with Galway County Council. In this NUI Galway/EPA WRF, organic carbon, nutrients and solids were removed using a new low-cost robust biofilm technology – the PFBR system – that had been invented, developed and tested by NUI Galway at laboratory and pilot-plant scales. Sludge was finally treated on a novel woodchip filter, which was also invented and developed at NUI Galway. Other technologies were installed with the aim of bringing the treated effluent to potable water standards for reuse and these technologies include sand, activated carbon and zeolite filters, and an ultraviolet (UV) disinfection system. Two further NUI Galway inventions were located at the facility:

1. A single-house wastewater treatment system (HFBR); and
2. A fully enclosed low-energy SBR-type wastewater treatment system (ASF-BR) suitable for safe internal use, e.g. in buildings and on ships.

1. This programme has been replaced by the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007–2013.

The performance of the PFBR was monitored remotely using samplers, sensors, PLCs and a broadband connection. Performance data and design criteria were developed and published.

The NUI Galway/EPA WRF provides a unique national research facility for developing and testing novel indigenous environmental technologies and products, public education, technical education and training, policy formulation and planning.

1.3 Objectives

The main objectives of this large-scale ERTDI project are listed below in terms of eight tasks identified in the original proposal:

Tasks 1–3 (Chapter 3)

- The construction of an innovative, economic, simple-to-operate small-town wastewater treatment facility that will remove organic carbon, nutrients, solids, micro-organisms, FOG and possibly odours to acceptable high standards;
- To provide alternative tertiary facilities for polishing secondary treated wastewater;
- To provide facilities for treating sludge; and
- To instrument the facility with sensors, analysers, energy meters, flow measuring devices, and a broadband connection so that the system performance can be interrogated, assessed and controlled remotely.

Tasks 4–5 (Chapter 4)

- To monitor the plant for the removal of organic carbon, nitrogen, phosphorus, solids, micro-organisms, FOG and possibly odours to acceptable high standards and store the data in a database in a form suitable for graphical statistical analyses; and
- To synthesise the data to produce loading and removal rates for all constituents.

Task 6 and 8

- To complete the literature review, periodic and final reports, design manual and three to six international peer-reviewed papers; and
- To develop design criteria for each process suitable for the design of treatment plants for other population sizes.

Task 7

- To calibrate a computer model for the treatment process so that a range of operating scenarios can be explored and evaluated.

Additionally, a national centre for water and wastewater research and demonstration was constructed for:

- The development and testing of novel indigenous waste, water and wastewater technologies suitable for the marketplace;
- Future use as a base for graduate MSc and PhD research degrees in a wide range of waste, water and wastewater topics;
- Professional development, technical education and training;
- Undergraduate training;
- Policy development;
- Planning;
- Public education; and
- School tours to encourage the uptake of science and engineering at third level.

1.4 Report Structure

This report details the research work carried out as part of the EPA ERTDI large-scale study award (*Treatment and Monitoring of Nutrients, Odour and Sludge at a Small-Town Demonstration Wastewater Treatment System*, 2006-ET-LS-12-M3).

Chapter 2 presents a review of recent relevant literature. Chapters 3 and 4 introduce and describe the WRF and present the synthesised data accumulated on the main secondary wastewater treatment system (the PFBR) employed at the WRF. Chapter 5 describes the novel sludge treatment system developed and trialled at the WRF. In Chapter 6, a number of ongoing and related research projects being carried out at the WRF are outlined. Chapter 7 presents research dissemination carried out to date, including publications, media publicity, hosting key academics and stakeholders, and education. Chapter 8 details the potential of the WRF as a key piece of national research infrastructure in Ireland, with conclusions and recommendations from the project given in Chapters 9 and 10, respectively.

2 Literature Review

2.1 Regulations and Guidelines

2.1.1 Wastewater treatment

In the European Union (EU), construction of wastewater treatment systems should take into consideration, where relevant, the Urban Waste Water Treatment Directive (91/271/EEC), the Water Framework Directive (WFD) (2000/60/EC), the Groundwater Directive (2006/118/EC), the Surface Water Directive (75/440/EEC), the Bathing Water Directive (76/190/EEC), the Freshwater Fish Directive (2006/44/EC) and the Shellfish Directive (79/923/EEC), and the Water Services Act. Standards governing the design, construction, and safe operation of wastewater treatment systems over 50 PE are set down in Waste Water Treatment Plants: EN 12255:2000 Parts 1–16 (IS EN 12255:2002–2005). The Urban Waste Water Directive governs discharge limits for urban areas with populations greater than 2,000 PE (Tables 2.1a and b). However, these can be made more stringent in cases where local authorities feel it is necessary.

Table 2.1a. Regulations concerning discharges from urban wastewater treatment plants and subject to the measures of the Directive from 21 May 1991[a] (Urban Wastewater Treatment Directive 91/271/EEC).

Parameters	Concentration	Minimum percentage of reduction[b]
5-Day biochemical oxygen demand (BOD_5 at 20°C) without nitrification[c]	25 mg/l O_2	70–90%
Chemical oxygen demand	125 mg/l O_2	75%
Total suspended solids	35 mg/l[c]	90%[c]
	35 mg/l in high mountain regions for agglomerations with more than 10,000 PE	90% in high mountain regions for agglomerations of more than 10,000 PE
	60 mg/l in high mountain regions for agglomerations whose size falls between 2,000 and 10,000 PE	70% in high mountain regions for agglomerations whose size falls between 2,000 and 10,000 PE

[a]The values of concentration or percentage of reduction can be chosen indifferently.
[b]Reduction in relation to influent values.
[c]This requirement is optional.

Table 2.1b. Requirements for discharges from urban wastewater treatment plants to sensitive areas (Urban Wastewater Treatment Directive 91/271/EEC).

Parameters	Concentration	Minimum percentage of reduction[a]
Total phosphorus	2 mg/l (10,000–100,000 PE)	80%
	10 mg/l (>100,000 PE[c])	
Total nitrogen[b]	15 mg/l (10,000–100,000 PE)	70–80%
	10 mg/l (>100,000 PE[c])	

[a]Reduction in relation to the load of the influent.
[b]Total nitrogen means the sum of total Kjeldahl nitrogen (organic and ammoniacal nitrogen), nitrate-nitrogen and nitrite-nitrogen.
[c]The values for concentration are annual means as referred to in paragraph 4 (c) of the Fifth Schedule of the Urban Waste Water Treatment Regulations, 2001 (SI No. 254). However, the requirements for nitrogen may be checked using daily averages when it is proved, in accordance with paragraph 1 of that Schedule, that the same level of protection is obtained. In this case, the daily average must not exceed 20 mg/l of total nitrogen for all the samples when the temperature from the effluent in the biological reactor is superior or equal to 12°C. The conditions concerning temperature could be replaced by a limitation on the time of operation to take account of regional climatic conditions.

In Ireland, guidelines on the design and operation of wastewater systems up to 2,000 PE are given in the EPA Wastewater Treatment Manuals (EPA, 1999). Similarly, in Scotland, guidelines on the design of wastewater treatment systems up to 1,000 PE and guidance on flow design are available (SEPA, 2005). An extensive guide to small- and medium-size wastewater treatment systems for populations of 500–5,000 PE has been produced by the EU (IS EN 12255:2002–2005). It deals with various technologies that can be used and how the relevant directives can be met.

In the US, extensive guidelines and technology fact sheets for small towns and decentralised systems are available (US EPA, 2002). Each individual state publishes its own regulations concerning discharge limits.

2.1.1.1 Water Policy in Europe

The Groundwater Directive, the WFD and the Surface Water Directive give policy requirements, water quality monitoring obligations and limits of contaminants that must be met by Member States (91/271/EEC; 2000/60/EC; 75/440/EEC).

The WFD divides territories into individual 'river basin management districts' defined as the areas of land and sea, made up of one or more neighbouring river basins together with their associated ground, surface and coastal waters. Each district is identified under Article 3(1) as the main unit for management of river basins. River basin districts can be cross-territorial and may require international management plans. The WFD requires that sources of pollution to the river basin district be identified and appropriate measures implemented to ensure that pollutants from such sources are limited and/or prevented.

Indicators of increasing pollution levels must be drawn up so that deteriorating waters can be identified and remediated. The Directive cites 15 years as the time limit within which surface waters should be 'restored' and achieve good ecological and chemical status. This has implications for small-scale wastewater treatment systems and other point source discharges.

The ecological status of a waterbody is divided into five categories; 'high status', 'good status', 'moderate status', 'poor status' and 'bad status'. Artificial waterbodies or heavily modified waterbodies are categorised as follows: 'maximum ecological potential', 'good ecological potential', 'moderate ecological potential', 'poor ecological status' and 'bad ecological status'. The Directive also outlines monitoring frequency for various ecological, biological and physico–chemical properties. For example, nutrient monitoring should be carried out on a 3-monthly basis for rivers, lakes, coastal and transitional waters. Monitoring of potable water sources is also regularised depending on the population served.

Thirty-one priority substances are listed in the WFD as being of highest concern for their potential to pollute waterbodies. These substances include biocides, metals, polyaromatic hydrocarbons (PAHs), and other selected chemicals. The Groundwater Directive places threshold values on the following substances: arsenic, cadmium, lead, mercury, ammonium, chloride and sulphate. Table 2.2 lists some threshold values explicitly stated in the Directive (2006/118/EC).

The Surface Water Directive (75/440/EEC) outlines the minimum standard of treatment necessary for potable water sources based on micro-organism concentrations. In this Directive, there are three categories (Table 2.3a) of surface water sources for

Table 2.2. Groundwater quality standards referred to in the Groundwater Directive (2006/118/EC).

Pollutant	Quality standard
Nitrates	50 mg/l
Active substances in pesticides, including their relevant metabolites, degradation and reaction products[a]	0.1 µg/l 0.5 µg/l (total)[b]

[a]'Pesticides' means plant protection products and biocidal products as defined in Article 2 of Directive 91/414/EEC and in Article 2 of Directive 98/8/EC, respectively.
[b]'Total' means the sum of all individual pesticides detected and quantified in the monitoring procedure, including their relevant metabolites, degradation and reaction products.

Table 2.3a. Categories of surface water abstracted for potable water use (Surface Water Directive 75/440/EEC).

Category A1	Simple physical treatment and disinfection, e.g. rapid filtration and disinfection
Category A2	Normal physical treatment, chemical treatment and disinfection, e.g. pre-chlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorination)
Category A3	Intensive physical and chemical treatment, extended treatment and disinfection, e.g. chlorination to break point, coagulation, flocculation, decantation, filtration, adsorption (activated carbon), disinfection (ozone, final chlorination)

Table 2.3b. Requirements of some contaminants for each category (Surface Water Directive 75/440/EEC).

Directive 75/440/EC parameter number	**Parameter**	**Units**	**Standards for categories**		
			A1	**A2**	**A3**
1	pH		5.5–8.5	5.5–9.0	5.5–9.0
7	Nitrates	mg/l NO_3	50	50	50
25	Phosphates	mg/l P_2O_5	0.5	0.7	0.7
31	Dissolved oxygen saturation rate	% O_2	>60%	>50%	>30%
32	5-Day Biochemical oxygen demand (BOD_5) (at 20°C without nitrification)	mg/l O_2	5	5	7
33	Nitrogen by Kjeldahl method (except in NO_2 and NO_3)	mg/l N	1	2	3
34	Ammonium	mg/l NH_4	0.2	1.5	4
36	Total coliforms 37°C	per 100 ml	5,000	25,000	100,000
37	Faecal coliforms	per 100 ml	1,000	5,000	40,000
38	Faecal streptococci	per 100 ml	200	2,000	10,000
39	*Salmonella*		Not present in 500 ml	Not present in 100 ml	

drinking water with associated contaminant thresholds (Table 2.3b) and resulting treatment requirements.

World Health Organisation (WHO) guidelines in terms of bacterial quality of drinking water and treatment required are similar to those prescribed by the EU (WHO, 1993). These are summarised in Tables 2.4a and 2.4b. These quality guidelines have implications for wastewater discharges in terms of protecting water sources.

In 2003, the EPA published, in the absence of published criteria, an interim guide for groundwater parameters for good groundwater chemical status (EPA, 2003). The guidelines aimed to provide a consistent framework for groundwater characterisation in Ireland by proposing a set of interim guideline values (IGVs) that assist with the characterisation of groundwater bodies and to establish the need for additional investigations or further actions in the event of the guideline values being exceeded. A comparison between EU drinking water regulations, Geological Survey of Ireland (GSI) ‘triggers’ and the EPA IGVs are presented in Table 2.5 for orthophosphate, nitrate and nitrite.

2.1.2 Biosolids and sludge disposal

The increasing need for improved water and wastewater treatment systems has made it necessary

Table 2.4a. Bacteriological quality of drinking water[a] (WHO, 1993): Organisms' guideline value.

All water intended for drinking	*Escherichia coli* or thermo-tolerant coliform bacteria[b] must not be detectable in any 100-ml sample
Treated water entering the distribution system	*E. coli* or thermo-tolerant coliform bacteria[b] must not be detectable in any 100-ml sample. Total coliform bacteria must not be detectable in any 100-ml sample
Treated water in the distribution system	*E. coli* or thermo-tolerant coliform bacteria[b] must not be detectable in any 100-ml sample. Total coliform bacteria must not be detectable in any 100-ml sample. In the case of large supplies, where sufficient samples are examined, they must not be present in 95% of samples taken throughout any 12-month period

Table 2.4b. World Health Organisation-recommended treatments for different water sources to produce water with negligible virus risk[a] (WHO, 1993).

Type of source	Recommended treatment
Groundwater	Protected, deep wells: essentially free of faecal contamination. Disinfection[b] Unprotected, shallow wells; faecally contaminated. Need for filtration and disinfection
Surface water	Protected, impounded upland water; essentially free of faecal presence. Disinfection Unprotected impounded water or upland river; faecal presence. Filtration and disinfection Unprotected lowland rivers; faecal contamination. Pre-disinfection or storage, filtration, disinfection Unprotected watershed; heavy faecal contamination. Pre-disinfection or storage, filtration, additional treatment and disinfection Unprotected watershed; gross faecal contamination. Not recommended for drinking-water supply

[a]Immediate investigative action must be taken if either *E. coli* or total coliform bacteria are detected. The minimum action in the case of total coliform bacteria is repeat sampling; if these bacteria are detected in the repeat sample, the cause must be determined by immediate further investigation.
[b]Although *E. coli* is the more precise indicator of faecal pollution, the count of thermo-tolerant coliform bacteria is an acceptable alternative. If necessary, proper confirmatory tests must be carried out. Total coliform bacteria are not acceptable indicators of the sanitary quality of rural water supplies, particularly in tropical areas where many bacteria of no sanitary significance occur in almost all untreated supplies.

Table 2.5. Comparison between interim guideline value (IGV) and other guidelines/regulations (EPA, 2003).

Parameter	Drinking water standards[a] (mg/l)	GSI[b] triggers (mg/l)	EQSs[c] for surface waters (mg/l)	IGV (EPA) (mg/l)
Nitrate (as NO_3)	50	25	50	25
Nitrite (as NO_2)	0.1		0.2	0.1
Orthophosphate	0.03			0.03

[a]Drinking Water Directive (80/778/EEC).
[b]Geological Survey of Ireland (GSI) (GSI, 1999).
[c]Environmental quality standard (EQS) (SI No. 42, 1999).

to focus on the generation, collection and safe disposal of sludges and biosolids.

Regulations affecting the disposal of sludges and biosolids include the EU Directive 86/278/EEC which promotes the reuse of treated biosolids as a means of soil conditioning or as a fertiliser on agricultural land. Untreated sludge, under Directive 99/31/EC, cannot be used in this manner unless it is injected or incorporated into the soil. Since 2005, the disposal of organic waste to landfill is not permitted. Treated sludge, under this Directive, is defined as sludge that "*has undergone* *biological, chemical or heat treatment, long-term storage or any other appropriate process so as to significantly reduce its fermentability and the health hazards resulting from its use*". A reduction of biodegradable waste disposal of 75% by 2006, a further 50% by 2009 and a further 35% by 2016 from 1995 levels is proposed in this Directive. In conjunction, the EU has targeted a reduction in final sludge waste disposal by 20% compared with the 2000 levels by 2010 and by a further 50% by 2050 (Fytili and Zabaniotou, 2008).

The rules for disposal of hazardous waste in general are set out in Directive 91/156/EEC. Article 14 of the Urban Wastewater Treatment Directive states that "*sludge arising from waste water treatment shall be re-used whenever appropriate*".

In the US, disposal of wastewater sludges, residuals and biosolids is governed in general by Federal regulations, notably 40 CFR Part 258 (which regulates the surface disposal, land application and incineration of biosolids) and 40 CFR Part 503 (which concerns heavy metals and limits for pathogens and vector attraction). The 1988 National Sewage Sludge Survey provided the basis for this rule (US EPA, 1990, 1991, 1993).

Spinosa (2007), in a major global wastewater sludge overview, outlined the strategies, technologies, problems and markets on a global scale. A summary of this report of worldwide strategies is presented below.

In Asia, there is a variety of strategies employed for dealing with sludges. In South Korea, most sludges are still dumped at sea. Novel successful trials, such as using solids as feed for earthworms, as admixtures for coagulants and seed planting, and even as a protective layer against erosion on sloping cut ground are under way. Japan is moving from thermal treatment technologies to those that are less energy intensive. Composting and the use of de-watered cakes in Portland cements are alternative methods being considered. Singapore landfills most sewage sludges in a dedicated offshore island. Taiwan has employed the use of horticulture and co-incineration with municipal solid waste, with plans to ban landfilling by 2010. In Australia, the major strategies include recycling to land, farmland application, incineration and composting. New Zealand combines landfill and composting as its major disposal route. The use of landfilling and dumping at sea is also prominent in developing countries. Clean water supply and wastewater treatment in some regions are in their infancy and sludges are often stored on-site, or in many cases, de-sludging of treatment systems is often not undertaken.

2.1.3 Odour control and remediation

Policy and regulation in Ireland on odour control and remediation is derived mainly from EU legislation. The Irish EPA has been a major driver of these regulations with regard to odorous and gaseous emissions (EPA, 2007). Local authorities, in their waste management strategies, have to prepare odour management plans for the wastewater treatment plants they operate, landfill operations and other odour-producing activities (Van Harreveld et al., 2001). The EPA has moved to define criteria on emissions from agricultural sources and the mushroom growing substrate composting sector.

Environmental Impact Assessments (EIAs) are required for new and ongoing activities that might produce odorous emissions. An EIA should be prepared for projects that fall within Section 5 of the Planning and Development Regulations (2001–2002) (SI No. 90, 2003). This will often include possible effects and remediation measures of odorous gaseous emissions.

European Directives are in place to define and quantify gaseous emissions and air quality. In terms of defining quantitative air quality criteria for odours, dose-effect studies are used to determine a level where "*no justified cause for annoyance*" exists (Van Harreveld, 2003). EN 13725:2003 replaces national guidelines for EU countries and addresses the measurement and quantification of odorous emissions. Australia, New Zealand (AS/NZ, 2001) and Japan (Japanese Triangular Methods; Park, 2003) have adopted guidelines similar to European guidelines.

EN 13725 defines the European Reference Odour Mass (EROM), or a mass that is just detectable when evaporated into 1 m^3 of neutral gas, as equivalent to 123 µg *n*-butanol. *n*-Butanol is used as a reference odour and strict statistical and measuring practices are recommended. This reference standard has led to a marked improvement in the performance of olfactometry, and has been verified in an increasing number of blind inter-laboratory tests. This reference standard has proven necessary to define policy on what are nuisance and annoyance levels of odours.

EU legislation dealing with (i) odours produced from wastewater treatment systems (91/271/EEC) and (ii) the generation and treatment of odours (SI No. 787, 2005), in general, is becoming increasingly stringent, and should lead to the harmonisation and implementation of odour nuisance regulations and guidelines that currently differ from country to country within Europe (Schlegelmilch et al., 2005). At present, buffer zones are often used around treatment facilities in order to allow for dispersion of gases and odours produced, but these buffer zones are not sustainable and do not reduce emission loads and some of their effects, while increasing the cost of the land necessary for such facilities.

Directives on air quality, most recently 2004/107/EC, detail specific limits for air pollutants such as PAHs and certain metals. Separate legislation – EPA Act 1992 and SI No. 286 of 2006 – sets limits and guidelines on volatile organic compounds (VOCs) and ozone-depleting substances (SI No. 7, 1992; SI No. 53, 2004). Recent studies have shown that between 16 and 33 odorous compounds such as alkyl VOCs, naphthalene and hydrocarbons can be emitted from municipal wastewater treatment facilities, mainly from primary clarifiers and through sludge de-watering (Huang et al., 2011). Such studies show that air quality around wastewater treatment plants is of growing concern. As an example, a recent estimation of costs for the treatment of VOC emissions from a primary clarifier in Taiwan was about $ USD 0.1/m^3 wastewater treated (Cheng et al., 2008).

2.2 Challenges Facing Wastewater Engineers, Scientists, Planners and Policy Makers for Small-Scale Wastewater Treatment Systems

2.2.1 Wastewater treatment and reuse

In Ireland, discharges from urban wastewater treatment systems are one of the main sources of water pollution. About 90% of urban wastewater treatment plants (>500 PE) receive secondary treatment or better; this figure steadily increased over the last two decades having a significant positive effect on the quality of waterways (EPA, 2009). Under the WFD, by 2015, good status must be achieved for all waterways. To this end, the improvement of current and the development of new wastewater treatment facilities must continue. Small wastewater treatment systems bring with them a number of particular challenges and problems that need to be addressed. Treatment systems that can remove carbon, nitrogen and phosphorus and achieve good bacterial and micro-organism removal in an economic, carbon-friendly and sustainable manner are required.

Balkema et al. (2004) defined three areas under which wastewater treatment systems can be assessed in terms of their long-term sustainability: economic, environmental and socio–cultural. van den Bergh and van der Straaten (1994) define similar sustainability concepts under biological, economic and social headings. Public involvement during the planning stages of such systems can be beneficial to their acceptability, operation and future sustainability.

EU countries have relatively abundant water resources when compared with other regions worldwide. The Urban Waste Water Treatment Directive (1991) calls for the reuse of wastewaters whenever 'appropriate' (91/271/EEC). The WFD does not specifically mention water reuse. In southern Europe, water reuse is not widespread, though it is used in some irrigation schemes. The focus in northern Europe has been the protection of water resources. In the EU, water reuse has, in the past, been largely overlooked as an integral part of water resource management (Lazarova, 2000; Angelakis and Bontoux, 2001). However, the issue of water reuse is becoming topical due to concerns relating to climate change and changing water supplies (Angelakis et al., 2003; Lazarova et al., 2003). Countries that have specific water reuse regulations include France, Italy, Spain, Belgium, Greece, Portugal, Sweden, the Netherlands and the UK. Other countries (including Ireland) have, as of yet, no regulatory framework (Angelakis et al., 2003).

The public acceptance of wastewater reuse may be one of the biggest challenges facing planners and policy makers into the future. Kantanoleon et al. (2007), in a pilot-scale study in Greece, found that lack of knowledge, along with little information on water quality and economic analysis, negatively affected public perception towards wastewater reuse.

2.2.2 Operation, control and maintenance

To guarantee satisfactory performance and integration into the local community of small and decentralised wastewater treatment systems, a number of problems must be overcome. Boller (1997) noted that only when skilled operation, control and maintenance of small treatment systems are in place can performance be guaranteed. Norton (2009) outlined some of the main problems as mechanical component failure, high energy requirements due to inefficient operation and the need for full-time on-site operators as drawbacks with many decentralised wastewater treatment plants. However, as decentralised wastewater treatment becomes more advantageous due to the local value of water and the cost of water conveyance offsetting the economies of scale of larger plants (Norton, 2009), it is essential that technologies are developed and optimised to overcome these problems.

There is also a growing need for the throughput and efficiencies of wastewater plants to be improved while simultaneously decreasing maintenance and running costs (Alkhaddar et al., 2005). This requires trained operators. To improve the situation a number of different approaches can be taken:

- Construction of treatment systems that require low levels of control and maintenance;
- Enforcing service contracts for regular maintenance by skilled operators and manufacturers; and
- Organisation of adequate operator training and establishing regular training programmes for operators and engineers.

Recent studies have focused on the control of wastewater treatment systems using advanced ‘intelligent control’ systems. Characteristic profiles, on systems such as SBRs, using dissolved oxygen (DO), NH_4-N, NO_3-N, pH and oxidation–reduction potential (ORP) probes can monitor the processes of nitrification and denitrification, leading to enhanced nitrogen removal and resulting in energy savings but reduced aeration and cycle times (Yang et al., 2007).

2.2.3 Odour nuisance

Odour and gaseous emissions can be a major issue with local wastewater treatment systems and can give rise to significant public anxiety and complaints. Emissions from wastewater treatment and biosolids storage/treatment facilities include carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), hydrogen sulphide (H_2S), VOCs and nitrous oxide (N_2O).

Odours generally result from organic degradation that leads to the formation of volatile or gaseous compounds. When a biological reactor is operating under aerobic conditions, odour is generally minimal. If wastewaters become anaerobic, pungent odours such as hydrogen sulphide or sulphur dioxide (SO_2) are formed (Gray, 1999). Anaerobic conditions can be due to operational problems at the treatment system. In cases where there is sludge storage on-site, odours can be a major issue. A range of biological, chemical, absorption and physical methods are available for odour treatment, including bioscrubbers, biofilters, chemical filters, clean water absorption and activated carbon absorption (Burgess et al., 2001).

Intensive research has been undertaken to quantify the effects on human health of gaseous and odorous emissions from various agricultural, municipal waste and wastewater systems and industrial processes. This has established links between decreased physical and psychological well-being in public areas exposed to such emissions. Population increases and increased industrial and agricultural activity have amplified the need for effective remediation systems.

Complaints such as eye, nose and throat irritations, headaches and drowsiness are more common in areas exposed to agricultural, crop, waste management and other forms of odorous emissions (Bowker et al., 1989; Palmquist et al., 1997; Schiffman, 1998; Schleslinger, 1999). Increased mental and social health problems have been identified where odour irritations were reported (Donham et al., 2007). Effects have often proven difficult to quantify scientifically, with odours reported as a significant irritant even where no ill-health effect has been measured (Schustermann, 2001). Other effects of these emissions can include reduced property values, conflict between neighbours and generally a reduction in community relations and a deterioration in 'public mood' (Nelson et al., 1992; Schiffman et al., 1995; Aneja et al., 2006).

Emissions from various waste sources, including wastewater treatment systems, in Ireland, the EU, the USA and Thailand are presented in Tables 2.6–2.9. There is significant scope for the reduction of the carbon footprint and remediation of nuisance odours from these sources by biological treatment methods.

Studies on wastewater treatment systems have shown that the nature of the wastewater, the type of processes used for treatment and the level of maintenance on the system can all affect the emissions of various gases and odorous compounds from these systems. Table 2.9 shows typical methane emissions from various municipal treatment plants and their individual processes from a study in Thailand. It is possible to isolate the processes that create the most damaging air emissions and put technologies in place to treat these emissions.

In small-scale wastewater treatment systems the production of biogas is uneconomic in terms of usage as a fuel for energy generation. Thus, the on-site remediation of such gases is important and can reduce the overall carbon footprint of the treatment plant while increasing public confidence in the facility. Sustainable, innovative and economic technologies are required for odour mitigation in small community waste and wastewater facilities.

Table 2.6. Base average projection (2008–2012) for carbon emissions from various sources in Ireland (DoEHLG, 2006).

Sector	Mt CO_2 equiv.
Energy	18.75
Residential	6.83
Industry/Services/Commerce	14.20
Agriculture	17.64
Transport	13.03
Waste	**1.83**

Table 2.7. Actual and projected EU carbon emissions due to waste processing (adapted from Bates and Haworth, 2000).

Sector	1990 (Mt CO_2 equiv.)	2010[a] (Mt CO_2 equiv.)
Landfills	137.7	140.1
Wastewater handling	15.3	15.3
Waste incineration	0.5	0.5
Other	1.5	1.5
Total	**155.0**	**157.4**

[a]The emissions for wastewater handling, waste incineration and other waste have not been estimated, and have been assumed not to change from 1990 values.

2.2.4 *Daily flows and contaminant concentrations*

Varying daily flows are a common feature of small wastewater treatment plants (Pujol and Liénard, 1990). Design guidelines are published in many countries to aid engineers in designing and predicting the flows and contaminant concentrations that must be treated. Balance tanks can be used to help deal with varying

Table 2.8. Emissions of greenhouse gases from landfill and wastewater facilities in the USA (adapted from US EPA, 2007).

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
	(Mt CO_2 equiv.)							
Methane	**185.8**	**182.2**	**158.3**	**153.5**	**156.2**	**160.5**	**157.8**	**157.4**
Landfills	161.0	157.1	131.9	127.6	130.4	134.9	132.1	132.0
Wastewater treatment	24.8	25.1	26.4	25.9	25.8	25.6	25.7	25.4
Nitrous oxide	**6.4**	**6.9**	**7.6**	**7.6**	**7.7**	**7.8**	**7.9**	**8.0**
Domestic wastewater treatment	6.4	6.9	7.6	7.6	7.7	7.8	7.9	8.0
Total	**192.2**	**189.1**	**165.9**	**161.1**	**163.9**	**168.4**	**165.7**	**165.4**

Table 2.9. Concentration of gaseous emissions from various wastewater treatment facilities (adapted from Chou and Chen, 2005).

WWTPs	Concentration ranges of gaseous emission (C_g, ppmv as CH_4)										
	Primary treatment						Biological treatment and effluent system			Sludge treatment	
	Neutralisation tank	API/CPI	Aerated degritter	Primary clarifier	Rapid/Slow mixing tank	Dissolved air flotation	Aerated tank[f]	Bio-clarifier	Effluent tank	Sludge thickener	Belt press machine
A		N.A.[a]			N.A.[a]	553 ± 226[b]	118 ± 93[b]	3.4 ± 0.2[d]			
B	N.A.[a]				N.A.[a]		4.3 ± 4.3[c]	1.1 ± 1.1[c]	1.0 ± 1.0[c]		
C	11 ± 11[c]						2.3 ± 2.3[c]	1.2 ± 1.2[c]	1.0 ± 1.0[c]	1.4 ± 1.4[c]	1.7 ± 1.7[d]
D		1,198 ± 778[b]			87 ± 83[b]	N.A.[a]	N.D.[b,e]	N.D.[b,e]			
E	4,764 ± 237[b]						N.D.[c,e]	N.D.[c,e]		N.D.[c,e]	
F	718 ± 491[b]						762 ± 762[c]	1.2 ± 1.2[c]	0.4 ± 0.4[c]		
G	0.2 ± 0.2[c]			2.1 ± 1.9[c]			71 ± 69[c]		20 ± 20[c]	14 ± 14[c]	40 ± 38[d]
H	1,586 ± 1,065[b]						108 ± 42[b]			30 ± 30[b]	
I				N.A.[a]			3.7 ± 0.6[c]	0.6 ± 0.6[c]			
J		1,052 ± 27.2[b]				N.A.[a]	77 ± 7.0[b]				
K		20 ± 9.0[c]				N.A.[a]	151 ± 36[b]	27 ± 2.7[b]			
M		1,413 ± 1,400[b]			6,030 ± 6,000[b]	6,500 ± 3,500[b]	1,148 ± 1,081[b]	11 ± 8.0[b]			
N	646 ± 488 [b]	N.A.[a]					25 ± 7.0[b]				

[a]Not applicable. Tanks are covered and exhausted via suction blowers to prevent gaseous emission.
[b]Detecting the gaseous emission and exhaust speed at the vents of the cover on tanks.
[c]Detecting the gaseous emission at 10 cm above the surface of water.
[d]Detecting the gaseous emission at 10 cm above the surface of screen or de-watering belt.
[e]Not detected. The detecting value was under 0.1 ppm as CH_4.
[f]Activated sludge for wastewater treatment plants (WWTPs) A, B, C, D, E, I, K, and N; biocontacted aeration for F, G, H, and M; and sequenced batch reaction (SBR) for J.
API, American Petroleum Institute; CPI, Corrugated Plate Interceptor.

flows and extra storage in the primary settlement tanks can be provided. Treatment systems should be flexible and able to handle both periods when the plant is underloaded and when it has occasional surge flows. New technologies such as the PFBR, developed at NUI Galway, can be effective in overcoming such problems.

2.2.5 Fats, oils and grease

Fats, oils and grease can cause major problems in treatment systems. It is good practice for these to be removed at source as much as possible. Grease and fat traps are commonly available and are often installed in-house at restaurants and other such commercial premises. Despite this, some presence of FOG can be expected at treatment systems and these need to be removed or biologically broken down within the system (Odegaard et al., 1994; Henze et al., 2002).

2.2.6 Sewage sludge

Biosolids are generated in settlement tanks, biological reactors and chemical treatment units during the wastewater treatment processes. The removal and treatment of these solids can be very expensive. However, they have the potential to cause serious operational problems to the treatment system if not dealt with adequately. More stringent wastewater treatment standards and increasing numbers of wastewater treatment facilities are resulting in increased biosolids generation. The previous practice of landfilling is an unsustainable option and the land-spreading of biosolids without prior treatment may cause damage to groundwaters and surface waters. Incineration, with its fuel and transport costs, can be an expensive method of dealing with these wastes and can lead to major objections from local communities.

About 11.6 million t/annum of dry solids (DS) were estimated to be produced in 2010 in the EU. This is set to increase with new Member States adopting wastewater directives and constructing new wastewater treatment facilities. Table 2.10 details the estimated sludge production in 15 European countries in 2010 and 2020 and the percentage going to various final disposal routes. Overall, there is expected to be limited change in the total amount of sludge production in this 10-year period and the final disposal routes are not expected to change (Fig. 2.1a and b).

However in the recent 12 EU accession states, which have less developed wastewater infrastructures, it is expected that total sludge production will increase from 1.4 million tonnes DS in 2010 to 2.46 million tonnes in 2020.

Currently, the EU is reviewing the Sewage Sludge Directive (86/278/EC), which encourages the use of treated sewage sludge in agricultural applications. However, due to concerns, including environmental concerns and public and political perceptions and concerns, this is being reviewed. Five options are being considered (Milieu Ltd, WRc and RPA, 2010):

- **Option 1**: do nothing, keeping the Directive as it is (i.e. the baseline scenario described in Table 2.10);
- **Option 2**: introduce certain more stringent standards, especially for heavy metals, standards for some organics and pathogens, and more stringent requirements on the application, sampling and monitoring of sludge;
- **Option 3**: introduce more stringent standards across all substances and bans on application of sludge to some crops;
- **Option 4**: total ban on the use of sludge on land; and
- **Option 5**: repeal of the Directive.

A recent EPA report (EPA, 2006) stated that 52,827 t DS of sludge were reported by local authorities to have been produced in 2005. This equates to about 5,000,000 m^3 of biosolids prior to de-watering. In 2005, about 5,471 t of hazardous sludges and filter cakes were exported from Ireland – 4,606 t of which were for disposal and 865 t for recovery. Also, 6,034 t of non-hazardous sludges and filter cakes were exported for disposal.

To reduce the initial handling costs of sludge, it is necessary to reduce its volume. Methods to achieve this include de-watering, sludge thickeners, stabilisation ponds and drying beds (Strauss et al., 1997). Aerobic and anaerobic digesters can be used to treat solids, and disposal methods include incineration, subsoil injection on agricultural land (Fytili and

Table 2.10. Sludge production and final disposal methods in the EU (adapted from Milieu Ltd, WRc and RPA, 2010) (http://ec.europa.eu/environment/waste/sludge/pdf/part_i_report.pdf).

Country (EU 15)	2010					2020				
	Total sludge produced (t DS/year)	Recycled to land (%)	Incineration (%)	Landfill (%)	Other (%)	Total sludge produced (t DS/year)	Recycled to land (%)	Incineration (%)	Landfill (%)	Other (%)
Austria	273,000	15	40	>1	45	280,000	5	85	>1	10
Belgium	170,000	10	90			170,000	10	90		
Denmark	140,000	50	45			140,000	50	45		
Finland	155,000	5			95	155,000	5	5		90
France	1,300,000	65	15	5	15	1,400,000	75	15	5	5
Germany	2,000,000	30	50	0	20	2,000,000	25	50	0	25
Greece	260,000	5		95		260,000	5	40	55	
Ireland	135,000	75		15	10	135,000	70	10	5	10
Italy	1,500,000	25	20	25	30	1,500,000	35	30	5	30
Luxembourg	10,000	90	5		5	10,000	80	20		
Netherlands	560,000	0	100			560,000	0	100		
Portugal	420,000	50	30	20		750,000	50	40	5	5
Spain	1,280,000	65	10	20		1,280,000	70	25	5	
Sweden	250,000	15	5	1	75	250,000	15	5	1	75
United Kingdom	1,640,000	70	20	1	10	1,640,000	65	25	1	10

DS, dry solids.

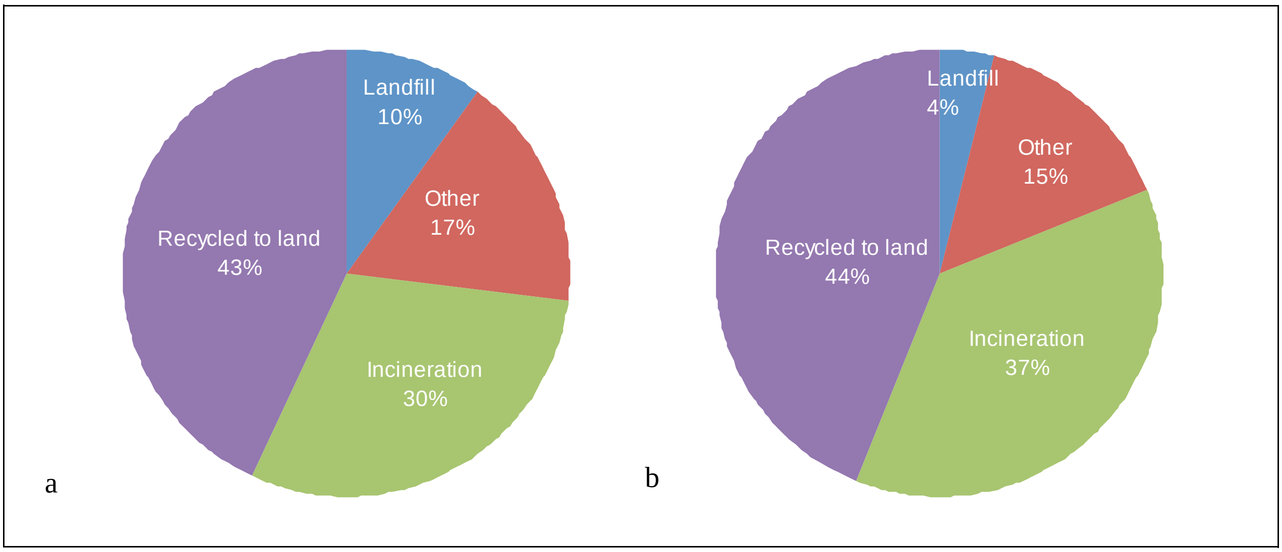


Figure 2.1. Disposal routes for sewage sludge in (a) 2010 and (b) 2020.

Zabaniotou, 2008) or, as is used in Sweden, subsoil introduction to short-rotation willow groves. It is essential that groundwater is protected when introducing sludge into the subsoil and further research into application rates and methods is required for Ireland. Figure 2.2 and Table 2.11 show typical costs (in €/t DS) associated with sewage sludge disposal in the EU (Odegaard, 2003).

As with odour control and wastewater treatment, the remediation, reuse and control of sewage sludge provide challenges to develop new environmentally sustainable and low-cost methods for sludge disposal that meet the European Directives. In small-scale wastewater treatment systems, there is potential to introduce economic savings and social benefits by treating sludge on-site through suitable operational procedures and technology improvements. The reduction in transport volume and costs would be of economic, environmental and social benefit.

Knowledge gaps in this area identified by the EU (EU, 2002b) include:

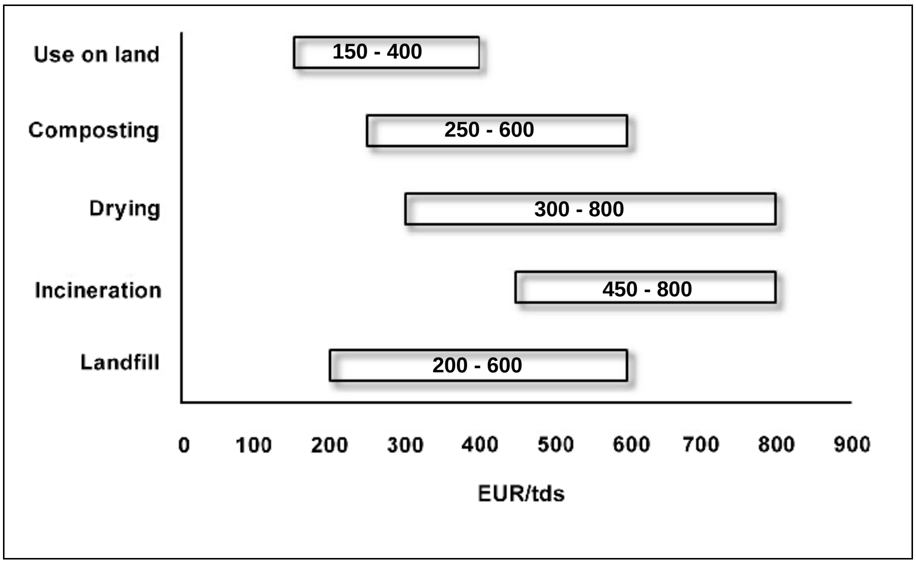


Figure 2.2. Range of sludge treatment and disposal costs (adapted from Odegaard, 2003).

Table 2.11. Average investment and operating costs for sludge disposal/treatment in Europe (EU, 2002a).

Range of values (€/t dry solids)	Disposal/Treatment routes
160–210	• Land-spreading of semi-solid sludge in agriculture • Land-spreading of semi-solid digested sludge in agriculture
211–300	• Land-spreading of solid sludge • Silviculture (plantation) • Co-incineration with other wastes • Landfilling • Land reclamation
301–330	• Land-spreading of composted sludge • Specific incineration

- Research into the fate and impact of pollutants from sludge after land-spreading;
- Pollutants such as pathogens and heavy metals need to be further studied;
- Verification of new technologies using actual sludges; and
- Further study into the final impact and benefits of treated sludge in areas such as land reclamation, land-spreading and composting.

2.2.7 Overall capital and operational costs

Devisscher et al. (2006) successfully reduced operational costs by using advanced on-line monitoring and mathematical modelling in four wastewater treatment plants in Belgium. In France, a comprehensive survey of capital and running costs was carried out for treatment plants for 1,000 inhabitants (Boutin et al., 1997). The results show general trends in capital and running costs but also the large differences that can occur when taking into consideration the standards required and site-specific considerations.

Table 2.12 summarises research carried out in Greece to estimate the cost of various technologies to include land, construction and operational costs (Tsagarakis et al., 2003). All costs included preliminary treatment, disinfection or polishing and sludge handling. These

Table 2.12. Construction cost of municipal wastewater treatment plant in €/PE for different systems and sizes (annual operation and maintenance costs shown in parentheses).

	System capacity (PE)		
	500–10,000	**10,000–100,000**	**>100,000**
Reed beds (€/PE)	141 (1.9)	–	–
WSP (€/PE)	51.7[a] (1.8)[a]	–	–
EA with AD (€/PE)	94.2 (4.9)	40.9 (2.8)	–
EA with MD (€/PE)	95.7 (5.0)[a]	74.9 (2.9)	50.2[a]
Conventional[b] (€/PE)	–	89.5 (4.5)	80.3 (2.5)

[a]Less than three plants were used.
[b]Use of aeration tanks.
PE, population equivalent; WSP, waste stabilisation pond (anaerobic, facultative and maturation ponds and filtration); EA, extended aeration; AD, air drying; MD, mechanical drying.

data provide a good relative comparison between technologies (although costs would be greater in Ireland). With increasing national and international environmental awareness, systems that have low carbon footprints will become more prominent.

2.3 Wastewater Treatment and Sludge Treatment Technologies

2.3.1 *Wastewater treatment technologies*

There are various technologies used in wastewater treatment systems and each has advantages and disadvantages. In the Environmental Engineering Laboratories, Civil Engineering, NUI Galway, development work has focused on biofilm systems, e.g. the PFBR, the VMBR and the HFBR; these systems were developed by the project leader and his team of researchers (Zhan et al., 2005; Rodgers et al., 2006a,b, 2008a; O'Reilly et al., 2008a,b). The PFBR is one of the technologies used in the EPA demonstration project at Tuam, Co. Galway. Table 2.13 lists other technologies; both biofilm and suspended growth systems are included along with their advantages and disadvantages (Perara and Baudot, 2001; US EPA, 2002; Metcalf and Eddy, 2001).

Table 2.13. Treatment processes for small communities.

System type	Advantages	Disadvantages
Activated sludge	• Low capital costs • Generally low odour and fly nuisance • Can achieve carbon removal, nitrification • Most common treatment technology • Robust in cold weather	• High energy costs • Sensitive to shock loads and toxic streams • Large volumes of sludge produced • Not very flexible and requires further processes for denitrification and phosphorus removal • Frequent maintenance requirement • Testing regime needed for return sludge
Extended aeration plants	• Plants are easy to operate • A greater retention time means these systems are often better at handling organic load and flow fluctuations • Package extended aeration plants are easy to install • Systems can have a small footprint and are mostly odour free • No primary clarifier • Low sludge yields	• Denitrification and phosphorus removal achievable only with additional processes • Limited flexibility • Longer aeration periods increase energy usage • Require more tankage than some other processes
Sequencing batch reactors (SBRs)	• Can achieve nitrification, denitrification and phosphorus removal • Large operational flexibility • All processes occur in one tank saving space and costs • Low operational and maintenance problems • Control of mixed liquor suspended solids (MLSS) and solids retention time (SRT)	• It can be difficult to adjust cycle times for small communities • Equalisation before and after the SBR may be required • Frequent sludge disposal required in suspended growth SBRs • High energy consumption
Oxidation ditches	• Well suited for municipal waste • Low energy usage, operational and maintenance costs • Can be used without clarifiers • Can provide good carbon removal and nitrification • Can handle shock loads and have a relatively low sludge yield • Do not require high operator skills	• Can be noisy and tend to produce odours when not operated correctly • Not suited to very toxic waste streams • Systems have a high footprint • Systems are not very flexible should effluent requirements change

Table 2.13 ***contd***

System type	Advantages	Disadvantages
Trickling filters	• Low operating costs • Low energy requirements • Does not require very skilled operators • Can handle shock loads and toxic loads well • Moderate odour problems. • Very robust • Excellent suspended solids and biochemical oxygen demand (BOD) removal and nitrification • Low sludge yields	• High capital costs • Can have a large footprint • Can have fly nuisance problems • Low flexibility of operation • Biofilm sloughing can occur • Denitrification and phosphorus removal achievable only with additional processes
Rotating biological contactors (RBCs)	• Low land footprints • Low capital costs • Little odour and fly problems • Low sludge production • Excellent process flexibility • Low pumping costs • Good sludge settleability • High BOD removal and good nitrification	• High energy and operating costs • Frequent maintenance of motors and bearings required • Excessive biofilm build-up can occur on the media • Requires skilled operators • Denitrification and phosphorus removal achievable only with additional processes
Reed beds (vertical and horizontal flow)	• Low energy and operating costs • Integrate well into surroundings • Low noise and odour nuisance • No need for highly qualified operators	• Large land requirements • Reeds need to be harvested • Risk of insects and rodents • Low flexibility
Lagoons (natural and aerated)	• Very low energy requirements for natural lagoons • Low capital costs • Integrate well into natural surroundings • Low sludge handling and removal costs • Can remove nutrients to a high level in summer	• Large land requirements • Quality of discharge can vary with season • For aerated lagoons noise can be a problem • Not flexible

2.3.2 Sludge treatment technologies, reuse method, and disposal routes

Reports suggest that more sustainable technologies that can address growing concerns with carbon emissions, and air and water pollution issues and that are publicly acceptable will be necessary. Table 2.14 summarises some literature on various sludge handling, treatment, reuse and disposal methods currently in use.

2.4 Stakeholder Survey Conducted by NUI Galway

During the months of August and September 2006, the project team carried out a market survey to explore whether there was demand among stakeholders for the establishment of an independent world-class on-site WRF. The survey (available upon request) was prepared by the NUI Galway project team and sent to companies and bodies with interests in the water and waste industries. Surveys were sent to the following groups:

- Engineering consultants;
- Environmental consultants;
- Representatives of state/semi-state bodies;
- Local authorities;
- Sensor, analyser and test equipment providers;
- Solid waste companies;

Table 2.14. Sludge handling, treatment, reuse and disposal methods (adapted from Werther and Ogada, 1999; EU, 2002b; Babatunde and Zhao, 2007; Spinosa, 2007).

System type	Advantages	Disadvantages
Conditioning and Stabilisation Methods		
Composting	• Cost-effective • Aerobic or anaerobic process • Reusable end product for fertilisation • Disinfection at high temperatures	• Bioaerosol production • Care needed during handling • Risk of exposure to pathogens
Digestion	• Stabilisation of sludge by microbial digestion • Reduces organic content of the biosolids • Aerobic or anaerobic process • Useful biogases can be an end product • Most popular method employed in Europe • Reduction of sludge volume	• If anaerobic then energy costs can be high • Production of greenhouse gases that may not be useful as biogases at small scales • Often not suitable for industrial sludge or solids containing heavy metals • No major pathogen reduction • Lowering of sludge calorific value
Heat treatment	• Removal of pathogens and breakdown of organics at high temperatures (30–75°C followed by 75–190°C at c. 26 bar). The time for treatment will depend on the initial conditions and the final disposal route. Generally times >30 min are required • Sludge is de-watered and its handling costs can be reduced • Odours generally not a problem with heated sludges • No chemical additives	• High energy costs • Little reduction in overall dry solids quantities • Liquid wastes from this process can contain high concentrations of ammonia, heavy metals and dissolved organics that need treatment • Further digestion of remaining solids may be necessary
Lime stabilisation	• Increases pH of sludge to 12 or higher • Micro-organisms cannot survive at this high pH • Sludge does not putrefy and a reduction in odours follows	• pH needs to be kept at this level • Use of chemicals (lime) • Lowers calorific value of the sludge significantly • Increase in sludge dry volumes
De-Watering Methods		
Belt filter presses	• Low capital and operating costs • Very simple process • Can produce a very dry, stable cake	• High odour potential • Not conducive to automatic operation • Sensitive to incoming sludge characteristics • Production of liquid wastes that must be treated
Centrifuges	• Clean appearance • Produces a relatively stable sludge cake • Low capital costs relative to processed sludge volumes	• Skilled maintenance needed • Frequent maintenance necessary • Skilled personnel necessary for operation and maintenance • Production of liquid wastes
Sludge drying beds	• Very cheap method • No chemicals • Little maintenance and operational costs	• Odour and vector problems • Groundwater pollution potential • Publicly unacceptable on large scales • High footprint
Vacuum filters	• Reduce sludge volumes • Increase sludge density • Facilitate easier handling of solids • Facilitate further treatment and reuse of sludge	• Production of liquid wastes that must be treated • Can be expensive to operate

Table 2.14 ***contd***

System type	Advantages	Disadvantages
Reuse and Disposal Methods		
Application as a fertiliser on agricultural land	• Good fertilising and soil conditioning properties • Reduces the need for expensive chemical fertilisers • Reduces energy costs associated with fertilising of land • Popular and easy disposal method	• Recent opposition due to concerns about the presence of heavy metals and pathogens in some sludges • Careful pretreatment should be employed • Further study necessary • Possibility of water source pollution has led to regulations limiting concentrations that can be applied
Forestry and silviculture	• Good fertilisation properties • Can be practical all year round in forestry • Improvement of soils • Can be applied in most local regions • Low transport costs if used locally	• Can lead to nutrients in the run-off • Possibility of microbial habitat destruction • Careful management needed • Further study needed
Incineration	• Generation of energy • Combustion at incineration temperatures • Complete removal of pathogens and organic compounds	• Energy inputs and running costs very dependent on moisture content of incoming sludge • Formation of residue (ash) of about 30% the original volume • Residue needs further disposal often to landfill • Emissions to air • Water emissions possible due to flue gas treatment • Public concern • Transport costs
Landfilling	• Most sewage sludge worldwide disposed in this way • Previously regarded as a cheap disposal option	• Generally disposed of separately to other wastes • Questionable future – being phased out in Europe and other developed countries • Concerns of effect on groundwaters near poorly designed landfills • Increasing costs due to difficulty in sludge handling and stringent stability and dry mass guidelines prior to disposal • Emissions of odour and gases • Transport costs
Land reclamation and restoration	• Restoration of bad or derelict sites • Restoration of old industrial sites • Used on embankments, golf courses, etc. • Low transport costs if used locally	• Careful monitoring necessary • Good application management necessary • Further impact studies necessary
Emerging Technologies (technologies that have been used at a pilot or large scale)		
Gasification	• Process of conversion with controlled oxygen or other combustible gas at 1,000–1,400°C • Reduction of flue gas volume • Production of inert solid waste	• Not very well documented yet • Energy costs • Solid waste needs further disposal

Table 2.14 *contd*

System type	Advantages	Disadvantages
Pyrolysis	• Thermal process in the absence of oxygen • Products still have a high calorific value • Reduced gas emission over incineration • Reduced investment costs over incineration	• Very high temperatures (300–600°C) • Considered a pretreatment • Further treatment of gases and solids necessary, 'valorisation' • Technical constraints on building an airtight structure
Wet oxidation	• Liquid sludge oxidised with oxygen in a hot (250°C), wet environment • No significant preliminary treatment required • Heavy metal agglomeration and organic pollutant breakdown	• Energy inputs for high pressures and temperatures • Liquid wastes that require treatment • Mercury can be emitted as a gas • Filtration of residues and liquids necessary at the end

- Pharmaceuticals;
- Single-house wastewater treatment plant providers;
- Larger wastewater treatment plant providers;
- Membrane technology providers;
- Food processors; and
- Composting companies.

The aims of the survey were to:

1. Ascertain the level of interest there would be for the WRF and the type of services it could provide; and
2. Establish the specific areas of interest that the above groups are concerned with, in the immediate, medium and long terms.

The results from the survey indicate that the main interests of the industry coincide with the direction of the WRF and of current ongoing research in the Environmental Engineering Laboratories at NUI Galway. In particular, the main interests are:

- Nutrient removal: removal of nitrogen and phosphorus – identified by almost every stakeholder category;
- Certification of wastewater treatment plants ≤50 PE to EN 12566:2005;
- Biosolids waste handling and treatment; and
- Municipal wastewater treatment.

The survey clearly shows that there is critical mass in Ireland in the water and waste environmental technologies industry. Ireland has the capability to become a world leader in water and waste treatment and to create high-quality jobs, skills and exports in the water and waste section of the environmental technologies industry, provided that there is a strong independent base or centre that will provide the industry stakeholders with facilities for:

- Applied and fundamental independent research;
- Joint technology development;
- Advice, consultancy, education and training;
- Accreditation and certification; and
- Computer modelling techniques.

3 Water Research Facility

This chapter describes the WRF that was established at the TWWTP in Co. Galway.

3.1 Associated Task Overview

Tasks 1–3 of the original proposal relate to the establishment of the WRF and are presented briefly hereunder.

Task 1: Selection and preparation of a suitable site for the WRF

Three local authority sites in Co. Galway were considered for the location of the WRF: Moycullen, Oughterard and Tuam. All three sites are existing Galway County Council wastewater treatment plants of varying ages and sizes within 30 km of NUI Galway. Tuam was considered to be the most suitable for the following reasons:

- Adequate land was available on-site belonging to Galway County Council;
- There were existing facilities on-site, such as a small laboratory and toilet/washing facilities; and
- Location and access.

A site survey was conducted and drawings were completed with possible on-site locations for the treatment system identified.

The project team prepared a detailed proposal for the WRF and presented it to Galway County Council. The Council raised a number of issues that had to be addressed. These issues included:

- The new access road and concrete slabs for the WRF tanks;
- The need for an independent ESB connection;
- Health and safety; and
- Influent and effluent lines and locations.

Further detailed meetings with Galway County Council local area engineers were held at which the Council agreed to construct the access road to the proposed site, the concrete slabs required for the WRF and a tarmacadam surface dressing. These costs were borne by Galway County Council. An application for an independent electricity connection was made to ESB Networks with Galway County Council providing the necessary civil engineering works for the new connection. The best locations for the underground influent and effluent pipelines were discussed at length and designs were prepared for the chosen location to guide the Council in carrying out the installation work. Health and safety documentation and procedures were prepared and maintained throughout the project.

Task 2: Designs, contract documents and tenders for the WRF

Full designs for the WRF were prepared based on the PFBR technology that had been developed and tested at NUI Galway (Rodgers et al., 2004b). Initial advice was subsequently revised due to health and safety legislation issues raised by Galway County Council on advice from the Health and Safety Authority (HSA). New, more comprehensive contract documents were drawn up by the project team for the public procurement process under the Model Form (MF/1) General Conditions of Contract for the supply of electrical, electronic or mechanical plant. An independent consulting engineering firm was appointed as project supervisor, design stage (PSDS) to fulfil health and safety legislation and insurance requirements. The extensive tender documentation prepared by the project team was uploaded to http://www.etenders.gov.ie to ensure that the contract could be awarded through an open and transparent process, allowing all possible interested parties to tender for the construction phase of the WRF. Following an evaluation process and consultation with the consultant engineering firm, the contract was awarded to the successful tenderer, which was appointed project supervisor, construction stage (PSCS).

Delays were experienced during Task 2 due to the unforeseen protracted nature of the tendering and public procurement requirements and process. After the revision of initial advice, the project team ensured that the delays were kept to a minimum.

Task 3: Construction of the demonstration WRF

Galway County Council commenced the civil engineering works as agreed and carried out the following tasks:

- Stripping the site of overburden to a suitable depth and removing the overburden off-site;
- Backfilling with hardcore and installing kerbing around the entire site;
- Construction of a 'U'-shaped (in plan) reinforced concrete slab for the wastewater treatment and polishing activities;
- Digging of trenches for influent and effluent lines; and
- Digging of a 300-m trench and installing a 160-mm duct to cater for the ESB mains connection.

Once completed, the main contractor began the installation of the equipment for the wastewater treatment system. As is normal in this type of installation, a number of obstacles were encountered during the installation process; the project team endeavoured to progress the project by devising solutions to engineering problems whenever they arose.

3.2 Influent Wastewater at the WRF

Influent wastewater was pumped to the WRF from the nearby TWWTP, which had been commissioned in 1996 with a design PE of 25,000. In 2006, Tuam had urban and environs populations of 2,997 and 3,888, respectively, and average daily flows to the TWWTP of 5,000 m^3/day (CSO, 2010 (http://www.cso.ie); GCC, 2010). A parallel dual-stream conventional activated sludge process was employed at the TWWTP with the capacity to pass the secondary effluent through a sand filter to effect tertiary treatment (Fig. 3.1).

Prior to entering the TWWTP, raw municipal wastewater passed through a basic 25-mm bar screen at a pumping station about 1 km upstream of the plant and was then pumped to the TWWTP. A portion of this inflow was pumped at user-defined intervals to the WRF from the influent channel of the TWWTP (prior to the storm overflow location and primary settlement tanks, see *Extraction point* in Fig. 3.1). Wastewater entering the WRF was pumped to the primary settlement tanks of the field-scale PFBR. From there, it was available for technologies being tested at the WRF that required settled influent wastewater.

A PLC program, coupled with a submersible centrifugal pump (Fig. 3.2a) and flow meter (Fig. 3.2b), facilitated the determination of user-defined volumes entering the WRF every half-hour over 48 half-hour segments (i.e. 24 h – Fig. 3.3). This allowed users to define diurnal flow patterns to the plant as required, simulating the flows entering small decentralised wastewater treatment plants.

When the maximum water level in the primary settlement tanks was reached (in this case 95%), no further inflow was permitted until the water levels dropped below 90% as the settled wastewater was conveyed onwards for secondary treatment at either

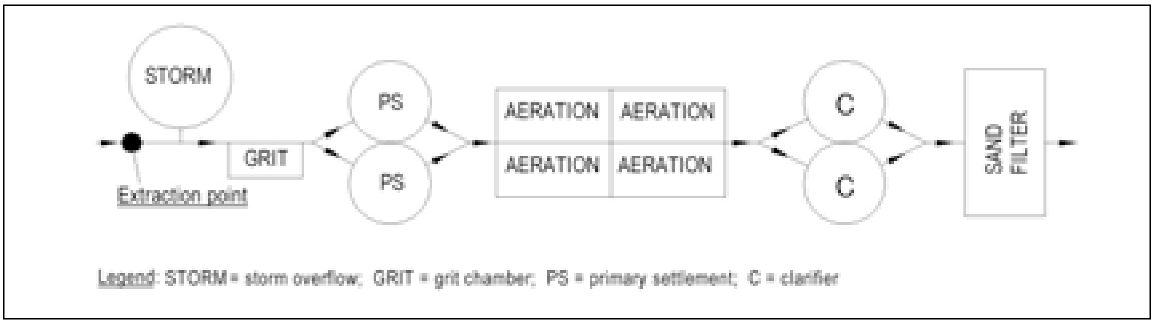


Figure 3.1. Schematic of Tuam Wastewater Treatment Plant showing extraction point location for the Water Research Facility.

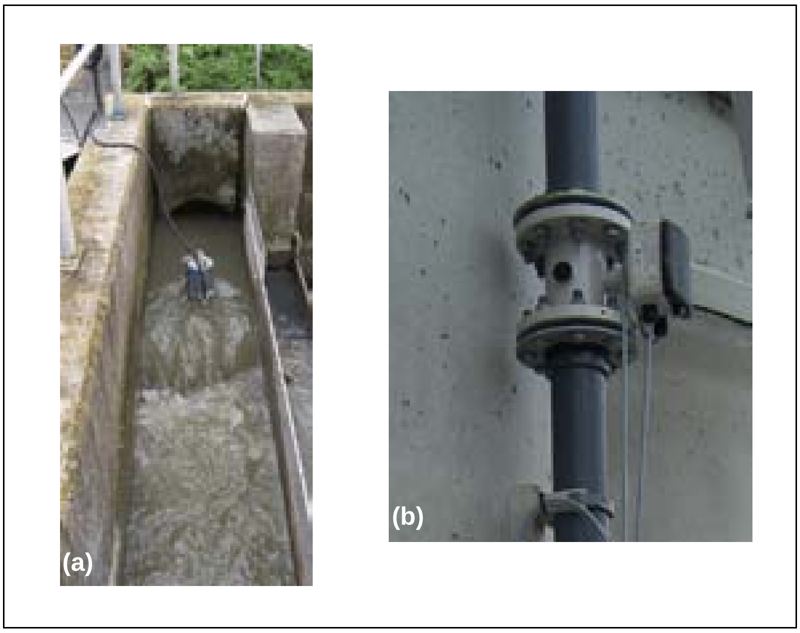
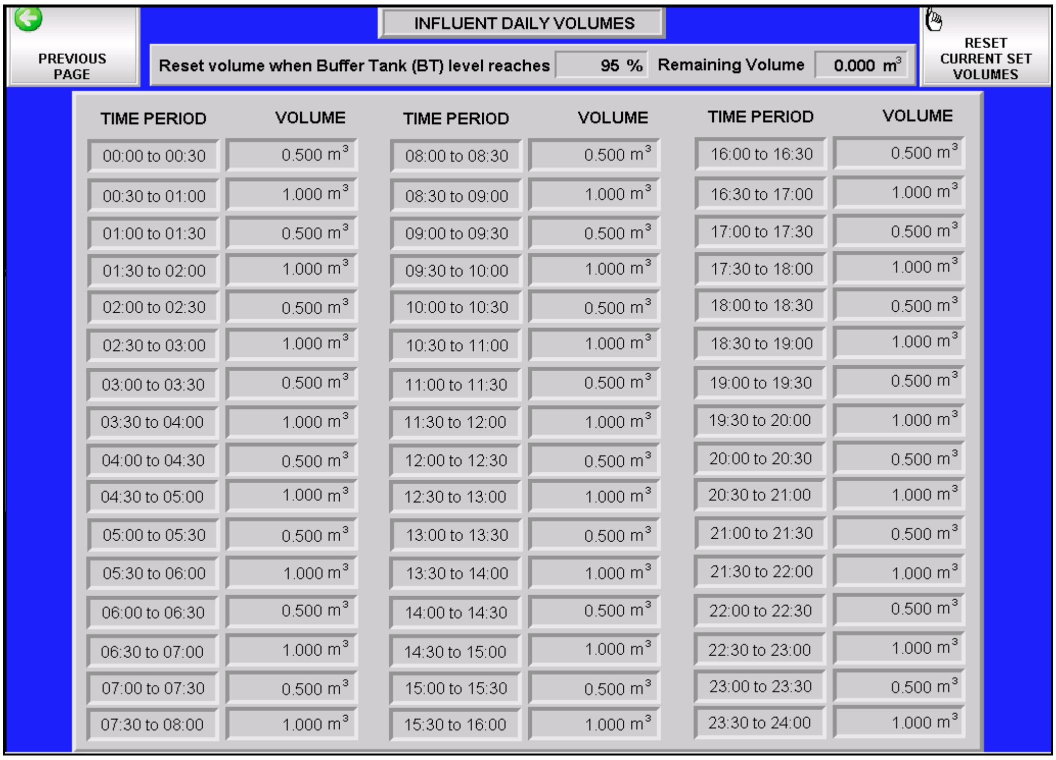


Figure 3.2. (a) Extraction pump during installation, and (b) flow meter.



TIME PERIOD	VOLUME	TIME PERIOD	VOLUME	TIME PERIOD	VOLUME
00:00 to 00:30	0.500 m^3	08:00 to 08:30	0.500 m^3	16:00 to 16:30	0.500 m^3
00:30 to 01:00	1.000 m^3	08:30 to 09:00	1.000 m^3	16:30 to 17:00	1.000 m^3
01:00 to 01:30	0.500 m^3	09:00 to 09:30	0.500 m^3	17:00 to 17:30	0.500 m^3
01:30 to 02:00	1.000 m^3	09:30 to 10:00	1.000 m^3	17:30 to 18:00	1.000 m^3
02:00 to 02:30	0.500 m^3	10:00 to 10:30	0.500 m^3	18:00 to 18:30	0.500 m^3
02:30 to 03:00	1.000 m^3	10:30 to 11:00	1.000 m^3	18:30 to 19:00	1.000 m^3
03:00 to 03:30	0.500 m^3	11:00 to 11:30	0.500 m^3	19:00 to 19:30	0.500 m^3
03:30 to 04:00	1.000 m^3	11:30 to 12:00	1.000 m^3	19:30 to 20:00	1.000 m^3
04:00 to 04:30	0.500 m^3	12:00 to 12:30	0.500 m^3	20:00 to 20:30	0.500 m^3
04:30 to 05:00	1.000 m^3	12:30 to 13:00	1.000 m^3	20:30 to 21:00	1.000 m^3
05:00 to 05:30	0.500 m^3	13:00 to 13:30	0.500 m^3	21:00 to 21:30	0.500 m^3
05:30 to 06:00	1.000 m^3	13:30 to 14:00	1.000 m^3	21:30 to 22:00	1.000 m^3
06:00 to 06:30	0.500 m^3	14:00 to 14:30	0.500 m^3	22:00 to 22:30	0.500 m^3
06:30 to 07:00	1.000 m^3	14:30 to 15:00	1.000 m^3	22:30 to 23:00	1.000 m^3
07:00 to 07:30	0.500 m^3	15:00 to 15:30	0.500 m^3	23:00 to 23:30	0.500 m^3
07:30 to 08:00	1.000 m^3	15:30 to 16:00	1.000 m^3	23:30 to 24:00	1.000 m^3

Figure 3.3. Screenshot of the Extraction Pump Schedule interface.

the field-scale PFBR or one of the alternative technologies being trialled at the WRF. For the duration of the field-scale PFBR studies, a regular 24-h inflow was maintained (Fig. 3.4) as the biological treatment efficiency of the PFBR in particular was being examined rather than the ability of the primary settlement/balance tanks to handle diurnal flow patterns.

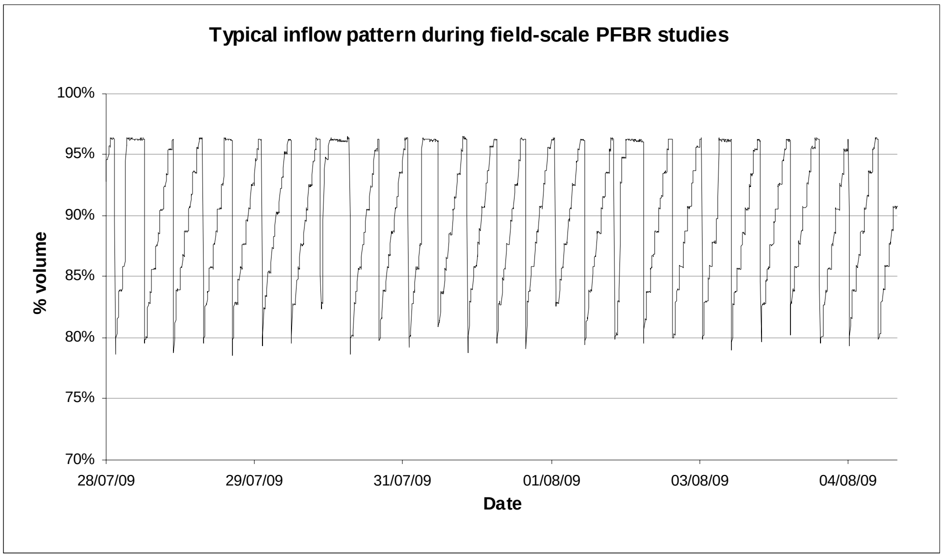


Figure 3.4. Typical inflow patterns as maintained during the field-scale pumped flow biofilm reactor (PFBR) studies at the Water Research Facility.

3.3 Facility Layout

Overall, the WRF had an area of over 700 m^2, within which a number of activities took place. Figure 3.5 presents the layout of the WRF. Once on-site, settled influent wastewater was pumped as required from the primary settlement tanks to the following technologies being trialled:

- Pumped flow biofilm reactor (PFBR);
- Horizontal flow biofilm reactor (HFBR); and
- Air suction flow biofilm reactor (ASF-BR).

Secondary sludge was treated in the novel woodchip bioreactor filters.

Effluent from the PFBR was directed to an effluent distribution tank where it was made available for tertiary treatment in a series of pressurised filters – sand, activated carbon and zeolite. Final effluents from the trialled technologies were collected in the effluent collection tank and returned by gravity prior to the primary treatment stage of the TWWTP. This ensured that the WRF posed no risk to the environment in terms of unregulated or untreated discharges to receiving waters and allowed researchers maximum flexibility when operating and testing different technologies.

3.4 PFBR Plant

3.4.1 Plant layout

The complete field-scale PFBR plant comprised seven precast concrete process tanks that included primary settlement with primary sludge storage, a balance tank, two PFBR reactors (Reactors 1 and 2), a clarifier and separate secondary sludge storage (Figs 3.5 and 3.6). Raw influent was pumped from the TWWTP to Primary Settlement Tank 1 and flowed by gravity to Primary Settlement Tank 2 and the Balance Tank. Settled wastewater was pumped at the beginning of each treatment cycle from the Balance Tank to Reactor 1 for secondary treatment. Treated effluent from the reactors was pumped to the Clarifier at the end of each treatment cycle and flowed by gravity from the Clarifier, thereafter returning to the TWWTP. Table 3.1 characterises the volumes and equipment in each of the seven process tanks used in the PFBR plant.

3.4.2 Reactor set-up

Two reactors (Reactors 1 and 2) were positioned side by side and connected with a motorised valve. About 20 m^3 of biofilm media modules (with a specific surface area of 180 m^2/m^3) were placed in each reactor and maintained 600 mm above the base of the reactor tanks. These rectangular cuboidal media modules with vertical tubes – supplied measuring 0.6 m × 0.3 m × 2.4 m – were cut to shape where necessary to fit into the

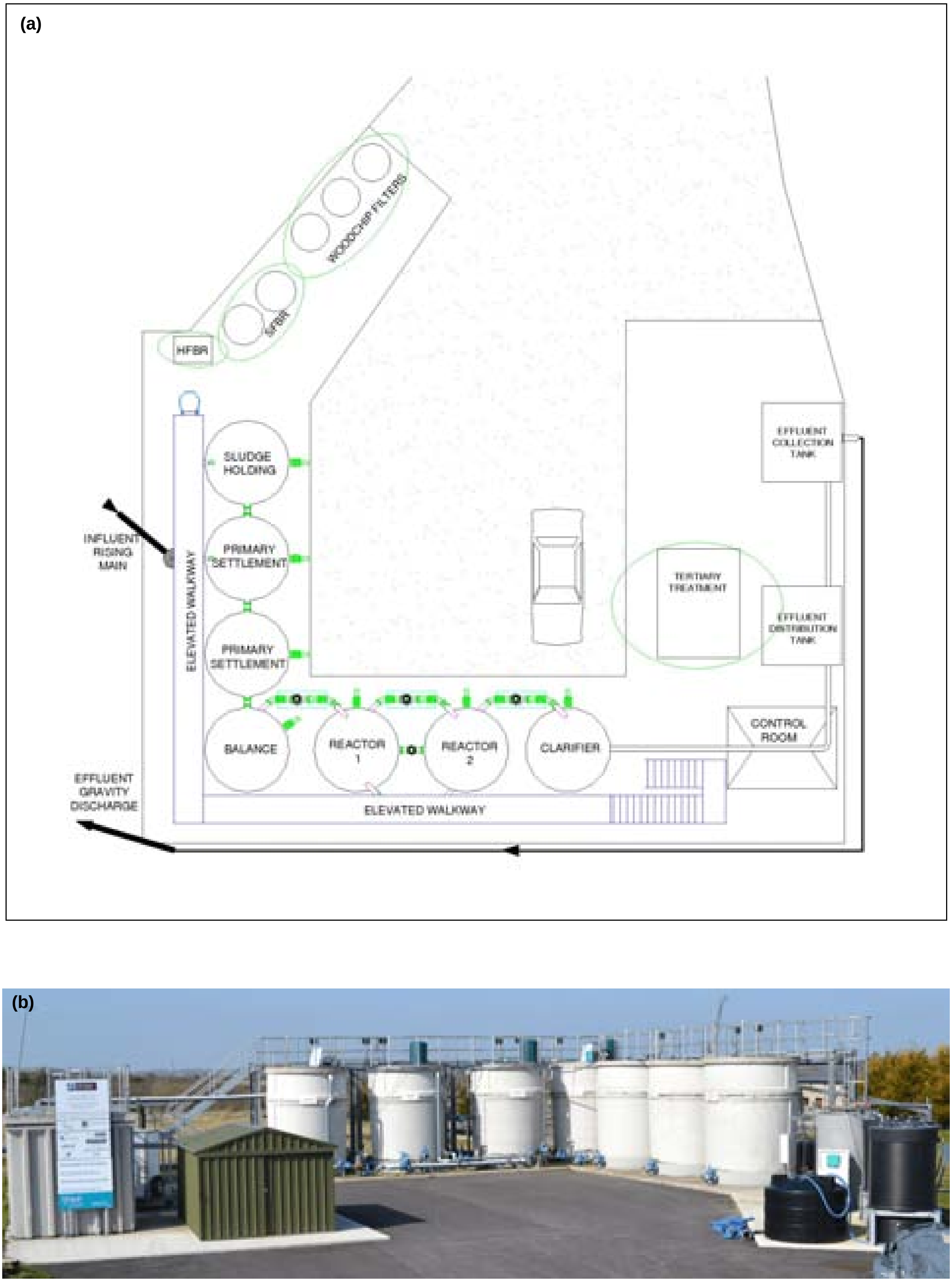


Figure 3.5. (a) Layout of the Water Research Facility; (b) photograph of the Water Research Facility.

Figure 3.6. Photograph of the field-scale pumped flow biofilm reactor at the Water Research Facility

Table 3.1. Pumped flow biofilm reactor process tank characteristics.

Tanks	Working volume (m^3)	Equipment	Instrumentation
Sludge Holding	20	–	–
Primary Settlement 1	20	–	1 × DO probe 1 × pH probe
Primary Settlement 2	20	–	1 × DO probe 1 × pH probe
Balance	20	Feed pump	1 × DO probe 1 × pH probe 1 × Level sensor
Reactor 1	20	20 m^3 biofilm media Circulation Pump 1 Reactor 1 Sludge Pump Motorised valve	3 × DO probes 3 × ORP probes 3 × pH probes 1 × Level sensor
Reactor 2	20	20 m^3 biofilm media Circulation Pump 2 Discharge Pump Reactor 2 Sludge Pump	3 × DO probes 3 × ORP probes 3 × pH probes 1 × Level sensor
Clarifier	20	–	1 × DO probe 1 × ORP probe 1 × pH probe

DO, dissolved oxygen; ORP, oxidation–reduction potential.

cylindrical reactors. As one reactor was full of bulk fluid, the biofilm attached to the media in that reactor had access to organic carbon and nutrients in the wastewater (Fig. 3.7a). Simultaneously, the biofilm in the other reactor was exposed to the atmosphere, providing the bacteria with an ample supply of atmospheric oxygen (Fig. 3.7b). During a typical 6-h treatment cycle, biofilm could be exposed for between

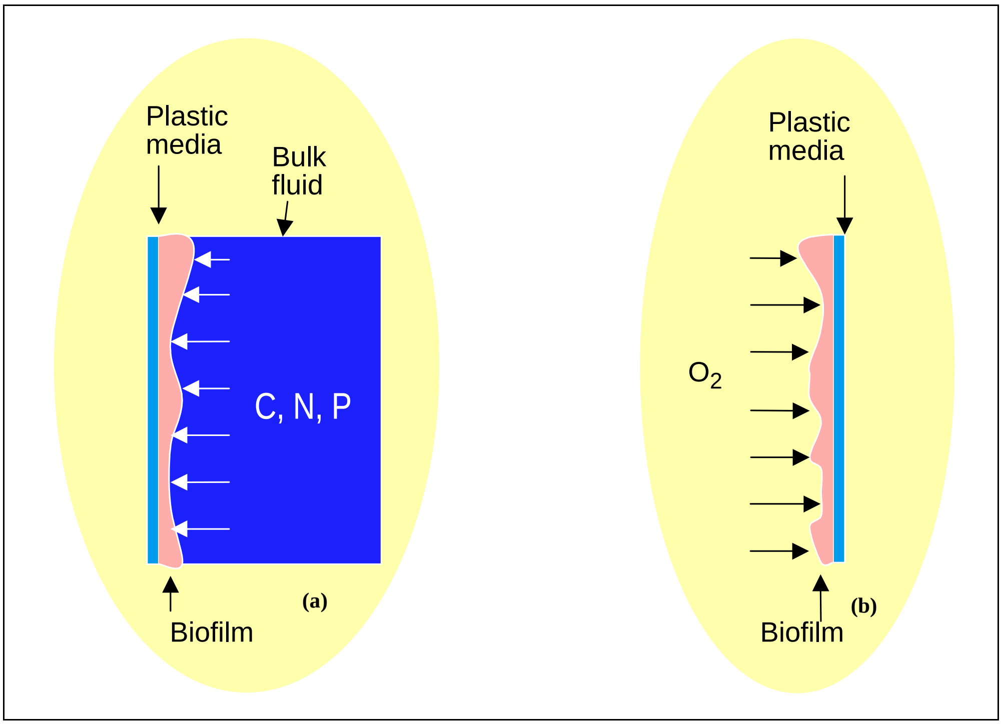


Figure 3.7. (a) Biofilm submerged, and (b) biofilm exposed.

60 and 120 min. The length of exposure depends on the treatment required and, in particular, whether nitrogen and biological phosphorus removal are being achieved. Endogenous respiration is one possible consequence of leaving the biofilm exposed and this could help control biofilm growth but may also limit the removal efficiency. Though it is thought that the effect of biofilm exposure is reasonably limited, further work could be carried out in this regard.

3.4.3 PFBR control

Control of the PFBR was managed from the Control Room (Fig. 3.5) from where all power and control signal cabling was routed. A comprehensive PLC program was used in conjunction with inputs from level sensors, pump controllers, and user-inputted information to control the operation of the PFBR. Data from the 30 probes and sensors, a flow meter and an energy meter were logged by the PLC and were accessible (along with the control program) through a human machine interface (HMI), with a touch screen control interface. The user-defined values (percentage volumes, times and cycle counts) were input by touching each value on the screen and entering the required value.

4 Operation of the Pumped Flow Biofilm Reactor at the Water Research Facility

4.1 Associated Task Overview

Tasks 4 and 5 of the original proposal relate to the operation and testing of the PFBR at the WRF and are presented briefly hereunder.

Task 4: Monitoring of the PFBR carbon and nitrogen removal treatment system and polishing facilities
Task 4 was amalgamated with Task 5 to expedite the delivery of stated milestones.

Task 5: Monitoring of the PFBR carbon, nitrogen and phosphorus removal treatment system and polishing facilities
As above, Task 4 was amalgamated with Task 5 to expedite the delivery of stated milestones. Four separate studies were carried out on the PFBR operating at the WRF and are summarised in Table 4.1.

Biodegradable carbon, nitrogen and phosphorus removal was investigated during **Study-phase 1** of the operation for about 180 PE over a period of 100 days. A dedicated anaerobic period was incorporated into the treatment cycle to encourage the development of PAOs for biological phosphorus removal. Good carbon and nitrogen removals were achieved during Study-phase 1. However, little or no phosphorus removal was recorded, indicating that sufficient PAOs had not become established in the reactors during the 100-day period. The daily influent flows to the reactors were increased during **Study-phase 2,** which resulted in an organic reactor loading of over 300 PE (in terms of BOD_5 at 60 g/PE/day) and a hydraulic reactor loading (at 0.18 m^3/PE/day) of 420 PE for a period of 75 days in order to examine SS removal, carbonaceous oxidation and nitrification. Carbon removals were lower than that experienced in Study-phase 1. It is likely that nitrification activity was inhibited due to the addition of landfill leachate at the TWWTP inlet pumping station. Further research is taking place in this regard, including monitoring of the performance of the TWWTP with and without influent leachate. Analyses of the leachate indicate the presence of metals that could inhibit nitrification. During **Study-phase 3**, of 100 days duration, the system was configured for SS and carbon removal only with an organic loading of around 320 PE. Total nitrogen concentrations entering the WRF during this phase were over three times normal municipal wastewater concentrations, again probably due to leachate additions. Organic carbon concentrations were largely unchanged, resulting in an alteration to the typical carbon/nitrogen ratio in the influent. The loadings were reduced in **Study-phase 4,** which lasted 75 days, and a dedicated anoxic phase was incorporated to investigate system efficiency at removing nitrogen through the nitrification/ denitrification process.

A summary of the average influent and effluent concentrations and removal efficiencies is presented in Table 4.1.

4.2 Introduction

The PFBR technology was installed as part of the NUI Galway WRF (see Chapter 3), located at the Galway County Council TWWTP. The system's performance was examined on a full-scale basis treating a wastewater side-stream originating from a medium-sized Irish town with some industrial activity, including, as referred to in Section 4.1, imported landfill leachate.

The full-scale PFBR system comprised primary settlement and secondary treatment and was designed and constructed using findings from previous laboratory and field studies (Zhan et al., 2005; O'Reilly et al., 2008a,b; Rodgers et al., 2009a) and EPA guidelines (EPA, 1999). Influent wastewater was pumped from the inlet channel of the TWWTP to the WRF with final effluent returning to the TWWTP prior to entering its primary settlement tanks. Extensive monitoring equipment, such as DO, ORP and pH probes, and flow and energy meters, were also installed in the PFBR, allowing detailed analysis of set

Table 4.1. Pumped flow biofilm reactor summary results from Study-phases 1–4 at the Water Research Facility.

	Study-phase 1			Study-phase 2			Study-phase 3			Study-phase 4		
Days	100			75			100			75		
m^3/day	28.3			75.6			66.8			24.8		
Cycle (h:min)	07:00			04:30			02:36			07:00		
PE (BOD_5)	180			300			320			120		
PE (flow)	160			420			370			140		
Parameters of interest	Suspended solids Biodegradable carbon Nitrogen Phosphorus			Suspended solids Biodegradable carbon Nitrification			Suspended solids Biodegradable carbon			Suspended solids Biodegradable carbon Nitrification Denitrification		
SBBR phases used	Anaerobic Aerobic			Aerobic			Aerobic			Anoxic Aerobic		
	Inf[a] (mg/l)	**Eff[b] (mg/l)**	**% removal**	**Inf[a] (mg/l)**	**Eff[b] (mg/l)**	**% removal**	**Inf[a] (mg/l)**	**Eff[b] (mg/l)**	**% removal**	**Inf[a] (mg/l)**	**Eff[b] (mg/l)**	**% removal**
BOD_5	370	14	96%	220	79	64%	290	77	73%	290	12	96%
COD_t	390	55	86%	240	95	60%	346	196	43%	335	56	83%
TN	–	–	–	–	–	–	140	37	74%	38	15	61%
NH_4-N	38	4.7	88%	22	17.5	20%	94	34.8	63%	33	11.4	65%
NO_3-N	–	2.2	–	–	1.7	–	–	0.3	–	–	3.6	–
PO_4-P	2.6	2.5	–	1.8	1.7	–	3.8	3.6	–	1.95	1.7	–
Suspended solids	190	14	93%	105	81	23%	189	41	78%	82	11	87%

[a]Samples taken from primary settlement Tank No. 1 (Inf, influent).
[b]Samples taken from Reactor 2 (Eff, effluent).
PE, population equivalent (flow = 0.18 m^3/PE/day; BOD_5 = 60 g/PE/day); SBBR, sequencing batch biofilm reactor; BOD_5, 5-day biochemical oxygen demand; COD_t, total chemical oxygen demand; TN, total nitrogen; NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen; PO_4-P, orthophosphate-phosphorus.

parameters to be carried out. All monitoring and control equipment was combined in one PLC with a HMI.

The operation of the PFBR at the WRF was examined over four main operating conditions, Study-phases 1–4. This chapter presents the PFBR set-up at the WRF and typical results obtained from the PFBR and the associated probes and sensors during Study-phase 1 of operation (a 100-day study). Similar data are available for Study-phases 2–4 and can be obtained from the research team. The data from all four phases are summarised in Table 4.1 and in Section 4.7.

4.3 Material and Methods

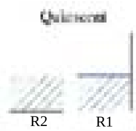
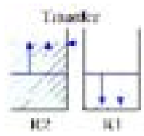
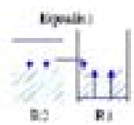
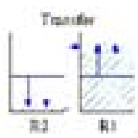
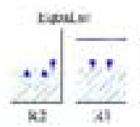
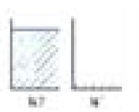
4.3.1 System set-up

The novel patented process comprised two linked reactor tanks (Reactors 1 and 2, Fig. 3.5) located side by side, each containing stationary plastic biofilm media modules. At any one time, no more than one reactor volume of water was in the two-tank reactor system and was cycled between the reactors using gravity and hydraulic pumps during aeration periods. The full-scale PFBR system installed at the NUI Galway/EPA WRF comprises Primary Settlement

Tanks 1 and 2, a Balance Tank, and Reactors 1 and 2 (as described in Chapter 3) and a Clarifier.

Typical treatment phases for the full-scale PFBR system, operating as a sequencing batch biofilm reactor (SBBR)-type process, are detailed in Table 4.2. Combining these phases and introducing rest periods allow the user to achieve organic carbon, SS and nitrogen and phosphorus removal. During Study-phase 1, the full-scale PFBR was operated and examined during two different operational settings: Setting 1 for 48 days and Setting 2 for 52 days. Both

Table 4.2. Description of the treatment process in a typical cycle for the full-scale pumped flow biofilm reactor system (biofilm media not shown for clarity).

Phases	Description		Schematics of water levels
Initial set-up	Two reactor tanks (R1 and R2) were located side by side, R2 was full with treated wastewater and R1 was empty at the start of a treatment cycle		
Fill/Draw	Simultaneously, treated effluent was discharged from R2 and settled influent wastewater was pumped into R1		
Anaerobic[a]	Untreated wastewater remained quiescent in R1 to encourage anaerobic conditions to develop		
Aeration[b]	Transfer to R2	The water in R1 was pumped to R2. The water remained quiescent in R2	
	Equalisation	A motorised valve was opened allowing water from R2 to flow by gravity into R1	
	Transfer to R1	The remaining water in R2 was pumped to R1. The water remained quiescent in R1	
	Equalisation	A motorised valve was opened allowing water from R1 to flow by gravity into R2	
Settle	Water was pumped to R2 and remained quiescent for a brief settlement period		

[a]The anaerobic phase was included for Setting 1 only.
[b]Aeration steps were repeated a number of times during each treatment cycle (see Table 4.3).

settings used the following treatment phases: fill/draw, aerate, and settle (Table 4.2). An anaerobic period was included in Setting 1 only to encourage the establishment of PAOs within the system. However, after the initial 48 days (Setting 1), the operation was changed to optimise nitrification and nitrogen removal (Setting 2).

The full-scale PFBR was controlled by a PLC that allowed the users to vary control parameters such as pumping durations, water levels, pause times, and aeration cycle counts. The PLC also received data signals from a number of DO, pH and ORP probes installed at three different depths in each reactor, which data were used to generate DO, pH and ORP concentration profiles during individual treatment cycles. The data collected were logged by the PLC every 5 min.

4.3.2 System operation

Study-phase 1 comprised two separate experimental regimes: Setting 1 and Setting 2. Table 4.3 presents the operation conditions for both settings. Municipal wastewater was pumped to Primary Settlement Tank 1 at regular intervals and flowed by gravity to Primary Settlement Tank 2 and the Balance Tank. Settled wastewater was pumped from the Balance Tank to Reactor 1 at the beginning of each treatment cycle.

One of the main differences between the settings (Table 4.3) was the absence of an anaerobic period and the increased aeration in Setting 2 – 398 min versus 275 min. The cycle lengths in Settings 1 and 2 were 431 and 428 min, respectively.

Throughout Study-phase 1, daily wastewater samples were taken from the Balance Tank at the beginning of a treatment cycle and from Reactor 2 at the end of the corresponding settlement phase using refrigerated automatic samplers. Grab samples were also taken from Primary Settlement Tanks 1 and 2, with all samples analysed in accordance with the Standard Method (APHA et al., 2005) for the following parameters: BOD_5, COD, NH_4-N, nitrite-nitrogen (NO_2-N), NO_3-N, orthophosphate-phosphorus (PO_4-P) and SS.

Three phase studies were conducted during Study-phase 1 – one during Setting 1 and two during Setting 2. During the phase studies, samples were taken at frequent intervals during the individual treatment cycles and tested for the aforementioned parameters. Dissolved oxygen profiles for the three phase studies were also recorded using the PLC.

Table 4.3. Full-scale pumped flow biofilm reactor operation conditions (standard deviations in parentheses).

Parameter	Units	Setting 1	Setting 2
Study duration	days	48	52
Fill/Draw time	min	8	9
Anaerobic time	min	134	0
Aeration time	min	275	398
Settle time	min	14	21
Total cycle time	**min**	**431 (2.1)**	**428 (2.5)**
Average daily flow	m^3/day	29.2 (2.8)	26.4 (1.6)
Average volume/cycle	m^3	8.74	7.85
Reactor volume	m^3/reactor	20.56	20.56
Average organic loading rate[a]	g BOD_5/m^2/day	1.37	1.25
Per-capita BOD_5 loading[b]	PE	200	165

[a]A total media surface area of about 4,250 m^2 was provided in Reactors 1 and 2.
[b]Using Primary Settlement Tank 1 5-day biochemical oxygen demand (BOD_5) data and 60 g/PE/day.

4.4 Overall Results

4.4.1 Organic carbon

Organic carbon was analysed as BOD_5 (influent samples), carbonaceous BOD_5 ($cBOD_5$ effluent samples), and total and filtered COD (COD_t and COD_f, respectively), and the data are presented in Fig. 4.1. The COD_t (125 mg/l) and $cBOD_5$ (25 mg/l) indicators are the European Urban Wastewater Treatment Directive (Directive 91/271/EEC) discharge limits for municipal wastewaters.

Table 4.4 shows BOD_5 and COD settled influent and effluent concentrations during Study-phase 1. The absence of the anaerobic phase and increased aeration time during Setting 2 shows an improved performance in the average BOD_5 removal efficiency of 88%, compared with 74% during Setting 1. In Setting 2, during Days 70–100, the average effluent $cBOD_5$ and COD_t concentrations were 14 mg/l and 50 mg/l, respectively, representing removal efficiencies of 94% and 80%.

When the organic carbon values from Primary Settlement Tank 1 were considered, the removal efficiencies for COD_t and BOD_5, respectively,

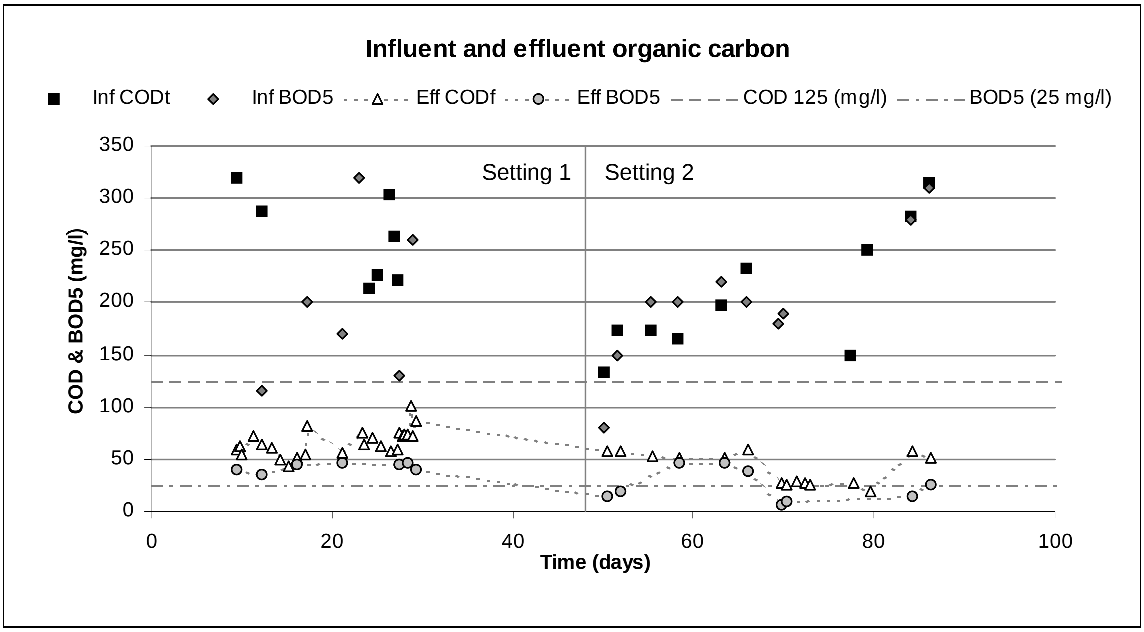


Figure 4.1. Influent (Inf) and effluent (Eff) organic carbon (BOD_5, 5-day biochemical oxygen demand; COD, chemical oxygen demand, COD_t, total COD; COD_f, filtered COD).

Table 4.4. Average influent and effluent organic carbon concentrations (mg/l) during Study-phase 1 (standard deviations given in parentheses).

	Setting 1			Setting 2		
	Influent[a]	**Effluent[b]**	**% removal**	**Influent[a]**	**Effluent[b]**	**% removal**
BOD_5	199 (79)	43 (5)	74%	201 (63)	24 (15)	88%
Total COD	262 (42)	86 (17)	67%	208 (60)	69 (21)	67%
Filtered COD	187 (48)	66 (10)	65%	112 (51)	41 (15)	63%

[a]Samples taken from Balance Tank.
[b]Reactor 2 effluent.
BOD_5, 5-day biochemical oxygen demand; COD, chemical oxygen demand.

increased to 87% and 90% in Setting 1, and 86% and 94% in Setting 2. This represented organic loading rates for the system as a whole (including primary settlement) of 2.8 and 2.3 g BOD_5/m^2/day for Settings 1 and 2, respectively.

4.4.2 Nitrogen

The additional aeration time provided during Setting 2 resulted in an increase in the nitrification efficiency. Little NO_3-N was evident in the effluent during Setting 1 (Fig. 4.2), where average DO concentrations were lower during the aeration phase than in Setting 2. Good NH_4-N removal was recorded in Setting 2 with an average removal efficiency of 72% recorded (Table 4.5). This efficiency improved between Days 70 and 100, with an average removal efficiency of 80% achieved. Definitive denitrification rates were undetermined during Study-phase 1 as no total nitrogen data were available. However, it was reasonable to assume that some denitrification occurred due to the high NH_4-N removals and relatively low NO_3-N in the effluent.

4.4.3 Phosphorus

One of the initial aims of the 100-day study was to examine the performance of the full-scale PFBR at removing phosphorus biologically. However, as can be seen in Fig. 4.3, little or no phosphorus removal occurred during the period when the anaerobic phase was in effect (Setting 1). Added to that, the influent PO_4-P concentrations were relatively low to begin with making it difficult to detect noticeable trends in the

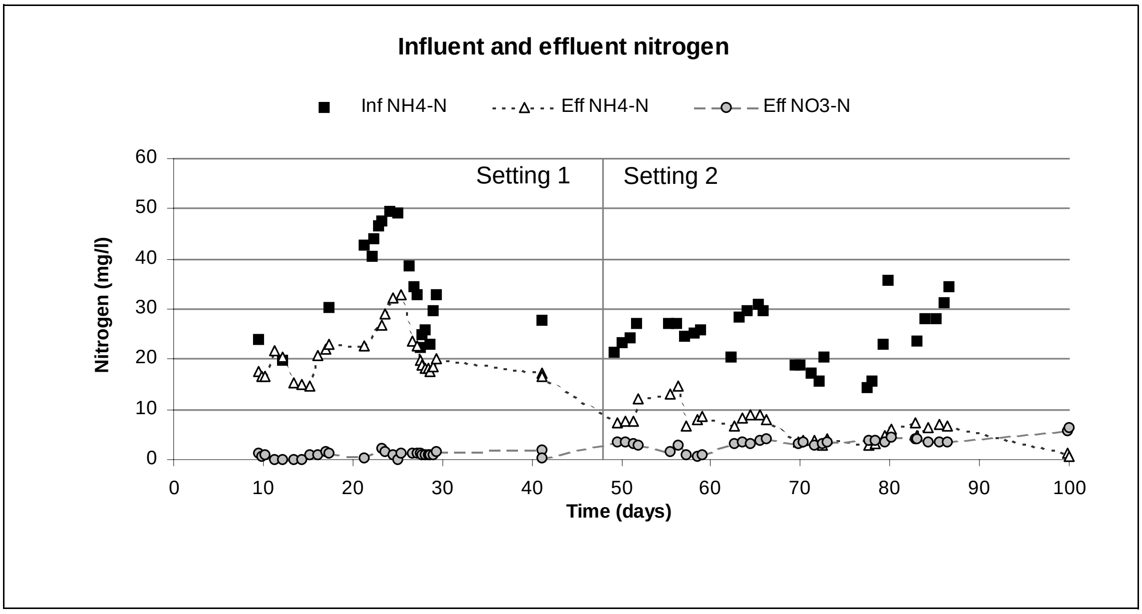


Figure 4.2. Influent (Inf) and effluent (Eff) nitrogen (NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen).

Table 4.5. Average influent and effluent nitrogen concentrations (mg/l) during the Study-phase 1 (standard deviations given in parentheses).

	Setting 1			Setting 2		
	Influent[a]	Effluent[b]	% removal	Influent[a]	Effluent[b]	% removal
NH_4-N	34.7 (9.9)	20.9 (4.9)	40%	24.7 (5.8)	7.0 (3)	72%
NO_3-N	0 (0.02)	0.93 (0.57)	–	0.03 (0.06)	3.12 (0.97)	–

[a]Samples were taken from Balance Tank.
[b]Reactor 2 effluent.
NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen.

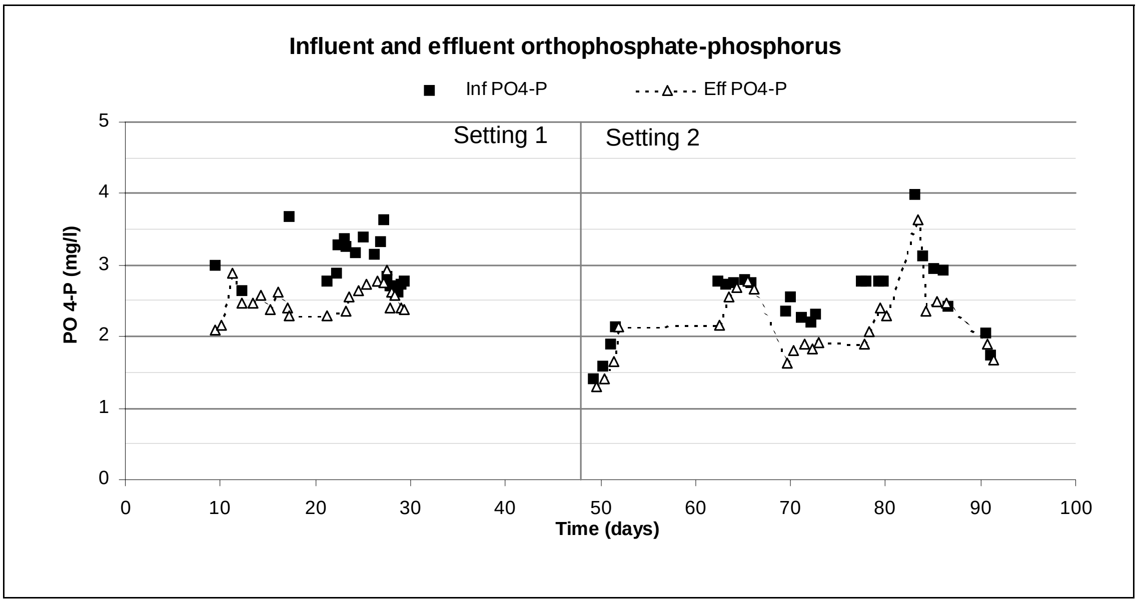


Figure 4.3. Influent (Inf) and effluent (Eff) orthophosphate-phosphorus (PO_4-P).

effluent PO_4-P concentrations. The landfill leachate in the influent may have inhibited biological phosphorus removal. Also, not having seeded the plant with an external sludge containing PAOs may have inhibited phosphorus removal. The presence of oxygen during the anaerobic period and lack of readily biodegradable organic carbon were probably the main reasons for the non-establishment of PAOs. A longer study may allow PAOs to develop within the reactors after seeding with sludge containing PAOs.

4.4.4 Suspended solids

Excellent SS removals were recorded in Setting 2, and in particular, between Days 70 and 100, when an average effluent concentration of 14 mg SS/l and an average removal efficiency of 79% were achieved in comparison with 53 mg SS/l and 40% during Setting 1 and 22 mg/l and 70% during Setting 2 as a whole (Fig. 4.4). The average effluent SS concentrations during the last 40 days of Setting 2 remained well within the EU Urban Waste Water Treatment Directive discharge limit of 35 mg SS/l. It should be noted that all effluent samples were taken from Reactor 2 and not the Clarifier.

The SS removal efficiencies increased to 85% and 86% for Settings 1 and 2, respectively, when the data from the Primary Settlement Tank 1 were considered.

4.5 Phase Studies

Three phase studies (PS 1, 2 and 3) were undertaken during the 100-day Study-phase 1 of the full-scale PFBR, one during Setting 1 (PS 1, Day 37) and two during Setting 2 (PS 2, Day 83 and PS 3, Day 99). During these phase studies, wastewater samples were taken at regular intervals from both Reactors 1 and 2 and analysed for COD, NH_4-N and NO_3-N; DO, pH and ORP profiles were also recorded during each phase study with readings logged every 5 min.

4.5.1 Organic carbon

Little COD was removed in PS 1 during the anaerobic phase while the water in Reactor 1 remained quiescent. As the bulk fluid from both reactors was mixed and the bulk fluid DO concentrations increased, a 50% reduction in COD_t was recorded during the aerobic phase. A reduced COD_f removal occurred throughout PS 1, with a 40% removal efficiency observed. Organic carbon removal in the full-scale PFBR occurred quickly when the anaerobic phase was removed in Setting 2. During PS 2, 71% COD_f and 62% COD_t were removed during the first 22 min of the aerobic treatment cycle (Fig. 4.5) as sufficient oxygen was available for the heterotrophic bacteria to effectively oxidise the organic carbon in the bulk fluid. Overall, 77% COD_t and 76% COD_f were removed during PS 2.

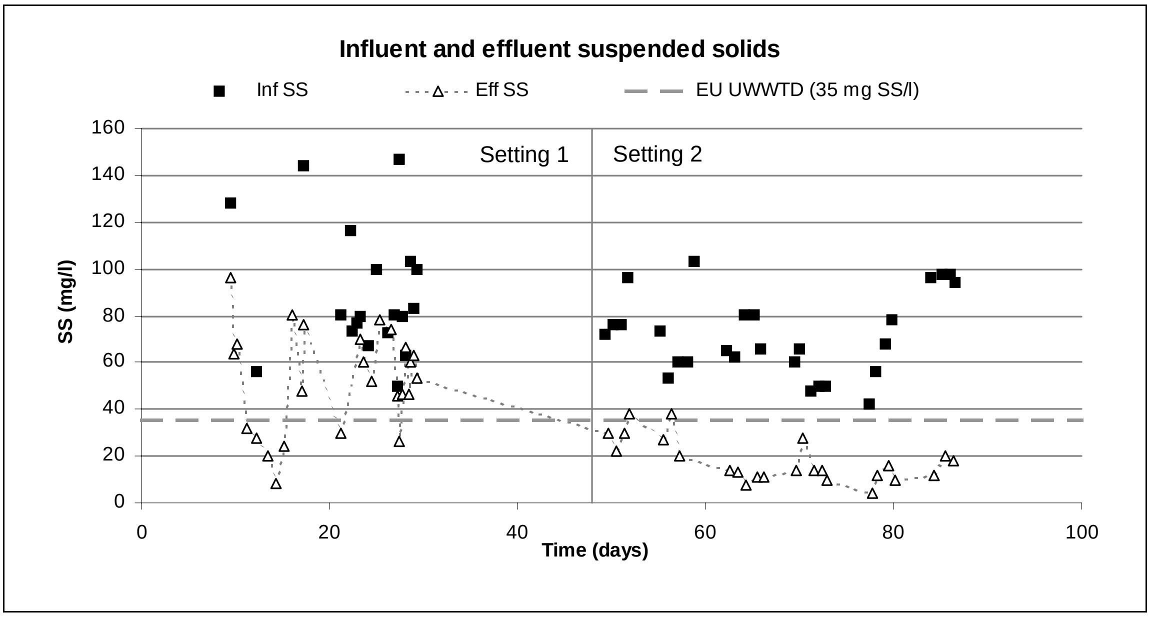


Figure 4.4. Influent (Inf) and effluent (Eff) suspended solids (SS) (EU UWWTD, European Union Urban Waste Water Treatment Directive).

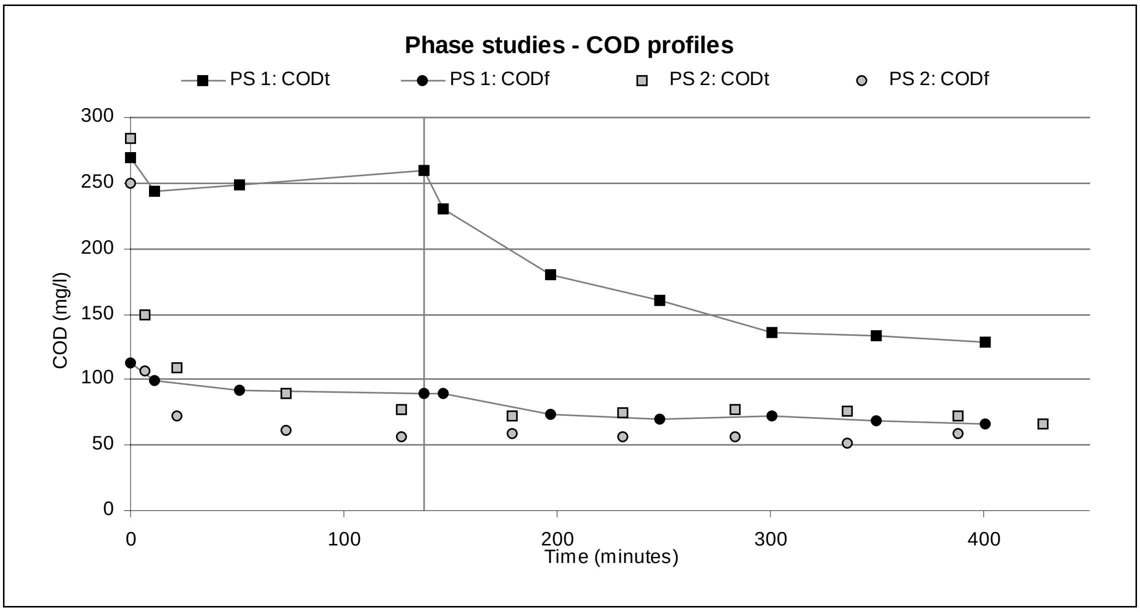


Figure 4.5. Chemical oxygen demand (COD) profiles for Phase-study (PS) 1 and 2 (vertical line represents the anaerobic phase for PS 1) (COD_t, total COD; COD_f, filtered COD).

4.5.2 Nitrogen

A clear improvement in NH_4-N removal was evident between the three phase studies (Figs 4.6–4.8). After the organic carbon was depleted in PS 2 and PS 3, nitrification was observed. The immediate supply of oxygen to the biofilm after the Fill Phase (see Table 4.2) and the simultaneous rapid reduction in organic carbon allowed the nitrifying autotrophs to oxidise the NH_4-N. This was most effective during PS 3, where the final NH_4-N concentration at the end of the treatment cycle was 0.5 mg/l, representing a 97% NH_4-N removal efficiency, compared with 41% for PS 1, and 76% for PS 2. The ammonium oxidation and nitrification rates are summarised in Table 4.6.

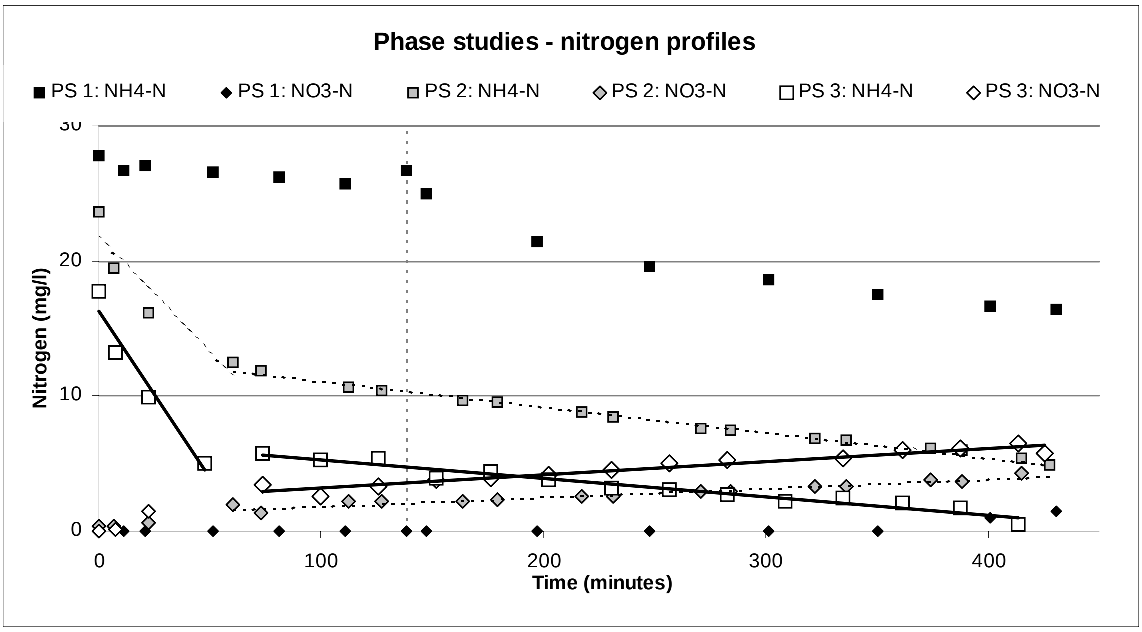


Figure 4.6. Phase study nitrogen profiles (vertical dashed line represents the anaerobic phase for Phase-study (PS) 1) (NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen).

Table 4.6. Summary of ammonium oxidation and nitrification relationships.

Nitrogen removal process	Derived relationships		R^2
Ammonium oxidation (initial aeration phase)	PS 2:	NH_4-N = –0.1665 (t) + 21.65	0.87
	PS 3:	NH_4-N = –0.2481 (t) + 16.282	0.948
Ammonium oxidation (aeration phase)	PS 2:	NH_4-N = –0.0188 (t) + 13.003	0.99
	PS 3:	NH_4-N = –0.0136 (t) + 6.6303	0.949
Nitrification (aeration phase)	PS 2:	NO_3-N = 0.0066 (t) + 1.2204	0.941
	PS 3:	NO_3-N = 0.0097 (t) + 2.2518	0.927

PS, Phase-study; NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen.

4.5.3 Installed sensor probes

A set of DO, ORP and pH probes was installed near the top, in the middle, and near the bottom of each reactor (a high, mid and low probe) to measure the relevant concentrations in the bulk fluid. Both the high and mid probes were exposed to atmospheric air each time water was transferred from a reactor. The low probe remained constantly submerged in water throughout the treatment cycle. Figure 4.7 gives typical readings taken from the set of probes in Reactor 1 during a PS 2 treatment cycle where no anaerobic phase was used.

Concentrating on the lower readings of each probe, an upwards trend in DO and ORP was generally noticed as the treatment cycle progressed through the aeration phase and the DO in the bulk fluid increased corresponding to a decreased organic load. A slight general decrease in pH was observed, consistent with the decrease in pH when nitrification is occurring. In the above example, the wastewater was transferred between the reactors eight times. The average lowest reading between transfers for each set of probes is presented for all three phase studies in Fig. 4.8.

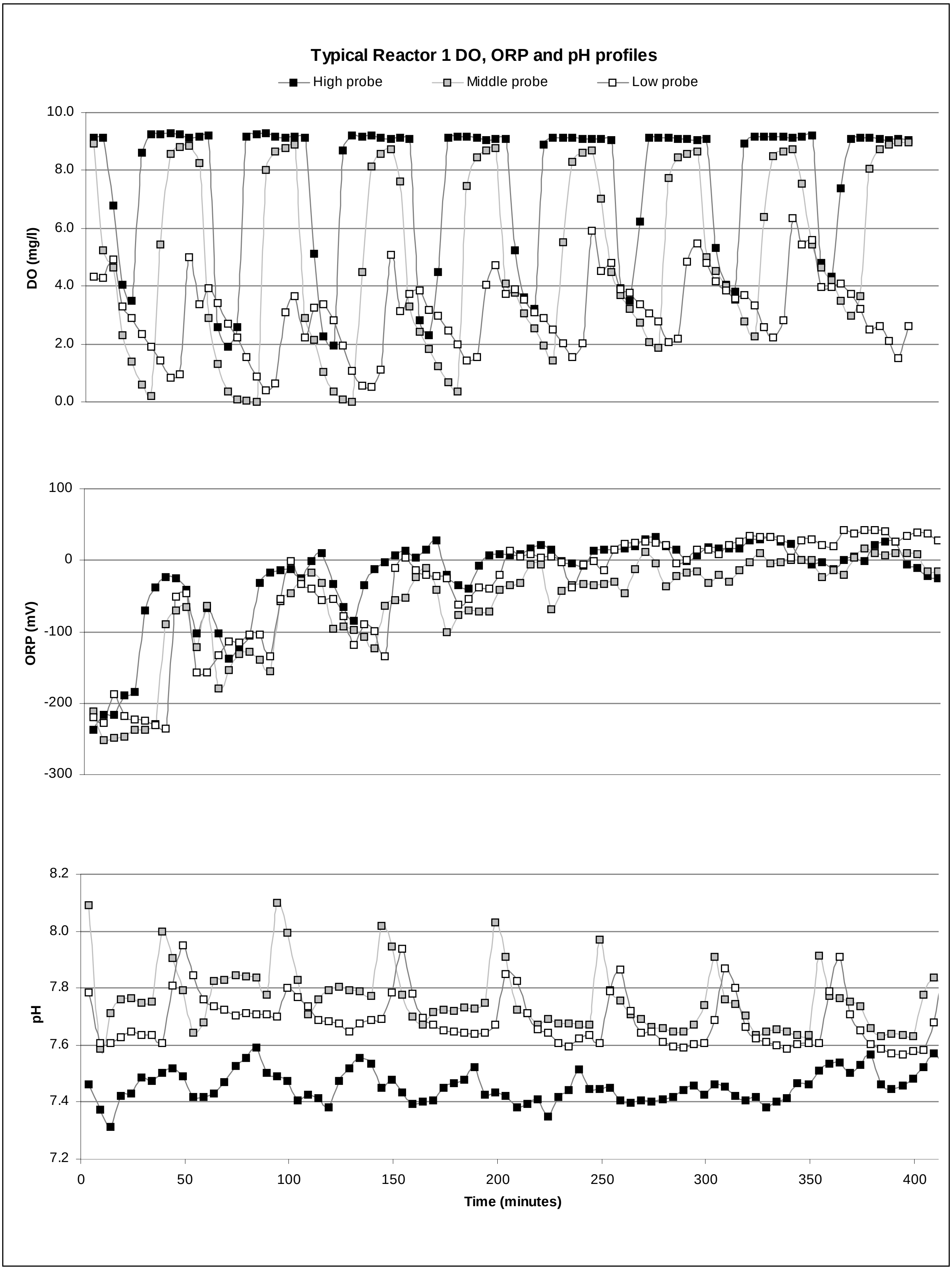


Figure 4.7. Typical Reactor 1 dissolved oxygen (DO), oxidation–reduction potential (ORP) and pH profiles for one treatment cycle.

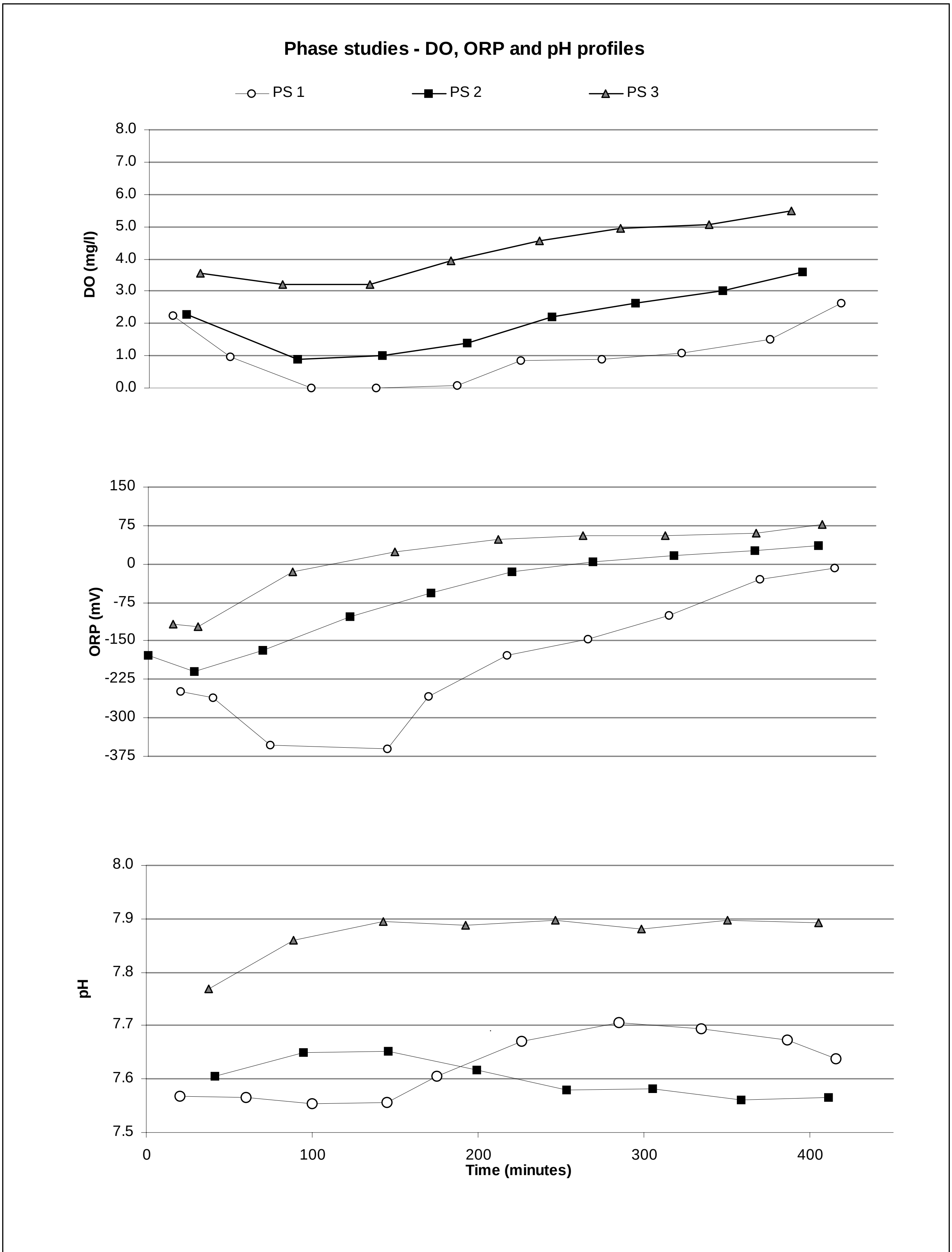


Figure 4.8. Average dissolved oxygen (DO), oxidation–reduction potential (ORP) and pH profiles for Phase-study (PS) 1, 2 and 3 (vertical dashed line represents anaerobic phase for PS 1 only).

During PS 1, with the anaerobic conditions in place, the overall DO remained lower than in PS 2 and PS 3 but 3 mg DO/l was still achieved by the end of the treatment cycle. A similar trend is observed for ORP. The increases in the bulk fluid DO concentrations during the phase studies coincided with increased NH_4-N reductions and NO_3-N increases. The phase studies show clear relationships between DO and ORP for both carbon removal and nitrification. It is possible that these cost-effective, robust sensors could be used to optimise plant control and thus achieve energy savings.

4.6 Energy, Sludge Observations and Maintenance

4.6.1 *Energy consumption*

The total energy consumed (kWh) by the PFBR system included the energy utilised by the following system pumps:

- A 1.5 kW foul pump;
- A 1.4 kW feed pump;
- 2 × 2.4 kW circulation pumps;
- A 2.4 kW discharge pump; and
- 3 × 1.0 kW sludge pumps.

The control equipment and probes were also included in the monitored energy. Table 4.7 presents the energy usage data for the PFBR system for the complete treatment system, including primary settlement and secondary treatment, while Fig. 4.9 plots the daily energy and flow data for Study-phase 1.

4.6.2 *Desludging*

Sludge was removed from Reactors 1 and 2 only after Study-phase 1 was concluded and pumped to a sludge-holding tank. No desludging took place, nor was required, during the study period. Estimates were made on the overall sludge production for the study period by considering the effluent volumes and SS concentrations, and the waste sludge volumes and SS concentrations when desludging took place. From these figures, it was estimated that 57.4 kg effluent SS exited during the study when treating 2,645 m^3 municipal wastewater and 11.4 kg SS were removed from Reactors 1 and 2 due to desludging. This corresponded to an estimated sludge yield of about 0.13 g SS/g COD_t removed. This figure compares well with a reported average of 0.315 g SS/g COD_t removed for 30 activated sludge plants from a study conducted by Ginestet and Camacho (2007) and could be attributed to the low sludge yields in attached growth processes. Low sludge yields can significantly reduce the waste sludge generated and lead to lower sludge handling and treatment costs. This can be particularly useful in decentralised wastewater treatment facilities where sludge transport is required.

4.6.3 *General maintenance*

Due to the employment of no moving parts except hydraulic pumps and a motorised valve, maintenance was kept to a minimum. Most of the maintenance was required to ensure that the DO, ORP and pH sensors were not hindered with biofilm growth. The pumps were maintained on a biannual basis or when required. However, in discussions with various contractors and local authorities, the advantage of only having to maintain pumps has been highlighted as a major advantage when compared with other technologies. During the Phase-study 1, the only maintenance required was probe cleaning.

4.7 Conclusions

Operating at the WRF, the PFBR was examined under four differing operational conditions (Study-phases 1–4) to fulfil the requirements of Tasks 4 and 5 of the project proposal.

4.7.1 *Study-phase 1 conclusions*

Study-phase 1 was presented as a typical set of results on a full-scale PFBR–SBBR system treating municipal wastewater and was further divided into two sub-settings – Setting 1 when an anaerobic period of 134 min was included and Setting 2 when the anaerobic period was replaced by an additional aeration period. Aeration was achieved by alternately exposing biofilm media to the atmosphere and wastewater in two separate reactor tanks by moving the wastewater between the tanks. The following conclusions were drawn from the overall study:

(a) During Setting 1 when an anaerobic period was included in the treatment cycle, over 40%

Table 4.7. Energy usage data for the pumped flow biofilm reactor system (standard deviations).

	Study-phase 1 Setting 1	Study-phase 1 Setting 2
kWh/day	13.4 (1.0)	16.2 (1.1)
kWh/PE/year	24.5	35.8
kWh/m^3 treated	0.46	0.63
kWh/kg BOD_5 removed[a]	1.25	1.76

[a]Calculated using Primary Settlement Tank 1 5-day biochemical oxygen demand (BOD_5) values.
PE, population equivalent.

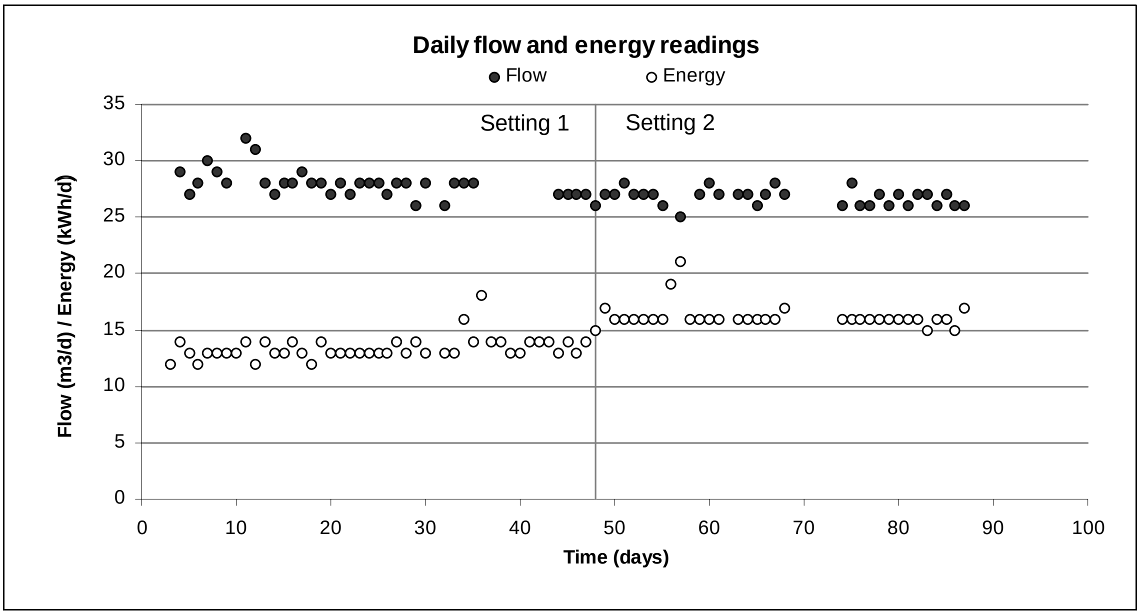


Figure 4.9. Daily energy and flow readings during Study-phase 1.

nitrification was achieved at a reactor loading rate of about 1.37 g BOD_5/m^2/day at an average wastewater temperature of 14°C.

(b) The system had a maximum BOD_5 removal efficiency of 94% recorded in the final 30 days of Setting 2, corresponding to an average effluent concentration of 14 mg BOD_5/l and a settled influent organic loading rate of 1.5 g BOD_5/m^2/day. Average organic loading rates for the PFBR system including primary settlement were 2.8 and 2.3 g BOD_5/m^2/day for Settings 1 and 2, respectively.

(c) Excellent suspended solids removal was also recorded, with average effluent values of 14 mg SS/l achieved over the final 30 days of the 52-day Setting 2 period.

(d) Good NH_4-N removal was also recorded during Setting 2, with a maximum average removal efficiency of 80% achieved over the final 30 days when excellent nitrification also occurred.

(e) Average energy requirements of 0.46–0.63 kWh/m^3 treated wastewater and 1.25–1.76 kWh/kg BOD_5 removed were recorded. It is estimated that additional savings of at least 20% could be made with the use of higher efficiency pumps.

(f) The estimated sludge yield during Study-phase 1 was 0.13 g SS/g COD_t.

Three phase studies were undertaken during Study-phase 1 yielding the following conclusions:

(g) Removal of organic carbon occurred in the early aerobic stages of the treatment cycle, e.g. 72% of COD_f was removed in the first 22 min of PS 2 in Setting 2.

(h) The best NH_4-N removal was recorded in PS 3 in Setting 2 where final concentrations were 0.5 mg NH_4-N/l, which was equivalent to a 97% removal efficiency.

4.7.2 General conclusions

Based on the operation of Study-phases 1–4, a number of general conclusions relevant to decentralised small-scale wastewater treatment systems include:

- Technologies are required to be adaptable to varying wastewater flows. These include periods of flows that are significantly lower than the design loading. The treatment systems should be able to perform efficiently in meeting discharge limits while reducing energy costs, even when underloaded.
- Decentralised wastewater treatment systems should have adequate balance capacity available to allow for storm periods or periods when influent wastewater volumes are high (such as tourism seasons in many towns/villages).
- Technologies that are easily maintained and use robust, reliable equipment are essential. The PFBR required very limited maintenance, which was easily completed.
- Energy costs at the WRF are low compared with other plants of its size. The plant can be remotely operated and monitored, which can lead to significant cost reductions and more efficient trouble-shooting. Similar systems should be investigated for deployment at other decentralised treatment facilities.
- The use of sensors at the WRF proved efficient in monitoring plant performance. However, consideration should be given to employing more expensive self-cleaning sensors, as these can reduce overall costs by removing the need for frequent probe cleaning.
- Sensor equipment should be calibrated according to the manufacturers' recommendations.

5 Sludge Treatment and Effluent Polishing at the Tuam Water Research Facility

5.1 Associated Task Overview

Tasks 3, 4 and 5 partly related to the installation and testing of a system for treating wastewater sludges and to the installation and testing of polishing technologies that could further treat secondary-treated wastewater to remove carbon, nitrogen, phosphorus and micro-organisms. The relevant sections from each task are shown below.

Task 3: Construction of the demonstration wastewater treatment system

A demonstration wastewater treatment system encompassing an on-site sludge treatment system was constructed, commissioned and operated.

Task 4: Monitoring of the PFBR carbon and nitrogen removal treatment system and polishing facilities

A new sludge treatment technology was developed by the research team and was installed at the WRF. It was considered that this system would be a more viable treatment technology than the willow groves originally planned for the following reasons:

- Treatment occurs on-site at the wastewater treatment facility – reduces transport costs and land requirements;
- Applying sludge on land (including willow groves) may meet with local resistance; and
- The end product of the proposed new technology comprises a mixture of solids and woodchips suitable for a number of applications – composting, co-firing for energy generation, gasification.

The new technology operated extremely successfully and pending further research could be an excellent alternative as an on-site sludge treatment technology.

A polishing system was installed, comprising an automatic sand filter, an ammonium zeolite filter, activated carbon filter and an ultraviolet disinfection system.

Task 5: Monitoring of the PFBR carbon, nitrogen and phosphorus removal in the treatment system and polishing facilities

The PFBR unit has been trialled at a number of different loading rates. Carbon, nitrogen and phosphorus were extensively monitored and other parameters such as DO, ORP and pH were logged. Energy costs have been investigated and are detailed in the report. Similarly, the pilot-scale woodchip bioreactor technology was extensively monitored on-site during its operation. Monitoring of the polishing facilities is ongoing for the removal of carbon, nitrogen phosphorus and micro-organisms. Samples and data will be analysed throughout the treatment facility.

5.2 Introduction

The application of biosolids to willow groves, as initially proposed, was not carried out, as the research team developed and trialled a system thought to be more sustainable. Sludge treatment was investigated using novel woodchip filter technology developed by the research team (Rodgers et al., 2009b). Laboratory trials on the technology were followed by successful pilot-scale trials at the NUI Galway/EPA WRF. The development of this technology was supported by Enterprise Ireland.

Shortly after the commencement of the project, attempts to secure areas of land on which to construct a willow grove proved difficult due to health and safety concerns. Furthermore, the research team believed that solutions that avoid transport of dilute solids may:

- Be more cost and energy efficient;
- Have a lower carbon footprint; and
- Be more publicly acceptable.

Investigations by the research team have shown that the alternative proposed may be a more environmentally sustainable treatment route – one that is in line with EU trends of using solids for composting and energy generation.

Reducing the water content of the sludge through the use of equipment such as picket fence, filter presses and centrifugal thickeners decreases the sludge volumes requiring off-site transportation. High initial capital investments and operating costs such as polymer dosing, lime addition, biological stabilisation, maintenance and high energy consumption render much of this equipment unsuitable for decentralised wastewater treatment facilities.

The disposal of sludge can represent 50% of the operating costs of a typical wastewater treatment plant and can consume large resources in terms of dealing with public complaints (Appels et al., 2008; Murray et al., 2008). Furthermore, the liquid resulting from sludge treatment processes can represent between 5% and 10% of the carbon load, and between 10% and 20% of the nitrogen load of a wastewater treatment plant (Henze et al., 1997; Caffaz et al., 2006), and treating this liquid has significant implications for capital and running costs.

The novel technology – 'A woodchip bioreactor' – is at an advanced stage of patent application, having passed the initial review stages. The sustainable woodchip-based technology could be an environmentally sustainable, low-cost technology for filtering wastewater sludges. The filtered solids, along with the woodchip, can then be composted, used as a fertiliser, a soil conditioner or as a fuel for gasification and subsequent energy generation (Rodgers et al., 2009b).

In this chapter, the novel woodchip bioreactor technology is outlined (Rodgers et al., 2009b). The results of the trials to date, and the potential of this technology as an alternative to existing sludge treatment systems are discussed.

Increasing attention is also being placed on better water resource management. One of the key areas to be addressed is the reuse of treated wastewaters. A recent report by the European Union Water Initiative highlighted the environmental, economic and social benefits of wastewater reuse in appropriate situations (EUWI, 2004). Various technologies can be employed depending on the removal requirements, the efficiency of the secondary treatment plant and the end use of the treated wastewater. This chapter also details a new polishing treatment system at the WRF. Proposed work which will be carried out in collaboration with the Marine Institute using the new effluent polishing system is also detailed.

5.3 Pilot-Scale Systems

5.3.1 Laboratory woodchip bioreactors

The laboratory set-up comprised nine stainless steel enclosures each having a transparent Perspex panel that allowed for visual monitoring of the woodchip filtration process (Fig. 5.1). The dimensions of each enclosure were 300 mm × 300 mm in plan with an overall height of 2,000 mm that included a stainless steel cap 300 mm high. Lodgepole pine (*Pinus contorta*) was chosen for use as the woodchip filtration medium because of its:

- Widespread availability in Ireland;
- Relatively fast growth rate; and
- Potential biodegradable carbon release into the filtration liquid which may increase denitrification of the filtrate.

5.3.2 Pilot-scale woodchip bioreactors (located at the WRF)

Three woodchip filter bioreactor units – each designed to treat sludge from about a 30-PE wastewater system – were designed, manufactured locally and positioned at the WRF (Fig. 5.2). Each filter tank, with an internal diameter of 1.2 m and a height of 1.5 m, was fitted with a lid through which air could be drawn and was supported on a steel stand. The tank filtrate discharged to a reservoir underneath.

Each tank was filled to a height of 0.5 m with a woodchip/sawdust mix of known particle size. An influent storage tank was used to distribute waste activated sludge from the TWWTP to each of the three reactors.

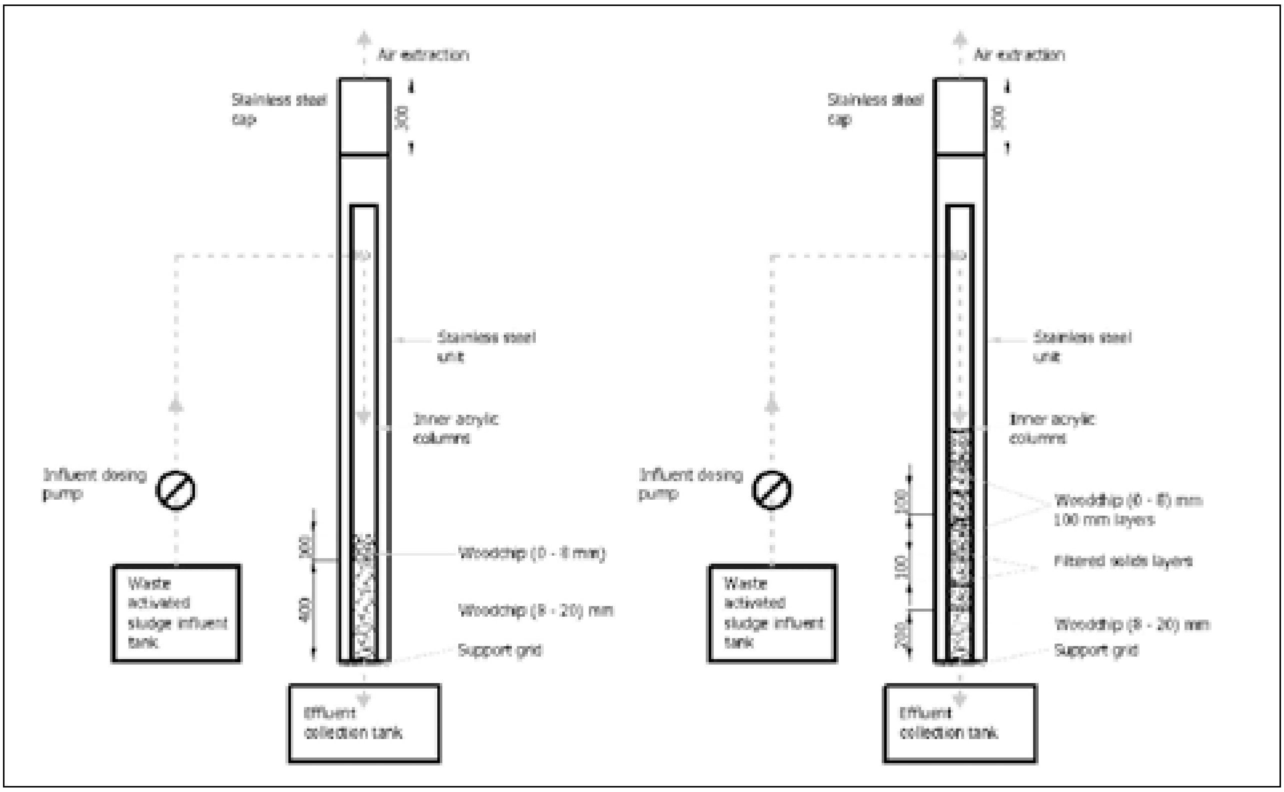


Figure 5.1. Typical schematic of the laboratory woodchip filtration units.

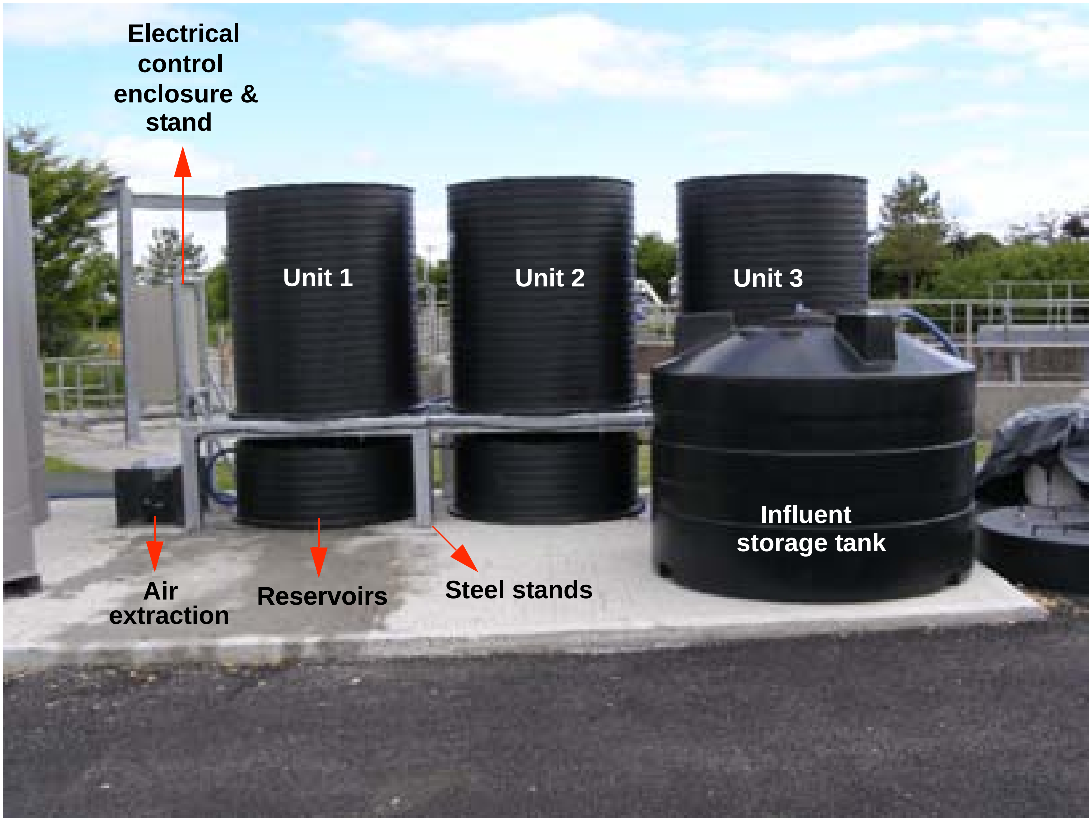


Figure 5.2. Pilot-scale woodchip bioreactors.

5.3.3 *Polishing technologies*

Treated wastewater from the main PFBR system at the WRF will be diverted to a number of polishing technologies. A 4 m × 3 m insulated steel shed has been installed by the research team at the WRF and this houses the polishing equipment. The equipment installed includes:

- An automatic sand filtration system;
- An activated carbon filtration system;
- An ammonium stripping zeolite medium; and
- A UV disinfection system.

Figures 5.3 and 5.4 show a schematic and picture, respectively, of the system, which includes:

- Ports for sampling the wastewater before and after each tertiary treatment system;
- Automatically controlled backwashing of the filter systems;

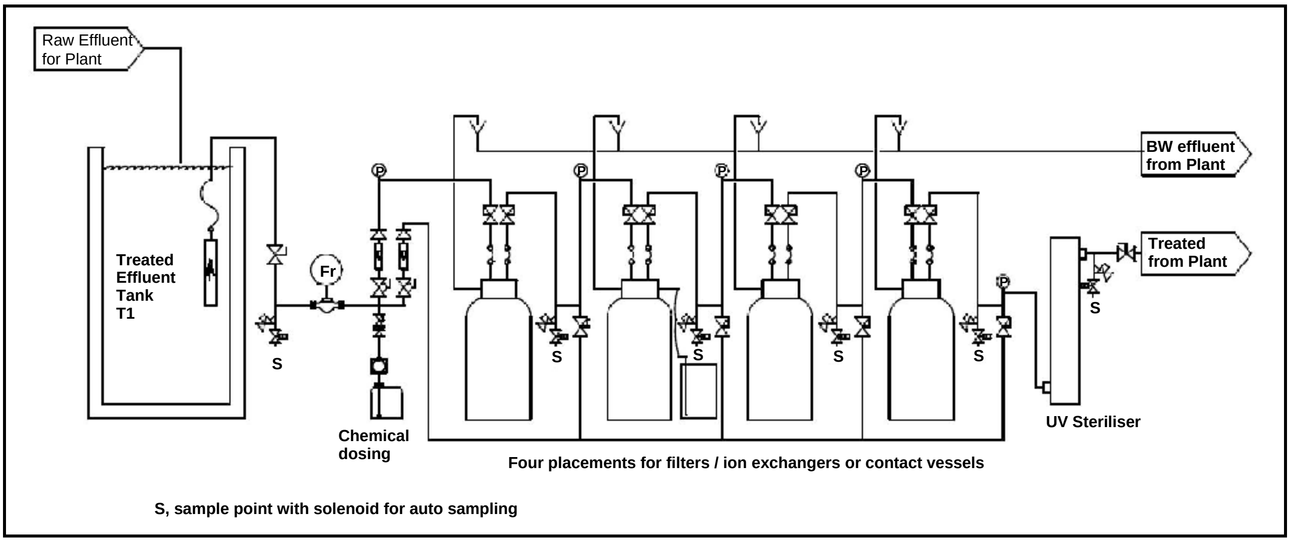


Figure 5.3. Overall schematic of the tertiary treatment system installed at the Water Research Facility.

Figure 5.4. Picture of the tertiary treatment system installed at the Water Research Facility.

- In-line pressure measurement that can provide essential information on system performance and clogging; and

- A user-friendly interface and control system.

5.4 System Operation – Pilot-Scale Woodchip Bioreactor

A brief overview of the operation and set-up of the laboratory pilot-scale woodchip bioreactor technology is given and the monitoring procedures are outlined.

5.4.1 System set-up

Each woodchip bioreactor was filled to a depth of 0.5 m with a specific and controlled mix of woodchips and sawdust. The results of the laboratory study indicated that particular mixes of woodchip particle sizes were significantly more suitable than others. The final mix chosen was most effective in removing solids while not clogging rapidly, thus increasing the lifetime of the filter.

A single submersible pump, intermittently operated using a timer, dosed each unit with waste activated sludge at equal time intervals daily. The solids were retained in the woodchip filter and the filtrate leached to a reservoir located under each woodchip reactor. Samples of filtrate exiting each reactor were periodically taken and analysed for COD, BOD_5, SS, NH_4-N, total nitrogen (TN), NO_3-N and PO_4-P.

5.4.2 System operation

Each bioreactor was dosed with about 65 l/day of waste activated sludge, four times daily, at regular 6-h intervals. Dosing periods lasted about 5 min. For 5 min before and 10 min after dosing, an air suction pump was activated that drew air through each reactor from the bottom to the top. This ensured that water ponding did not occur in the filter over the duration of the study.

The filters were operated for a period of about 60 days and were then monitored – without addition of further waste activated sludge – for a further period of 30 days. During this additional period the solids content and temperature of the trapped solids were recorded.

5.5 Overall Results – Woodchip Bioreactor

5.5.1 Laboratory-scale trials

The initial laboratory trials indicated the excellent potential of the woodchip bioreactors to remove solids from wastewater activated sludge. It was also noted that the effluent filtrate from the units was of excellent quality, showing that, with biological carbon removal, nitrification and denitrification had occurred in the filtration process. A variety of woodchip filter arrangements were trialled and the effect of hydraulic loading rate, woodchip depth and woodchip particle size and mix on treatment efficacy were investigated. A summary of typical results for various trials (i.e. C1, C2 and C3) is given in Table 5.1 and further information can be obtained from the project team on these and other trials.

For all the C1, C2 and C3 laboratory trials, excellent removals of SS, COD, and TN were observed, e.g. over 95.9% of all solids were retained in the woodchip filters. It was noted during the laboratory study that the total depth of woodchip, the layering of woodchips and the size of woodchip particles chosen were particularly important in influencing the removal efficiencies and the length of time before filter clogging occurred.

Good nitrification was observed in columns C1 and C2. Increases in concentrations of filtered COD were observed in all filters and the filtrate parameter concentrations were of better quality than normal influent municipal wastewaters, with the possible exception of PO_4-P. The increase in filtered COD may be due to carbon leaching from the woodchip and the previously captured solids as wastewater passed through the filter.

5.5.2 WRF pilot-scale trials

The woodchip bioreactors used for the pilot scale studies comprised a 0.5-m layer of a specific woodchip/sawdust mix. The mix was developed using readily available woodchip and sawdust sizes and could be replicated on a commercial scale. This mix was established after a number of laboratory trials and was found to offer the most efficient treatment along with allowing the filter to operate for a longer period of time without clogging.

Table 5.1. Average influent and effluent concentrations and percentage removals in laboratory-scale trials.

	Average C1 and C2 influent Days 10–30	C1 effluent 55.5 l/m²/day Days 10–30		C2 effluent 110 l/m²/day Days 10–18		Average C3 influent Days 10–60	C3 effluent 55.5 l/m²/day Days 10–60	
	(mg/l)	(mg/l)	% removal	(mg/l)	% removal	(mg/l)	(mg/l)	% removal
SS	**4,188 ± 723**	111 ± 47	97.3	170 ± 110	95.9	**4,093 ± 1,223**	120 ± 139	97.1
COD	**5,155 ± 669**	356 ± 108	93.1	331 ± 134	93.6	**4,549 ± 1,357**	259 ± 73	94.3
COD_f	**74 ± 18**	260 ± 50	–	198 ± 39	–	**54 ± 21**	219 ± 73.	–
TN	**426 ± 71**	68 ± 15	84.1	61 ± 11	85.8	**389 ± 110**	78 ± 25	80.0
TN_f	**72 ± 37**	59 ± 26	18.0	45 ± 16	37.9	**51 ± 27**	76 ± 24	–
NO_2-N	**0.1 ± 0.1**	0.6 ± 0.5	–	0.4 ± 0.1	–	**1.3 ± 4.1**	2.5 ± 3.1	–
NO_3-N	**0.4 ± 0.6**	6.9 ± 3.9	–	4.4 ± 0.1	–	**9.3 ± 19.8**	17.5 ± 15.6	–
NH_4-N	**51.3 ± 26.4**	33.3 ± 14.5	35.1	21.7 ± 3.5	57.7	**28.0 ± 19.0**	35.8 ± 10.1	–
PO_4-P	**49.9 ± 12.3**	40.6 ± 12.5	18.7	50.4 ± 10.5	–	**7.9 ± 8.9**	14.1 ± 4.3	–

C1, average results of triplicate filters operated at a loading rate of 55.5 l/m^2/day. The filter height was 500 mm and comprised a number of woodchip layers. Each layer had a different woodchip size distribution.
C2, as C1 above but operated at 110 l/m^2/day.
C3, average results of triplicate filters operated at a loading rate of 55.5 l/m^2/day.
SS, suspended solids; COD, chemical oxygen demand; COD_f, filtered COD; TN, total nitrogen; TN_f, filtered TN; NO_2-N, nitrite-nitrogen; NO_3-N, nitrate-nitrogen; NH_4-N, ammonium-nitrogen; PO_4-P, orthophosphate-phosphorus.

Waste activated sludge was applied at a loading rate of 70 l/m^2/day to the on-site units for 55 days. Excellent results were observed from the triplicate pilot-scale units. Table 5.2 summarises the removal of various contaminants from each woodchip bioreactor.

In all filters, the removal of solids was >98%. Excellent nitrification and nitrogen and carbon removal were also observed. It should be noted that the waste activated sludge was taken from a different wastewater treatment plant for the laboratory- and pilot-scale studies. Furthermore, a variation in the woodchip mix than that used in the laboratory trial columns was used. This resulted in more solids being trapped at the top of the column when compared with the laboratory trials which may have increased the carbon removal efficiency of the reactor and helped offset carbon released from the woodchips and previously captured solids.

The intermittent operation of the air pump, that drew air through the filters, ensured that clogging did not occur during the study. The sludge, retained on the woodchip filters, had an average solids content of about 10% (Fig. 5.5). This solids content reduces the volume of wasted activated sludge – typically 1–3% solids – to be transported, by up to a factor of 10.

Further research is necessary on the woodchip filter technology to further refine the process (outlined in Section 5.5.3). However, results of the laboratory- and pilot-scale trials to date indicate that the technology has significant advantages over existing technologies/methodologies that include sludge thickeners, gravity presses, and chemical treatment.

5.5.3 Potential of the woodchip bioreactor as a new technology for sludge treatment

The pilot-scale trials were extremely successful and have attracted commercial interest from a number of sources. The system required no maintenance during the pilot-scale study and running costs were low. The only mechanical components used were hydraulic pumps and an air pump. These are robust and easily maintained where necessary. The technology does not require the use of chemicals, such as polymers, to aid settlement or flocculation and uses a sustainable filter medium (woodchip) to separate the solids and liquid.

Table 5.2. Average influent and effluent concentrations and percentage removals in pilot-scale trials.

	Average influent Days 12–55	Unit 1 effluent 70 l/m²/day Days 12–55		Unit 2 effluent 70 l/m²/day Days 12–55		Unit 3 effluent 70 l/m²/day Days 12–55	
	(mg/l)	(mg/l)	% removal	(mg/l)	% removal	(mg/l)	% removal
SS	9,034	131	98.5	46	99.5	53	99.0
COD	8,008	314	96	254	97	235	97
COD_f	475	182	62	200	58	195	59
BOD_5	2,967	121	96	83	97	38	99
TN	519	81	84	83	84	83	84
TN_f	80	67	16	69	14	64	20
NO_2-N	0.03	0.78	–	0.79	–	0.62	–
NO_3-N	1.0	61.9	–	59.6	–	67.4	–
NH_4-N	80.9	11.0	86	12.8	84	5.8	93
PO_4-P	32.9	43.5	–	43.7	–	43.9	–

SS, suspended solids; COD, chemical oxygen demand; COD_f, filtered COD; TN, total nitrogen; TN_f, filtered TN; NO_2-N, nitrite-nitrogen; NO_3-N, nitrate-nitrogen; NH_4-N, ammonium-nitrogen; PO_4-P, orthophosphate-phosphorus.

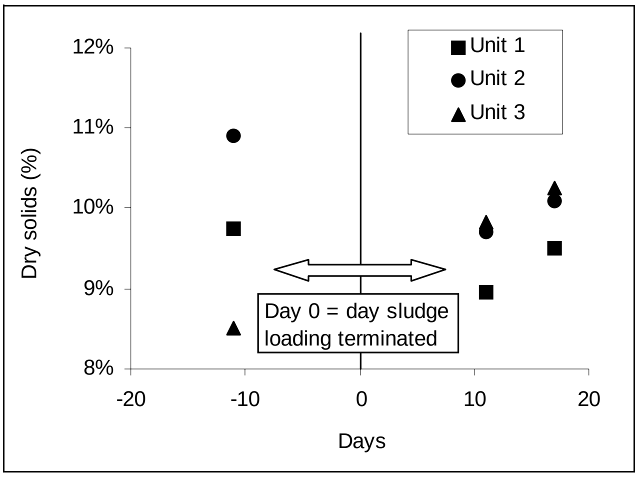


Figure 5.5. Dry solids content of filtered solids in pilot-scale trials.

A number of possibilities exist for the further reuse of the treated sludge and these include:

- In-tank composting of the woodchip/filtered solids mix after the capacity of the woodchip media has been reached;

- Use of the composted material as a fertiliser or a soil conditioner;

- Transport of the woodchip/solids mix to an on-site or off-site facility for thermal treatment and energy production – gasification, pyrolysis and co-burning are possibilities;

- For a typical sludge hub such as the TWWTP, initial indications are that the potential energy generated from such a sludge treatment process using gasification could be in excess of that required to operate both the wastewater and sludge treatment processes on-site; and

- Based on the laboratory- and pilot-scale trials, the filtrate from the woodchip bioreactor technology could account for between 0.5% and 1% of the total influent load to a wastewater treatment facility. In contrast with wastewater treatment plants that use current sludge treatment technologies, the sludge supernatant can account for between 5% and 10% of the total carbon and 10% and 20% of the total nitrogen load on a treatment plant. This would result in a significant saving in both the capital cost of new plants and the operating costs of new and existing plants.

Further research is necessary in order to optimise the loading rates on the woodchip bioreactors. In-tank composting could be investigated, with insulation being provided to the reactors and careful examination of the air flows required. The possibility of energy generation from the woodchip/solids mix through gasification could also be investigated.

5.6 Polishing Technologies at the WRF

The WRF has been designed such that various tertiary treatment processes can be operated in-train or individual processes can be plugged in and out of the treatment line. Initial work will focus on tertiary removal of solids, carbon, nitrogen, and phosphorus prior to disinfection. The polishing facility at the WRF will initially focus on the removal of a number of key contaminants.

- Influent landfill leachate at the WRF caused spikes in the influent nitrogen concentrations, and can result in increased effluent NH_4-N concentrations. A zeolite will be tested in a pressurised filter for its efficiency in removing residual NH_4-N from wastewater discharges.

- In conjunction with the Marine Institute, the use of a UV system to disinfect effluent wastewaters will be investigated. The project will last between 6 and 12 months and will initially focus on the removal of the norovirus, which can cause stomach flu or viral gastroenteritis, from treated wastewaters. The degree of treatment upstream of the disinfection process will be varied and its effect on the UV treatment efficiency will be investigated.

- An activated carbon process will be used to remove contaminants such as recalcitrant compounds (antibiotics, pesticides and hydrocarbons), metals and colour. Such treatment could be necessary to render wastewater suitable for reuse.

5.7 Conclusions

An alternative, novel and sustainable sludge treatment technology was developed (and is undergoing patenting) by the research team. The technology was seen as a more sustainable technology than the willow grove system originally proposed. The woodchip bioreactor could be a new and sustainable solution for sludge treatment at both decentralised small-scale and large wastewater treatment facilities. In relation to decentralised small-scale wastewater plants, a number of problems relating to sludge treatment exist:

- Sludge often receives limited treatment on-site prior to transport to a central sludge processing facility.

- Typically sludges are transported at between 1% and 5% solids – between 95% and 99% water – depending on facilities at the plants of origin. Thus transport costs are high with relatively high associated carbon footprints. There is also significant potential for public anxiety in relation to possible sludge odour emissions and liquid spills during the transport activity.

- Sludges are normally further treated at sludge hubs, which can include thickening, mechanical or thermal de-watering, and polymer and lime addition. Sludge hubs can attract public complaints due to odours and other health concerns.

- Treated sludge in Ireland is generally land-spread. Significant storage capacity at sludge hubs may be necessary when suitable land banks are not immediately available and where seasonal factors affect land-spreading.

- Throughout Europe land-spreading is increasingly being considered an unviable option.

- In some cases, sludge is being transported hundreds of kilometres across Ireland to central composting facilities.

- Sludge can be seen as an untapped resource with significant potential as a source of energy, a fertiliser or as a soil conditioner. Simple on-site sludge de-watering and treatment, using sustainable technologies like the woodchip filter, would reduce transport costs and could contribute to energy-self-sufficient wastewater treatment facilities.

- Low-energy technologies that reduce operation and maintenance costs associated with sludge treatment, decrease odour and gas emissions, and can be located in decentralised locations (thus reducing transport costs), are required.

- The woodchip bioreactor could be one such technology as the initial successful trials have shown. Further research into this technology could further optimise the process and allow composting and gasification trials to commence.

6 Technology Development and Research at the Water Research Facility

6.1 Introduction

One of the key objectives of the research team was the development of a research facility that could be used by research organisations such as Universities and Institutes of Technologies, state bodies and industry for carrying out technology research and development projects. The WRF site can facilitate projects in a number of areas, including water treatment, wastewater treatment and reuse, sludge treatment, sensors development and the development of new IT systems for controlling and monitoring water and wastewater facilities. A number of research projects are being carried out at the WRF or are planned for the near future and these are outlined below.

6.2 Horizontal Flow Biofilm Reactor

The HFBR, a novel wastewater treatment technology developed and patented in Civil Engineering, NUI Galway (Rodgers et al., 2004a), is an attached growth biofilm reactor designed to remove organic carbon, SS and nitrogen from low flow point sources – such as rural domestic houses. The technology has been proven both in the laboratory and at pilot scale, treating domestic/municipal (at the WRF) and agricultural (at a dairy farm) wastewater (Rodgers et al., 2008a; Rodgers and Clifford, 2009; Clifford et al., 2010).

6.2.1 Pilot-scale operation

A pilot-scale HFBR was operated for over a year at the WRF (see Fig. 6.3). Its efficacy in treating a mixture of municipal and landfill leachate wastewaters has now been proven. The novel HFBR technology has received awards at national and international levels and, following the study at the WRF, it has been commercially licensed. The pilot-scale HFBR unit comprised 56 acrylonitrile butadiene styrene (ABS) sheets, each measuring 1.34 × 0.93 m in plan. The unit was dosed with settled municipal wastewater from a primary settlement tank at the WRF for 4 min every hour. Influent, pumped onto the unit at Sheets 1 and 39, moved horizontally along each sheet, before falling through slots at the exit end of each sheet onto the sheet below (Fig. 6.1). Aeration was achieved passively. The flow through the unit during the pilot-scale study averaged 497 l/day or 399 l/m^2/day based on the top surface plan area (TSPA). Results are presented for the HFBR effluent over a 150-day period and for clarifier effluent over the last 80-day period, when the unit had reached a reasonable steady-state performance. Figures 6.1–6.4 show a schematic of the HFBR, the laboratory and on-site pilot-scale HFBR units and the custom-made mould designed by the research team at NUI Galway, respectively.

6.2.2 Results

Results are presented for the HFBR effluent over a 150-day period and for clarifier effluent over the final 80-day period, when the unit had reached steady-state performance. During the final 80-day period of the study, removals averaging 93% SS, 97% BOD_5 and 86% NH_4-N were achieved (Table 6.1).

The electricity usage of the HFBR averaged 0.176 kWh/day, with annual electricity costs estimated at €1.71/person (based on €0.16/kWh). In some sites with gravity flow onto the HFBR, the use of a tipping bucket arrangement could reduce energy costs per annum to zero.

Based on the pilot-scale results, a HFBR unit comprising 80 sheets with a TSPA of 3.3 m^2 could expect to achieve full carbon removal, full nitrification and up to 67% total nitrogen removal, when treating 900 l/day of septic tank effluent from a 6-PE household, at concentrations of 200–300 mg BOD_5/l and 35.5 mg NH_4-N/l (Rodgers et al., 2008a; Rodgers and Clifford, 2009; Clifford et al., 2010). As with all denitrification systems, nitrogen removal can be affected by carbon limitations.

The HFBR is an excellent alternative to existing systems for treating domestic wastewaters due to its:

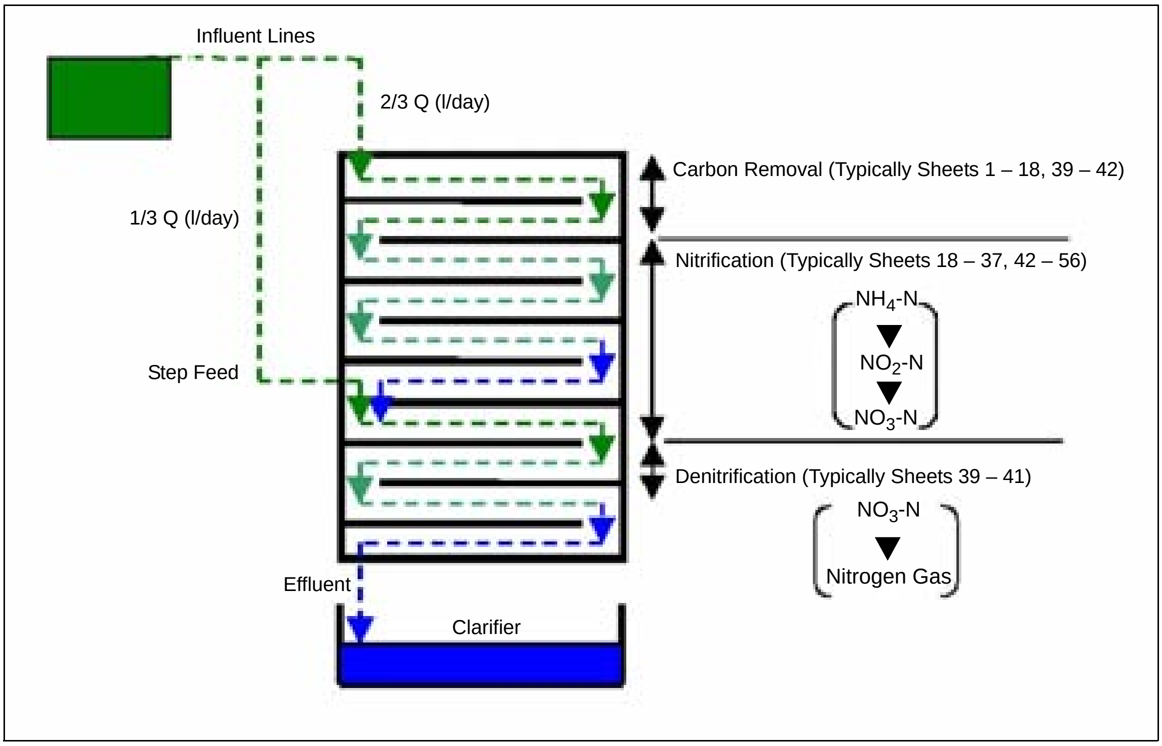


Figure 6.1. Typical schematic of flow patterns and removal mechanisms in a 60-sheet horizontal flow biofilm reactor.

Figure 6.2. Laboratory horizontal flow biofilm reactor units.

Figure 6.3. Horizontal flow biofilm reactor at Tuam Water Research Facility.

Figure 6.4. Aluminium vacuum mould for acrylonitrile butadiene styrene sheets.

- Excellent BOD_5, SS, NH_4-N and nitrogen removal;
- Low energy usage;
- Minimal maintenance requirements;
- Simple use of a single pump and timer control system;
- Simple and robust design; and
- Competitive capital costs.

6.3 Air Suction Flow Biofilm Reactor

Over the past 1.5 years, the same Civil Engineering research team from NUI Galway has developed a novel ASF-BR for wastewater treatment. The technology is currently at an advanced patent pending stage (Rodgers et al., 2008b). This two-reactor-tank technology has been extensively tested at laboratory scale and two pilot-scale units are currently being commissioned. One of these units is commissioned at the WRF and is treating wastewater for about 66 PE.

This biofilm system is characterised by:

- Its ease of operation and maintenance;
- Low operating costs;
- Low sludge production;
- Robustness;
- Comprising no moving parts or compressors, other than air vacuum pumps; and
- Its ability to capture nuisance and greenhouse gases for further treatment.

Aeration is achieved by alternately exposing the biofilm (attached to plastic media) in each of the two reactor tanks to atmospheric air, thereby eliminating the need for forced aeration, and wastewater. Uniquely, the ASF-BR uses air vacuum pumps (as opposed to hydraulic pumps) to move water between the two reactors, thus achieving passive aeration, while also significantly reducing operating costs. The use of sealed reactors allows gases developed during the biological treatment process to be captured and treated within the reactors or in a tertiary system.

Anoxic/Anaerobic conditions can be achieved by keeping the biofilm media immersed in the wastewater. By operating the system in an SBR mode to EU design loadings, the following can be achieved:

- BOD_5, COD, SS removal;
- Nitrification and denitrification; and
- Laboratory-scale biological phosphorus removal, and will be trialled at pilot scale.

Table 6.1. Summary of average horizontal flow biofilm reactor results (mg/l) between Days 0–150 (effluent) and Days 70–150 (clarifier).

Parameter[a]	5-Day biochemical oxygen demand	Suspended solids	Ammonium-nitrogen	Filtered total nitrogen
Average % removal (effluent)	92	85	75	23
Average % removal (clarifier)	97	93	86	34

[a]Average temperature 13°C; range 11–18°C.

6.3.1 System overview

The ASF-BR system comprises the following readily available components:

- 2 × sealed reactor tanks – no specific shape required;
- Plastic media;
- Motorised valves;
- 1 × vacuum pump (a partial vacuum of about 0.2 bar is used in the laboratory units);
- 1 × feed pump and 1 × discharge pump are generally required; however, a single vacuum pump may suffice for some sites;
- Reactor-tank-level sensors; and
- Basic PLC controls.

The ASF-BR system is operated as an SBR and, as such, requires primary settlement and a balance storage volume upstream of the reactor tanks.

6.3.2 Progress to date

Two laboratory systems, designed and commissioned at NUI Galway, have been operational for over 1 year. Laboratory Unit 1 is treating municipal-strength synthetic wastewater and Laboratory Unit 2 is treating high-strength synthetic wastewater. Both units can be controlled and monitored remotely and in real time using a bespoke control philosophy and a user-friendly SCADA PLC system (Fig. 6.5a and b). The SCADA system can be used to control units of any size and is being used for the pilot-scale units.

(a)

(b)

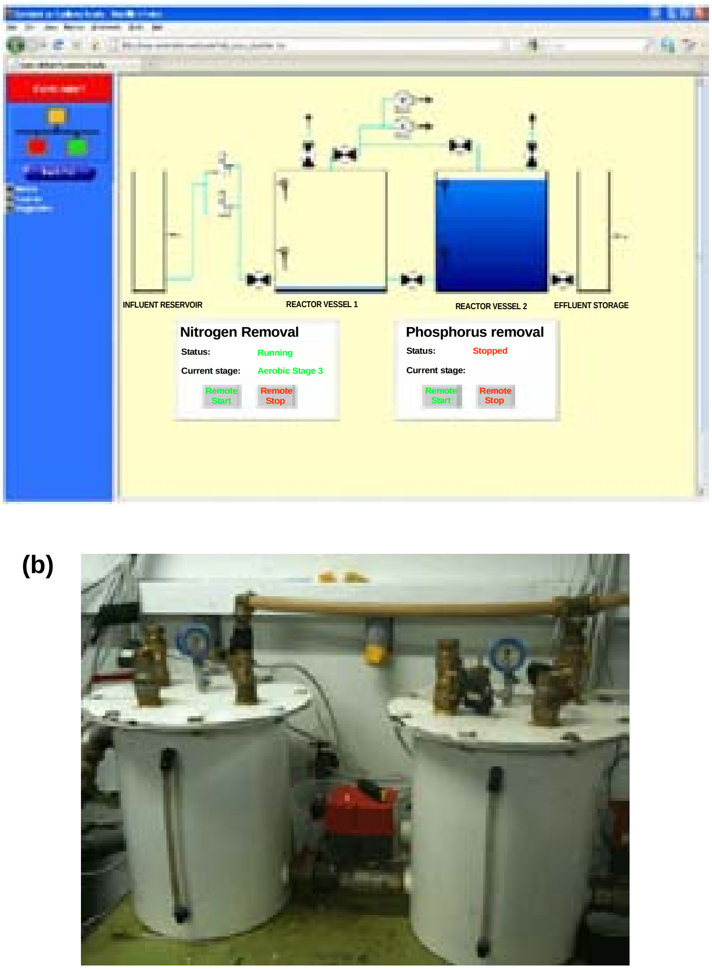


Figure 6.5. (a) SCADA programmable logic controller system and (b) laboratory units at NUI Galway.

Laboratory Unit 1

During Phase 1, the biofilm media surface area loading rate averaged 1.3 g COD/m^2/day and 0.15 g filtered total nitrogen (TN_f)/m^2/day. Average removals of 89% COD_f and 99% NH_4-N were achieved. During Phase 2 of operation the hydraulic loading rate was increased by 35%, resulting in biofilm media surface area loading rates of 2 g COD/m^2/day and 0.18 g TN_f/m^2/day. The higher loading rate was achieved by reducing the cycle time from 16.4 h to 11.9 h. During Phase 2, concentrations of effluent COD_f averaged 25.6 mg/l, while average removals of 56% COD_t and 95% NH_4-N were achieved. Studies on relatively high effluent SS concentrations indicate that the combined nature of the novel 'vacuum' process and the use of media balls may result in sloughing within the unit. Further work is being carried out in this regard.

Phase 3 is under way and will focus on nitrogen and phosphorus removal, while reducing energy consumption by a further 50%. A pilot-scale plant treating municipal wastewater is currently in operation at the WRF.

Laboratory Unit 2

During Phase 1, at a biofilm media surface area loading rate of 2.08 g COD/m^2/day and 0.22 g N/m^2/day, excellent average removals of 93% COD_t, 73% TN and 86% NH_4-N were achieved. The ASF-BR proved reliable, required minimal maintenance and was easy to control. During Phase 2 of operation, to further reduce energy costs, pumping frequency will be reduced by 50% (a 50% reduction in energy costs), while maintaining a similar loading rate to Phase 1. The remote monitoring process employed allows a single operator to manage a number of plants from a centralised location. A second pilot-scale ASF-BR is under construction at a landfill site and will treat landfill leachate.

Pilot-scale trials

Two pilot-scale units have been designed and constructed, and will be tested on-site, one at the NUI Galway/EPA WRF and the other at a landfill. One pilot-scale unit has been installed and commissioned at the WRF (Fig. 6.6) and is treating about 13.25 m^3 (equivalent to about 66 PE @ 200 l/PE/day).

6.3.3 Potential of the new technology

Decentralised systems in Ireland and Europe will continue to be built with upgrades to existing systems also being necessary. In the US, there is a major drive for decentralised wastewater treatment systems that can efficiently remove nitrogen – it is expected that energy requirements for wastewater treatment facilities will increase by 20% in order to meet future nitrogen discharge standards.

In all cases, systems are required to have low operational costs and be readily maintained. Furthermore, wastewater facilities, like much of the built environment, are being required to reduce their

Figure 6.6. Pilot-scale air-suction flow biofilm reactor units at the Water Research Facility.

carbon footprint. Wastewater treatment facilities can also cause public disquiet due to odorous emissions. In the maritime wastewater treatment market – worth about €4 billion/year internationally – odour and gas control is essential, particularly in the enclosed ship environment. The ASF-BR offers major advantages in this respect. Ships of over 400 gross tonnes or carrying more than 15 persons are required to have onboard wastewater treatment and/or storage and the modular nature of this system, with its gas capture capabilities, can prove an advantage for this market. Other markets (apart from municipal) for which the ASF-BR is suited include industrial and agricultural wastewater treatment.

6.4 Other Research at the WRF

6.4.1 Tertiary treatment of wastewaters for potential reuse in non-potable applications

As outlined in Chapter 5, the NUI Galway research team has installed a comprehensive pilot-scale tertiary treatment system at the WRF. The work will focus on further removal of carbon, nitrogen and phosphorus and the use of UV in removing the norovirus from treated wastewaters. The NUI Galway research team is collaborating with the Marine Institute in this work based at the WRF.

6.4.2 Mobile remote monitoring and control system (MRMC)

Supported by an EPA STRIVE Infrastructure grant (2007-INF-6-S5), the research team designed and developed the MRMC (Fig. 6.7). The system was developed in response to future monitoring and research needs. In many cases it is difficult and expensive to carry out intensive monitoring of decentralised water and wastewater treatment systems, and on pilot-scale technologies. The MRMC could be used by various interested stakeholders and could provide a template for further development of remote monitoring systems that are mobile and that could be cost-effective and more accurate when compared with manual sampling methods. A brief summary of the system is given in Table 6.2.

6.4.3 Development of SMART monitoring systems for deployment at water and wastewater treatment facilities

The research team is currently involved with two companies proposing to carry out research into the area of SMART (self-monitoring, analysis and reporting technology) monitoring and management of water and wastewater treatment facilities. With one company, a research proposal has been submitted under the STRIVE programme.

Figure 6.7. The mobile remote monitoring and control system.

Table 6.2. Main mobile remote monitoring and control system features.

Main system features	Parameters that can be monitored	
	Water	**Gas**
• Wastewater and sludge treatment plant monitoring • Troubleshooting of treatment facilities • Monitoring of discharges and receiving waters • Autonomous operating system – no manual sampling required • Data can be downloaded remotely • Data can be viewed in real-time via a GSM modem	• Chemical oxygen demand • Ammonium-nitrogen • Nitrate-nitrogen • Orthophosphate-phosphorus • Suspended solids • pH • Dissolved oxygen • Oxidation–reduction potential • Temperature • Flow	• Ammonia • Methane • Carbon dioxide • Hydrogen sulphide • Nitrous oxide

GSM, Global System for Mobile.

6.4.4 Monitoring of odorous, greenhouse and nuisance gas emissions at a decentralised treatment plant

Dr. Eoghan Clifford and Mr. Edmond O'Reilly, in collaboration with Dr. Xinmin Zhan (NUI Galway), have recently secured funding to purchase nitrous oxide sensors and other gas analysing equipment (RSF Grant – €60,000). These will be used to monitor nitrous oxide emissions (which have about 300 times the greenhouse gas impact of carbon dioxide) during wastewater treatment. The work will then concentrate on optimising denitrification processes while reducing nitrous oxide gas emissions.

The research team is currently evaluating a newly engineered version of the HFBR technology for its efficacy as a low-cost technology that can treat gaseous emissions from wastewater and sludge treatment facilities. Funding permitting, it is envisaged that a pilot-scale trial will be undertaken at the WRF. The laboratory work to date has been supported by Science Foundation Ireland and two PhD students are working on this project while collaborating with the Department of Microbiology at NUI Galway.

7 Research Dissemination

Throughout the project the research team has been active in presenting the research carried out and the facilities at the WRF to a wide range of audiences in various media. Many of these are outlined below. Further articles are planned as are articles for submission to *Engineers Ireland* and *Water 21* (the leading international magazine in the water and wastewater sector – an IWA publication).

7.1 Peer-Reviewed Publications (journal and conference)

- Clifford, E., O'Reilly, E. and Rodgers, M., 2011. A unique full-scale water research facility for applied and fundamental research, technology development, education and public outreach. (International Conference on Engineering Education (ICEE), Belfast, Northern Ireland. August 2011).

- O'Reilly, E., Rodgers, M. and Clifford, E., 2011. Operation of a full-scale pumped flow biofilm reactor (PFBR) under two aeration regimes. *Water Science and Technology* (in press).

- Keady, A., Rodgers, M., Clifford, E., and O'Reilly, E., 2010. The treatment of wastewater biosolids using woodchip filters (in preparation).

- O'Reilly, E., Clifford, E., and Rodgers, M., 2010. Municipal wastewater treatment using a full-scale pumped flow biofilm reactor (PFBR). WEF/IWA Biofilm Reactor Technology Conference 2010, Portland, Oregon, USA. August 2010.

7.2 Media Outlets

- RTÉ 1 – Six One News (with Jim Fahy)

- RTÉ 1 – EcoEye (with Duncan Stewart)

- Galway Bay FM

- Raidió na Life

- *Irish Times* (2006)

- *Environment, Energy and Management* (Jan/Feb issue), (2010)

- *Innovation for a Green Economy – Environment and Technology: A win-win story* (http://www.epa.ie/downloads/pubs/research/tech/name,26326,en.html) (2009)

- *Galway Independent*, *Tuam Herald* (2010); *Galway Sentinel* (2006)

- Numerous Irish and European engineering and environmental websites including: http://www.recyclingportal.eu/artikel/23660.shtml http://www.siliconrepublic.com/innovation/item/15173-nui-galway-water-research-f

7.3 Industry Presentations

- Enterprise Ireland Water Quality Group (2009)

- IDA, Veolia International Management Group (2010)

- IBM (2010)

- Coffey Group, EcoEmergence Ltd, Molloy Precast Products Ltd, Hanley Control and Measurement Ltd, EPS, Bord na Móna, etc.

7.4 Visiting Academics

Outside of the opening day in February 2010, leading national and international academics have visited the site including:

- Prof. Zbigniew Lewandowski (Montana State University, USA);

- Prof. Tom Stephenson (Cranfield University, UK);

- Prof. Wojciech Adamski (Wrocław University, Poland);

- Drs Nicolas Bernet and M. Torrijos (INRA, France);

- Profs. Calvin Rose and Hossein Ghadiri (Griffith University, Australia);

- Prof. Arup Sengupta (Leigh University, PA, USA); and
- A delegation from Questor (Queens University Belfast, Northern Ireland).

7.5 Educational

Site visits to the WRF have formed part of the following courses:

- NUI Galway Diploma in Environmental Sustainability;
- GMIT MSc in Water Resource Protection;
- Sligo IT, Research PhD students;
- Postgraduate and undergraduate students in Civil Engineering, NUI Galway; and
- Undergraduate engineering students from ENGEES, Strasbourg, France, and LeHigh University, Pennsylvania, USA.

8 Future Site Operation and Development

8.1 Potential of the WRF

The WRF offers a state-of-the-art world-class research facility in Ireland for industry, state bodies, universities, research institutes and other organisations to carry out fundamental and applied research on environmental technologies. The facility will provide an interactive platform where researchers, industry and the public sector can develop synergies that will lead to the protection of health and the environment and to creation of wealth in Ireland through the development of new technologies for the home and export markets.

New technologies will be trialled in real-life scenarios at a well-monitored and managed research facility. The extensive real-time access to the WRF allows researchers to remotely monitor research activities at the WRF. It is confidentially expected that after an initial start-up period the WRF will be financially self-sustaining. It is envisaged that a number of researchers, engineers and scientists would be employed at the facility and at NUI Galway to carry out and supervise varied research projects and liaise with industry. Thus, both fundamental and applied research could be carried out with a unique collaboration between industry, university, state bodies and other organisations.

The advantages of the WRF include:

- Access to wastewater at various stages of treatment allowing for technologies to be trialled for primary, secondary and tertiary treatment. The WRF can process up to 50 m^3/day of wastewater;
- A well-equipped site for testing new sensors and analysers for water and gaseous contaminant monitoring at various stages of treatment;
- The MRMC can be deployed to technologies on-site or can be used elsewhere, where new technologies are being applied on particular wastewaters, e.g. in food factories. The research team has real-time access to data from the MRMC, thus allowing instantaneous feedback on process efficiency;
- Access to wastewater sludge allowing new sludge treatment methods to be tested;
- An easily accessible site at Tuam, Co. Galway;
- Process samples are regularly taken and monitored and can be tested at the excellently equipped NUI Galway Environmental Engineering Laboratories; and
- Experienced NUI Galway research staff to operate and maintain the research facility.

9 Conclusions

9.1 Main Project Summary

9.1.1 Project overview

As part of a large-scale EPA study (2006-ET-LS-12-M3), a WRF was constructed at an existing medium-sized wastewater treatment plant (Tuam, Co. Galway) where a portion of the inflow was diverted to the WRF. The main aims of the large-scale study were:

- To construct an innovative, economic, simple-to-operate, small-town wastewater treatment facility that would remove organic carbon, nutrients, solids, micro-organisms, FOG, and possibly odours to acceptable high standards;
- To provide alternative tertiary facilities for polishing the secondary-treated wastewater;
- To provide facilities for treating sludge;
- To instrument the facility with sensors, analysers, energy meters, flow measuring devices, and broadband connection so that the system performance could be interrogated, assessed and controlled remotely;
- To monitor the plant for the removal of organic carbon, nitrogen, phosphorus, solids, micro-organisms, FOG, and possibly odours to acceptable high standards and store the data in a database in a form suitable for graphical statistical analyses;
- To synthesise the data to produce loading and removal rates for all removed contaminants; and
- To complete a literature review, periodic and final reports, design manual and three to six international peer-reviewed papers.

The WRF now provides a unique national test bed for the development and testing of existing and new indigenous waste, water and wastewater treatment technologies.

9.1.2 Project activities

Activities carried out under the defined project tasks have been detailed within this report and are summarised as follows:

- **Task 1: Selection and preparation of a suitable site for the WRF**

  Tuam wastewater treatment plant was considered the most suitable location for the WRF for the following reasons:

  - Adequate land was available on-site;
  - Existing facilities on-site; and
  - Access.

  The project team prepared a detailed WRF proposal for Galway County Council, which agreed to carry out the required civil engineering works.

- **Task 2: Designs, contract documents and tenders for the WRF**

  Full designs for the WRF were prepared based on the PFBR technology that has been invented, developed and tested at NUI Galway. The project was submitted for the public tendering process under the Model Form (MF/1) General Conditions of Contract for the supply of electrical, electronic or mechanical plant to http://www.etenders.gov.ie. An independent consulting engineering firm was appointed as project supervisors to the design stage. The tenders were evaluated and the contract was awarded to the successful tenderer, which was appointed PSCS.

- **Task 3: Construction of the demonstration WRF**

  Galway County Council carried out the civil engineering works as agreed. The main contractor installed the equipment for the wastewater treatment system. A number of items, such as process tanks and process controls, were removed from the tendered contract and were obtained directly from suppliers to ensure that budgets were maintained.

The pilot-scale sludge treatment and water polishing facilities were designed, constructed and commissioned by the NUI Galway research team.

- **Task 4: Monitoring of the PFBR carbon and nitrogen removal treatment system and polishing facilities**

  Task 4 was amalgamated with Task 5 to expedite the delivery of the stated milestones.

- **Task 5: Monitoring of the PFBR carbon, nitrogen and phosphorus removal wastewater treatment system and polishing facilities**

  1. Wastewater treatment system

  Four separate studies were carried out on the PFBR operating at the WRF. Biodegradable carbon, nitrogen and phosphorus removal were investigated during **Study-phase 1** of operation for about 180 PE over a period of 100 days. A dedicated anaerobic period was incorporated into the treatment cycle to encourage the development of PAOs for biological phosphorus removal. Good carbon and nitrogen removals were achieved during Study-phase 1. However, little or no phosphorus removal was recorded, indicating that the enhanced biological phosphorus removal did not become established during the 100-day study. The organic loading was increased during **Study-phase 2** with the aim of treating a population equivalent of over 300 PE in terms of BOD_5 and 420 PE hydraulically for a period of 75 days, to establish if SS removal, carbonaceous oxidation and nitrification could be achieved at these loadings. Carbon removal levels were lower than those experienced in Study-phase 1. It was believed that nitrification activity was inhibited due to the addition of landfill leachate to the municipal wastewater at the TWWTP. During **Study-phase 3**, the system was configured for SS and carbon removal only with the organic loading at around 320 PE. Total nitrogen concentrations entering the WRF during Phase 3 were over three times the normal concentrations for municipal wastewater. This high nitrogen loading caused high effluent SS and carbon concentrations. The loadings were reduced in **Study-phase 4** and a dedicated anoxic phase was incorporated to investigate system efficiency at removing nitrogen through the nitrification/denitrification process.

  2. Sludge treatment

  A pilot-scale sludge treatment system was operated for 55 days at the WRF. Excellent removals of solids were observed with DS contents of 10% being measured in the retained sludge in the woodchip filters. The system also achieved excellent treatment of the filtrate, resulting in a 'supernatant' load of between 5% and 10% of that resulting from existing technologies. Further research is necessary to develop the technology to a commercial scale.

  3. Polishing technologies

  An automated polishing technology system comprising an automatic sand filter, an ammonium stripping zeolite, an activated carbon filter and a UV disinfection system has been installed. The flexible design allows other polishing technologies, such as metal removal technologies, phosphorus absorbing resins, new disinfection technologies and other contact filters, to be easily installed.

- **Task 6: Literature review**

  A comprehensive literature review has been compiled in Chapter 2 of this report. The review outlines relevant legislation, technology developments and challenges in the wastewater, sludge and gas and odour sectors.

- **Task 7: Analysis and computer calibration**

  To date, mathematical models of two technologies that are in place in the WRF have been developed using AQUASIM (the PFBR and HFBR). Both of these models have been calibrated for laboratory data and it is planned to extend this work to include full-scale operations of these systems. To this end, the project team has been in contact with Hydromantis Ltd (developers of the world-leading GPS-X™ software) regarding the development of full-scale, user-friendly models of the PFBR and ASF-BR technologies. These models would then be integrated into the GPS-X™ software, thus making these technologies known on an international stage. It is hoped to secure funding for a PhD student to carry out this work and Hydromantis has given written confirmation that it would provide technical support.

- **Task 8: Reports and publicity**

Interim financial and technical reports have been submitted as required. The research team has endeavoured to use a variety of means to publicise and disseminate its research. These are detailed in Chapter 7 and include an international peer-reviewed conference presentation, three international journal papers submitted or to be submitted, television, radio, local, national and international print and web media, presentations to leading companies and to Enterprise Ireland and the IDA.

Visits from industry, academia, state and regulatory authorities have been and are being facilitated. Students from NUI Galway and GMIT are being accommodated on-site as part of various diploma or degree programmes.

10 Recommendations

The NUI Galway project team designed, constructed, operated and comprehensively monitored a novel attached-growth wastewater treatment process at Tuam WRF for 18 months as part of the large-scale EPA project: *Treatment and Monitoring of Nutrients, Odour and Sludge at a Small-Town Demonstration Wastewater Treatment System* (2006-ET-LS-12-M3). During this project, process issues – common to most types of wastewater treatment systems – were encountered and recommendations to address these issues are presented below. These recommendations are provided as guidance for:

- Policy makers (Department of the Environment, Community and Local Government, Department of Agriculture, Fisheries and Food, etc.) (see Table 10.1);
- Regulators (EPA, local authorities, etc.) (see Table 10.2);
- Wastewater managers and process designers (see Table 10.3);
- Industry innovators and research (including researchers and research funding agencies) (see Table 10.4); and
- Training (third-level institutions, Water Services National Training Group, Engineers Ireland, etc.) and public awareness (see Table 10.5).

10.1 Influent Characteristics

Influent wastewater characteristics and flows should be carefully evaluated, taking into account the following:

- Type of existing or proposed sewer system, e.g. a combined or separate storm and foul system. Infiltration and leakage should be investigated and eliminated.
- Comprehensive monitoring and characterisation of influent wastewaters, which will lead to improved plant design and operation, and should include:
  - Continuous flow monitoring during both wet and dry periods to establish daily flow patterns (maxima, minima and averages);
  - 24-hour composite sampling to establish weekly or monthly patterns;
  - Individual samples taken every 2–3 h to determine the daily variation in contaminant concentrations; and
  - Analyses of filtered and unfiltered samples to include, at a minimum: BOD_5, COD, TN, total phosphorus, NH_3-N, PO_4-P, NO_3-N, pH; SS and DO.
- The analysis and synthesis of the influent data could form part of the annual reporting for licensed treatment systems to the EPA, particularly in relation to the adequacy of treatment system capacities (normally Section 1.7 of EPA discharge licenses).
- Monitoring regimes, as recommended above, will enable operators and engineers assess the integrity of the sewerage system through quantifying infiltration and leakage flows. These flow data could form part of the rational basis for seeking funding for infrastructural improvements (usually Condition 5 of EPA discharge licenses).
- Design loading rates should be based on extensive monitoring, where possible, and should be calculated in accordance with relevant guidelines and standards.
- Designs should consider the consequences of the wastewater treatment plant being underloaded during the initial years of operation or seasonally, e.g. out-of-season tourist facilities. These consequences could lead to opportunities for energy savings during times of reduced flows

or to deterioration of the system micro-organism populations during very low flows.

- Additional possible influent loads to the treatment plant, e.g. wastewaters from local industry, landfills and composting facilities, and septage, should be quantified and accommodated in the overall design. Shock loading with additional wastewaters should be avoided to protect the beneficial micro-organisms in the treatment system. These wastewaters should be introduced into the treatment system intermittently – from storage tanks – over as long a period as possible or during periods when the normal influent flow is low, e.g. at night.

- At centralised sludge processing hubs located on-site at wastewater treatment plants, consideration should be given to the additional influent loads caused by supernatant arising from the treatment of sludge. Depending on the level of sludge treatment on-site, supernatant can comprise 15% of the influent carbon load and 25% of the influent nitrogen load at wastewater treatment plants.

- Adequate provision should be made in combined sewerage systems for storm flows using separate storm tanks or within the primary settlement tanks in small systems. Controlled pumping forward of the stored storm flow into the treatment system at appropriate times will generate balanced flow and proper treatment in the system.

- Extensive monitoring at 6-monthly intervals to establish any significant changes in the influent wastewaters could lead to improved plant operation.

- The collected and synthesised monitoring data sets could be used to inform and update future decentralised wastewater treatment guideline documents, in relation to average plant influent loads, infiltration and leakage, and per-capita wastewater production.

- Detailed periodic monitoring would facilitate compliance with annual reporting requirements of discharge licenses. The detailed monitoring data could also be used in mathematical modelling to predict when particular treatment plants are likely to be overloaded, thus facilitating orderly upgrading to prevent any environmental damage occurring.

10.2 Primary Treatment of Wastewaters

- Preliminary treatment using automatic or manual screens or grit chambers can be effective in preventing large solids from entering the treatment plant and preventing damage to equipment downstream. Scheduled regular maintenance of this equipment is necessary. Details of the maintenance required and observations on the screen and grit chamber performances should be recorded.

- A balance tank can act as a buffer to sudden storm loads and with controlled forward pumping can help ensure that influent wastewater flows through the plant remain reasonably steady.

- Primary settlement tanks are used to settle out solids prior to entering the biological zone of the treatment plant. For small-scale treatment plants, these tanks should be designed to accommodate adequate sludge storage. Tank sludge levels should be monitored to prevent primary sludge movement through the plant. Increased primary tank volume can reduce sludge disposal and transport costs, improve plant performance and provide a balance for storm flows. The plant at Tuam WRF has about 3–4 months of sludge storage in its primary settlement tanks when operating at full capacity.

10.3 Process Operation

10.3.1 Equipment selection

As many decentralised wastewater treatment facilities do not have full-time operators, recommendations are that:

- Equipment should be robust and easily maintained by one or two persons, depending on plant size, working on a part-time or full-time basis at the plant;

- Readily available replacement equipment should be used; and

- Operators should be able to remotely monitor equipment in a number of treatment facilities from a control centre.

10.3.2 Process control – monitoring and alarms

Monitoring wastewater treatment processes is critical to ensure that adequate performance is maintained and discharge standards are met. The following general recommendations are given:

- Comprehensive flow, pressure, level, temperature, energy and quality parameter concentration sensors, and control equipment, interfaced with ICT systems, should be installed to facilitate:
  - Remote monitoring of physical, chemical and energy parameters;
  - Transmission of warning alarms to the operational control centre; and
  - Corrective actions before any quality problems in the effluent can occur.

- Energy requirements should be continuously monitored to reduce costs and associated carbon footprints, and to detect any malfunctioning of equipment or plant.

- The use of robust water quality probes and data logging equipment should reduce the expense associated with day-to-day manual/automatic sampling and testing (see Section 10.3.3).

- The installation of simple, robust alarm sensors can signal rapidly when problems might be occurring, indicating that corrective action needs to be taken. Warning sensor examples include:
  - DO probes to indicate aerator malfunction;
  - Energy meters for problems with mechanical equipment; and
  - Level sensors in balance, chemical solution, settlement and reactor tanks.

10.3.3 Process control – sensors and probes

The provision for online measurement of parameters such as DO, pH, ORP, turbidity, SS, NH_4-N, NO_3-N and flow, can lead to efficient plant operation. When sensors and probes are used for online measurement, the following is recommended:

- Maintenance and calibration schedules should be implemented to ensure accurate readings and efficient operation. Biofouling of probes occurs at different rates, depending on the biological load on the wastewater treatment plant. For example, a DO probe will be affected by biofilm growth unless it is cleaned regularly. Self-cleaning systems should be employed, where possible, to reduce maintenance costs.

- Careful probe location selection is required as the readings of a particular parameter can depend on its probe location, e.g. DO readings in an activated sludge aeration basin may vary considerably depending on the position of the DO probe.

- The installation of chemical parameter probes can provide real-time information on treatment plant performance, e.g. using NH_4-N and NO_3-N sensor probes on the plant discharge will give indications on nitrification, nitrogen removal and also BOD_5 removal as NO_3-N usually only forms when nearly all of the BOD_5 has been oxidised.

- Process flow data should be continuously recorded at the inlet works, and also, desirably, within the plant using frequently calibrated robust measuring devices with data loggers and remote interrogation systems.

10.3.4 Sludge and odours

The disposal of sludge from decentralised wastewater facilities can:

- Be a major problem for plant operators;

- Incur significant costs; and

- Cause complaints and public disquiet.

The following general recommendations are given:

- The development of new, sustainable, robust, publicly acceptable and low-maintenance technologies for treating wastewater sludge on-site should be investigated.
- Technologies that promote the treatment and reuse of sludge locally may be more sustainable by:
  - Reducing transport costs and carbon emissions;
  - Reducing public concern due to odours and spillage occurring during transportation; and
  - Promoting sludge as a resource, e.g. a compost, fertiliser, soil conditioner or fuel.
- On-site odour and gas mitigation measures should be implemented.

10.4 Education and Training

- Public awareness programmes/seminars on wastewater treatment facilities, their importance and the public's role in their effective operation should be considered. Such programmes may reduce anxiety in relation to on-site sludge treatment and local reuse and may improve plant performance by eliminating the discharge of difficult-to-treat objects to the sewer system.
- Formal education programmes for local authority personnel, wastewater contractors, engineers, scientists, planners, policy makers, research personnel, students and other stakeholders are necessary to:
  - Ensure that plants meet new stringent discharge limits – notably for nitrogen and phosphorus;
  - Ensure that treatment plant operators and design engineers are fully familiar with the requirements of discharge licenses and the necessary actions – in terms of plant operation and monitoring – that are needed to meet the license requirements;
  - Increase awareness of the processes in wastewater treatment and thus improve troubleshooting, reduce the possibility for pollution events, and improve treatment plant efficiency; and
  - Improve energy efficiency in wastewater treatment plants.

10.5 Further Research

- Research into new, sustainable and energy-efficient technologies should continue with a focus on nitrogen and phosphorus removal. Such technologies could be trialled at the WRF with the objectives of commercialising the technologies and the creation of high-skilled jobs.
- A comprehensive survey of existing decentralised facilities should be completed to evaluate their performance and potential to meet new EPA discharge licenses.
- The implementation of new SMART monitoring and control systems should be piloted at a number of decentralised treatment plants. Such pilot studies should focus on:
  - Robust sensors and probes for monitoring and control of treatment plants;
  - The development of new, efficient and simple alarm systems that can provide real-time warnings of equipment failure or a potentially polluting discharge; and
  - The development of standardised user-friendly interfaces for operators, scientists and engineers.
- A pilot-scale project could be implemented at two to three decentralised wastewater treatment plants (the WRF could be one). The project should consider the requirements of local authorities, enforcement agencies, and industry so that it would test and develop the following:
  - Standardised user-friendly interfaces and web-based platforms for operators, scientists and engineers. Such a system could be common to all local authorities or to all systems within a local authority. It would be multilayered;

    - Various sensors for control, monitoring and alarm purposes;
    - Novel alarm systems to provide early warnings as to when plant performance may be deteriorating and thus allow targeted and rapid response;
    - Indicative sensors for measuring other parameters (e.g. NO_3-N measurements may indicate BOD removal),
    - Alarm systems for mechanical and electrical equipment;
    - Guideline documents to include performance data of sensors, maintenance and calibration requirements, data storage and presentation, and cost implications; and
    - A project encompassing all of the above elements and trialled at three sites could cost between €150,000 and €200,000, including staff costs.

- The on-site treatment of wastewater sludge should be further investigated for small treatment facilities. New technologies should focus on the reuse of treated sludge, with costs and public acceptance of treating and treated sludges as key issues.

- There exists significant potential to develop new odour and gas treatment technologies that can reduce the emission of greenhouse and nuisance gases.

- The efficacy of treating wastewater to potable water standards requires further investigation. Cost-effective systems could offer potential for on-site and local reuse of treated wastewaters.

- Mathematical modelling of wastewater treatment facilities has been shown to have significant potential in reducing treatment costs. Postgraduate research projects that train graduate students in modelling new and existing technologies can lead to:

    - Improved expertise and awareness of treatment processes for the graduate students entering the environmental engineering and environmental science workplaces;
    - Significant capital and operational savings at existing treatment facilities;
    - The detailed comparative examination of a range of wastewater treatment system options for proposed projects to meet the requirements of consulting engineers, contractors and local authorities; and
    - Economic stress testing of technologies proposed for implementation by contractors prior to contracts being awarded.

Table 10.1. Summary recommendations – Policy makers (Department of the Environment, Community and Local Government, Department of Agriculture, Fisheries and Food, etc.).

Related recommendation section	Summary recommendations
10.1 Influent Characteristics	• Provide guidelines and additional resources to allow for careful and ongoing influent monitoring
10.3.1 Equipment selection	• Encourage establishing remote interrogation capabilities • Provide monetary incentives for the installation of online monitoring
10.3.2 Process control – monitoring and alarms	• Encourage establishing remote interrogation capabilities • Provide monetary incentives for the installation of online monitoring
10.3.3 Process control – sensors and probes	• Provide sensor and probe maintenance and calibration schedules • Requirement for correct positioning of probes • Provide monetary incentives for the installation of indicator probes • Provide guidelines on, and encourage the development of, standardised interactive remote monitoring and control interfaces
10.3.4 Sludge and odours	• Prioritise the development of new sludge treatment technologies for decentralised systems • Prioritise the deployment and development of odour reducing/treatment technologies
10.4 Education and Training	• Encourage and support public awareness programmes/seminars on wastewater treatment
10.5 Further Research	• Provide further research funding for new, sustainable and energy-efficient technologies • Provide further research funding for the development and implementation of new SMART monitoring and control systems • Develop sustainable on-site sludge treatment technologies • Develop wastewater reuse guidelines and strategies

Table 10.2. Summary recommendations – Regulators (Environmental Protection Agency (EPA), local authorities, etc.).

Related recommendation section	Summary recommendations
10.1 Influent Characteristics	• Provide guidelines and additional resources to allow for careful and ongoing influent monitoring
10.3.2 Process control – monitoring and alarms	• Support monetary incentives for the installation of online monitoring • Encourage the implementation of new SMART monitoring systems • Highlight the benefits of early warning alarm systems
10.3.3 Process control – sensors and probes	• Maintain and assess flow data records • Guidelines on the use of quality parameter probes for process monitoring
10.3.4 Sludge and odours	• Support the development and implementation of new decentralised sludge treatment technologies
10.4 Education and Training	• Provide formal education and training programmes • Encourage and support public awareness programmes/seminars on wastewater treatment
10.5 Further Research	• Commission a comprehensive survey of existing decentralised facilities to evaluate their performance and potential to meet new EPA discharge licenses • Support the implementation of pilot-scale SMART monitoring installations in key locations

Table 10.3. Summary recommendations – Wastewater managers and process designers.

Related recommendation section	Summary recommendations
10.1 Influent Characteristics	• Carefully monitor influent characteristics, where possible, for optimal design, operation and upgrading of wastewater treatment plants • Monitoring should be undertaken during wet and dry conditions and should be carried out over a number of days • Design should consider system operation when the wastewater treatment plant is underloaded • Provision of balance volume can help alleviate shock loads such as those from external inputs (e.g. landfill leachate, septic tank effluents, etc.) • Adequate provision for storm flow
10.2 Primary Treatment of Wastewaters	• Adequate maintenance of preliminary treatment systems, such as screens and grit chambers, is essential for good plant operation • Balance tanks can be useful in buffering against sudden storm loads (and other external inputs) • Increased primary tank volume can be effective in providing longer-term sludge storage and allowing for more efficient plant operation
10.3.1 Equipment selection	• Ensure long-life, low-maintenance equipment is selected where possible • Provide for the provision to remotely monitor equipment
10.3.2 Process control – monitoring and alarms	• Ensure that remote monitoring capabilities are provided in all new and upgrading works • Provide training to ensure that operations staff are suitably trained to operate monitoring equipment • Adequate alarm systems should be in place in all wastewater treatment plants
10.3.3 Process control – sensors and probes	• Provide necessary training to ensure that maintenance and calibration schedules are met • 'Design in' the above probe recommendations for new and upgraded plants • Consider the installation of strategic indicator probes to save on day-to-day analysis costs • Establish correlations between easily monitored parameters and labour-intensive parameters (e.g. BODs, SS) for different operating conditions (e.g. wet/dry weather, etc.)
10.3.4 Sludge and odours	• Investigate the use of new technologies for decentralised systems that treat sludges on-site or reduce sludge volumes transported off-site, and mitigate odours • Allow for future deployment of such technologies when designing new/upgraded plants
10.4 Education and Training	• Consider ongoing formal education programmes for relevant staff

Table 10.4. Summary recommendations – Industry innovators and research (including researchers and research funding agencies).

Related recommendation section	Summary recommendations
10.3.2 Process control – monitoring and alarms	• Develop standardised remote monitoring interfaces for wastewater treatment plants • Investigate the most suitable software and hardware platforms for remote monitoring • Carry out research into energy efficiency in process operations • Develop online monitoring systems suitable for widespread deployment
10.3.3 Process control – sensors and probes	• Investigate optimum maintenance and calibration schedules for probes • Establish correlations between parameters for use in given conditions • Determine the most suitable probes for each parameter and correlation
10.3.4 Sludge and odours	• Develop new, effective, low-cost technologies for decentralised systems to treat sludges and/or reduce sludge volumes, and to treat odorous and greenhouse gases • Investigate alternative final disposal routes for sludges – sludge as a resource
10.5 Further Research	• Investigate new, sustainable and energy-efficient wastewater treatment technologies • Develop SMART monitoring and control technologies • Develop decentralised small-scale on-site sludge treatment technologies • Develop cost-effective systems offering potential for on-site and local reuse of treated wastewaters • Strengthen links between industry and academia to encourage knowledge transfer

Table 10.5. Summary recommendations – Training (third-level institutions, Water Services National Training Group, Engineers Ireland, etc.) and public awareness.

Related recommendation section	Summary recommendations
10.1 Influent Characteristics	• Highlight the importance of continuous influent monitoring
10.2 Primary Treatment of Wastewaters	• Continuing professional development training courses aimed at different levels from design and operations to strategic planning • Provide accredited courses and formal education programmes • Raise public awareness of wastewater treatment processes and their role in the effective operation of plants
10.3.1 Equipment selection	• Continuing professional development training courses aimed at different levels from design and operations to strategic planning • Provide accredited courses and formal education programmes • Raise public awareness of wastewater treatment processes and their role in the effective operation of plants
10.3.2 Process control – monitoring and alarms	• Continuing professional development training courses aimed at different levels from design and operations to strategic planning • Provide accredited courses and formal education programmes • Raise public awareness of wastewater treatment processes and their role in the effective operation of plants
10.3.3 Process control – sensors and probes	• Continuing professional development training courses aimed at different levels from design and operations to strategic planning • Provide accredited courses and formal education programmes • Raise public awareness of wastewater treatment processes and their role in the effective operation of plants
10.3.4 Sludge and odours	• Continuing professional development training courses aimed at different levels from design and operations to strategic planning • Provide accredited courses and formal education programmes • Raise public awareness of wastewater treatment processes and their role in the effective operation of plants
10.4 Education and Training	• Provide and support public awareness programmes

References

Alkhaddar, R.M., Phipps, D.A. and Cheng, C., 2005. Today and tomorrow! Research prospects for aerobic biological liquid waste treatment for reduction of carbon load. *E-Water. Publication of the European Water Association* 1–18.

Aneja, V.P., Schlesinger, H., Niyogi, D., Jennings, G., Gilliam, W., Knighton, R.E. and Duke, C.S., 2006. Emerging national research needs for agricultural air quality. *EOS, Transactions, American Geophysical Union* **87(3):** 25–36.

Angelakis, A.N. and Bontoux, L., 2001. Wastewater reclamation and reuse in EU Countries. *Water Policy* **3:** 47–59.

Angelakis, A.N., Bontoux, L. and Lazarova, V., 2003. Challenges and prospectives for water recycling and reuse in EU countries. *Water Science and Technology: Water Supply* **3(4):** 59–68.

APHA, AWWA and WEF, 2005. *Standard Methods for the Examination of Water and Wastewater.* Franson, M.A.N. (Ed.). Port City Press, Baltimore, USA.

Appels, L., Baeyens, J., Degreve, J. and Dewil, R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science* **34(6):** 755–781.

AS/NZ 4323.3, 2001. *Stationary Source Emissions – Part 3: Determination of Odour Concentration by Dynamic Ofactometry.* Australian/New Zealand Standard. ISBN: 0-7337-4087-1.

Babatunde, A.O. and Zhao, Y.Q., 2007. Constructive approaches toward water treatment works sludge management: An international review of beneficial reuses. *Critical Reviews in Environmental Science and Technology* **37(2):** 129–164.

Balkema, A.J., Preising, H.A., Otterpohl, R. and Lambert, F.J.D., 2004. Indicators for the sustainability assessment of wastewater treatment systems. *Urban Water* **4:** 153–161.

Bates, J. and Haworth, A., 2000. *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU.* AEA Technology Environment, Culham, England.

Boller, M., 1997. Small wastewater treatment plants – a challenge to wastewater engineers. *Water Science and Technology* **35:** 1–12.

Boutin, C., Duchène, P. and Liénard A., 1997. *Filières adaptées aux petites collectivités.* Document technique. FNDAE No. 22. CEMAGREF Éditions, Paris, France.

Bowker, R.P.G., Smith, JM. and Webster, NA., 1989. *Odour and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants.* Noyes Data Corporation, Park Ridge, NJ, USA.

Burgess, J., Stuetz, R.M. and Parsons, S.A., 2001. Developments in odour control and waste gas treatment biotechnology. *Biotechnology Advances* **19(1):** 35–63.

Caffaz, S., Lubello, C., Canziani, R. and Santianni, D., 2006. Autotrophic nitrogen removal from anaerobic supernatant of Florence's WWTP digesters. *Water Science and Technology* **53(12):** 129–137.

Cheng, W.H., Hsu, S.K. and Chou, M.S., 2008. Volatile organic compound emissions from wastewater treatment plants in Taiwan: legal regulations and costs of control. *Journal of Environmental Management* **88(4):** 1485–1494.

Chou, M.-S. and Chen, W.-H., 2005. Gaseous emissions and control in wastewater treatment plants. *Environmental Engineering Science* **22 (5):** 591–600.

Clifford, E., Nielsen, M., Sorensen, K. and Rodgers, M., 2010. Nitrogen dynamics and removal in a horizontal flow biofilm reactor for wastewater treatment. *Water Research* **44(13):** 3819–3828.

Council Directive of 16 June 1975 concerning quality required of surface water intended for the abstraction of drinking water (75/440/EEC). *Official Journal of the European Communities L 194 16.6.1975.*

Council Directive 76/160/EEC of 8 December 1975 concerning the quality of bathing water. *Official Journal of the European Communities L 031 05.02.1976*.

Council Directive of 30 October 1979 concerning the quality required for shellfish (79/923/EEC). *Official Journal of the European Communities* L 281 30.10.1979.

Council Directive 80/778/EEC of the 15 July 1980 relating to the quality of water intended for human consumption. *Official Journal of the European Communities L 229/11 30.8.1980*.

Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. *Official Journal of the European Communities L 181/6 4. 7. 1986*.

Council Directive 91/156/EEC of 18 March 1991 amending Directive 75/442/EEC on waste. *Official Journal of the European Communities L 182 18.3.1991*.

Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC). *Official Journal of the European Communities L 135 21.5.1991*.

Council Directive 91/271/EEC concerning urban waste-water treatment. *Official Journal of the European Communities L 135 30.5.1991*.

Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. *Official Journal of the European Communities L 182/1 16.7.1999.*

Council Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities L 327/1*.

Council Directive 2004/107/EC relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. *Official Journal of the European Communities L 23/3. 26.1.2005*.

Council Directive 2006/7/EC of the European Parliament and of the Council of 15 May 2006 concerning management of bathing water quality. *Official Journal of the European Communities L 64/37*.

Council Directive 2006/44/EC of the European Parliament and of the Council on the quality of fresh waters needing protection or improvements in order to support fish life. *Official Journal of the European Communities L 264/20. 25/9/2006.*

Council Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. *Official Journal of the European Communities L 372/19*.

De Paor, D., Rodgers, M. and Clifford, E., 2008. Dairy washwater treatment using a pilot-scale horizontal flow biofilm reactor. *Proceedings: IWA Biofilm Technologies*. Singapore. pp. 187–189.

Devisscher, M., Ciacq, L., Bendetti, L., Bixio, D., Thoeve, C., De Gueldre, G., Marsili-Libelli, S. and Vannrolleghem, P.A., 2006. Estimating costs and benefits of advanced control for wastewater treatment plants – the MAgIC methodology. *Water Science and Technology*. **53(4–5):** 215–223.

DoEHLG, 2006. *Determining the Share of National Greenhouse Gas Emissions for Emissions Trading in Ireland 2008–2012, Summary for Policymakers*. Department of the Environment, Heritage and Local Government, Dublin, Ireland.

Donham, K.J, Wing, S., Osterberg, D., Flora, J.L., Hodne, C., Kendall, M.T. and Thorne, P.S., 2007. Community health and socioeconomics issues surrounding concentrated animal feeding operations. *Environmental Health Perspectives* **115(2):** 317–320.

EPA, 1999. *Wastewater Treatment Manuals – Treatment Systems for Small Communities, Business, Leisure Centres and Hotels.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. ISBN: 1-89996-596-3.

EPA, 2000. *Treatment Systems for Single Houses.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. ISBN: 1-84095-022-6.

EPA, 2003. *Towards Setting Guideline Values for the Protection of Groundwater in Ireland.* Interim Report. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

EPA, 2006. *National Waste Report.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. ISBN: 1-84095-218-0. 67

EPA, 2007. *Air Emissions Monitoring Guidance Note No. 2.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

EPA, 2009. *Urban Wastewater Discharges in Ireland for Population Equivalents Greater than 500 PE.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. ISBN: 978-1-84095-058-8

EU, 2002a. *Disposal and Recycling Routes for Sewage Sludge: Part 4 – Economic Report.* DG Environment – B/2. Office of Official Publications, Luxembourg. ISBN: 92-894-1801-X.

EU, 2002b. *Disposal and Recycling Routes for Sewage Sludge: Part 3 – Scientific and Technical Report.* DG Environment – B/2. Office of Official Publications, Luxembourg. ISBN: 92-894-1801-1.

European Communities (Waste Water Treatment) (Prevention of Odours and Noise) Regulations, 2005. (S.I. No. 787 of 2005).

EUWI (EU Water Initiative), 2004. *Mediterranean Wastewater Reuse Report.* Produced by the Mediterranean wastewater reuse working group (MED WWR WG). November 2007. http://www.emwis.net/topics.

Fytili, D. and Zabaniotou, A., 2008. Utilisation of sewage sludge in EU application of old and new methods – A review. *Renewable and Sustainable Energy Reviews* **12:** 116–140.

GCC (Galway County Council), 2010. Personal communication with Tuam Wastewater Treatment Plant Manager, Galway County Council, Galway, Ireland.

Ginestet, P. and Camacho, P., 2007. Technical evaluation of sludge production and reduction. *Comparative Evaluation of Sludge Reduction Routes*. IWA Publishing Ltd, London, UK. ISBN: 1843391236

Gray, N.F., 1999. *Water Technology: An Introduction for Environmental Scientists and Engineers*. John Wiley & Sons, New York, USA.

GSI (Geological Survey of Ireland), 1999. *Protocol for the*

Delineation of Source Protection Zones (Including Nitrate Vulnerable Zones) Around Public Groundwater Supply Sources – Draft. Geological Survey of Ireland, Dublin, Ireland.

Healy, M.G., Rodgers, M. and Mulqueen, J., 2005. Denitrification of a nitrate-rich wastewater using wood media as a carbon source. *Journal of Environmental Science and Health Part A* **41(5):** 779–788.

Henze, M., Harremoes, P., La Cour Jansen, J. and Arvin, E. (Eds), 1997. *Wastewater Treatment: Biological and Chemical Processes*. Springer-Verlag, Berlin, Germany. 2nd Edition, 383 pp.

Henze, M., Harremoes, P., La Cour Jansen, J. and Arvin, E., 2002. *Wastewater Treatment: Biological and Chemical Processes*. Springer-Verlag, Berlin, Germany. 3rd Edition.

Huang, L., Wang G. and Zuo, J., 2011. Species of volatile organic compounds from municipal wastewater treatment plants. *Advanced Materials Research* **183–185:** 1075–1060.

ICF Consulting/DoEHLG, 2006.*Determining the Share of National Greenhouse Gas Emissions for Emissions Trading in Ireland 2008–2012*. Department of Environment, Heritage and Local Government, Dublin, Ireland.

IS EN 12255. *Wastewater Treatment Plants: Parts 1–16*. (2002–2005). The European Committee for Standardization (CEN), Brussels, Belgium.

IS EN 13725:2003., 2003. *European Standard on Determination of Odour Concentration by Dynamic Olfactometry.* The European Committee for Standardization (CEN), Brussels, Belgium. ISBN: 0-580-41884-7.

Kantanoleon, N., Zampetakis, L. and Manios, T., 2007. Public perspectives towards wastewater reuse in a medium size, seaside, Mediterranean city: A pilot survey. *Resources, Conservation and Recycling* **50:** 282–292.

Lazarova, V., 2000. Wastewater disinfection: assessment of the available technologies for water reclamation. *In:* Goosen, M.F.A. and Shayya W.H. (Eds.) *Water Conservation Vol. 3. Water Management, Purification and Conservation in Arid Climates*, Technomic Publishing Co. Inc., PA, USA. pp. 171–198.

Lazarova, V., Hills, S. and Birks, R., 2003. Using recycling water for non-potable, urban uses: a review with particular reference to toilet flushing. *Water Science and Technology: Water Supply* **3(4):** 69–77.

Metcalf and Eddy, 2001. *Wastewater Engineering Treatment and Reuse*. McGraw-Hill Book Company, New York, USA.

Milieu Ltd., WRc and RPA, 2010. *Environmental, Economic and Social Impacts of the Use of Sewage Sludge on Land. Final Report. Part I: Overview Report*. European Commission DG Environment. http://ec.europa.eu/environment/waste/sludge/pdf/part_i_report.pdf

Murray, A., Horvath, A. and Nelson, K.L., 2008. Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: A case study from China. *Environmental Science and Technology* **42:** 3163–3169.

Nelson, A.C., Genereux, J. and Genereux, M., 1992. Price effect of landfills on house values. *Land Economics* **68(4):** 359–365.

Norton, J.W., 2009. Decentralised systems. *Water Environment Research* **81(10):** 1440–1450.

O'Reilly, E., Rodgers, M. and Zhan, X-M., 2008a. Pumped flow biofilm reactors (PFBR) for treating municipal wastewater. *Water Science and Technology* **57:** 1857–1865.

O'Reilly, E., Rodgers, M. and Zhan, X.M., 2008b. Pumped flow biofilm reactors (PFBR) for treating municipal wastewater. *Proceedings 8th IWA specialized Conference on Small Water and Wastewater Systems and 2nd specialized Conference on Decentralized Water and Wastewater International Network*. Coimbatore, India.

Odegaard, H., 2003. Wastewater sludge as a resource. *Selected Proceedings of the IWA International Conference on Wastewater Sludge as a Resource – Biosolids*. Trondheim, Norway.

Odegaard, H., Rusten, B. and Westrum, T., 1994. A new moving bed biofilm reactor – applications and results. *Water Science and Technology* **29(10–11):** 157–165.

Palmquist, R.B., Roka, F.F. and Vukina, T., 1997. Hog operations, environmental effects, and residential property values. *Land Economics* **73(1):** 114–124.

Park, S.J., 2003. *Odor Measurement Review – The Regulation and Measurement of Odor in Korea,* Ministry of the Environment, Government of Japan. http://www.env.go.jp/en/lar/odor_measure/index.html.

Perara, P. and Baudot, B., 2001. *Extensive Wastewater Treatment Processes: Adapted to Small and Medium Sized Communities (500 to 5,000 Population Equivalents).* European Community, Luxembourg. ISBN: 92-894-1690-4.

Pujol, R. and Liénard, A., 1990. Qualitative and quantitative characterization of waste water for small communities. *Water Science and Technology* **22 (3–4):** 253–260.

Rodgers, M. and Clifford, E., 2009. Horizontal flow biofilm reactors for the removal of carbon and nitrogen from domestic-strength wastewaters. *Water Environment Research* **81(4):** 339–347.

Rodgers, M., Zhan, X.-M. and Gallagher, B., 2003. A pilot plant study using a vertically moving biofilm process to treat municipal wastewater. *Bioresource*

Technology **89(2):** 139–143.

Rodgers, M., Mulqueen, J., Lambe, A., Xiao, L. and Clifford, E., 2004a. *A Biofilm Reactor.* Publication No. WO/2006/003026. International Application No. PCT/EP2005/007453 (technology licensed to Bord na Móna, Ireland).

Rodgers, M., Mulqueen, J., Zhan, X. and O'Reilly, E., 2004b. *A Method and Apparatus for Biologically Processing Fluid.* International Patent No. PCT/EP2005/007452

Rodgers, M., Lambe, A. and Xiao, L.W., 2006a. Carbon and nitrogen removal using a novel horizontal flow biofilm system. *Process Biochemistry* **41(11):** 2270–2275.

Rodgers, M., Zhan, X.-M. and O'Reilly, E., 2006b. Small-scale wastewater treatment using an alternating pumped sequencing batch biofilm reactor. *Bioprocess and Biosystems Engineering* **28:** 322–330.

Rodgers, M., DePaor, D. and Clifford, E., 2008a. Dairy washwater treatment using a horizontal flow biofilm system. *Journal of Environmental Management* **86(1):** 114–120.

Rodgers, M., O'Reilly, E. and Clifford, E., 2008b. *A Biological Reactor for Wastewater.* Patent application No. 08016355.3–2104.

Rodgers, M., O'Reilly, E. and Zhan, X-M., 2009a. Synthetic dairy wash-water treatment by using an alternating pumped sequencing batch biofilm reactor. *International Journal of Environment and Pollution* **38:** 371–384 (invited paper).

Rodgers, M., O'Reilly, E., Clifford, E., Ruane, E., 2009b. *A Stratified Bioreactor.* European Patent Application No. 09006982.4.

S.I. No. 7 of 1992. *Environmental Protection Agency Act (1992).* Irish Statute Book. Government Stationery Office, Dublin, Ireland.

S.I. No. 42 of 1999. *Water Pollution Regulations: 1999.* Government Stationery Office, Dublin, Ireland.

S.I. No. 90 of 2003. *Planning and Development Regulations 2003.* Government Stationery Office, Dublin, Ireland.

S.I. No. 53 of 2004. *Ozone in Ambient Air Regulations (2004).* Irish Statute Book. Government Stationery Office, Dublin, Ireland.

S.I. No. 30 of 2007. *Water Services Act: 2007.* Government Stationery Office, Dublin, Ireland.

Schiffman, S.S., 1998. Livestock odours: Implications for human health and well-being. *Journal of Animal Science* **76:** 1343–1355.

Schiffman, S.S., Sattely Miller, E.A., Suggs, M.S. and Graham, B.G., 1995. The effect of environmental odours from commercial swine operations on the mood of nearby neighbours. *Brain Research Bulletin* **37(4):** 369–375.

Schlegelmilch, M., Stresse, J. and Stegmann, R., 2005. Odour management and treatment technologies: An overview. *Waste Management* **25:** 928–939.

Schlesinger, R.B., 1999. Toxicology of sulfur oxides. *In:* Holgate, S.T., Samet, J.M., Koren, H.S. and Maynard, R.L. (Eds), *Air Pollution and Health.* Academic Press. pp. 585–602.

Schustermann, D., 2001. Odour associated health complaints. *Chemical Senses* **26:** 339–343.

Science, Technology, Research and Innovation for the Environment (STRIVE 2007–2013), 2007. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. ISBN: 1-84095-238-5.

SEPA, 2005. *Sizing Criteria, Treatment Capacity for Small Wastewater Treatment Systems (Package Plants).* British Water, London, UK. ISBN 1-903-4810-5-8.

Spinosa, L., (Ed.), 2007. *Wastewater Sludge: a Global Overview of the Current Status and Future Prospects.* IWA Publishing, London, UK. ISBN: 1-893-391-442.

Stephenson, T., Judd, S., Jefferson, B. and Brindle, K., 2000. *Membrane Bioreactors for Wastewater Treatment.* IWA Publishing, London, UK. 179 pp.

Strauss, M., Larmie, S.A. and Heinss, U., 1997. Treatment of sludge's from on-site sanitation: Low-cost options. *Water Science and Technology* **35(6):** 129–136.

Tsagarakis, K.P., Mara, D.D. and Angelakis, A.N., 2003. Application of cost criteria for selection of municipal wastewater treatment systems. *Water, Air and Soil Pollution* **142:** 142–210.

Tuam Wastewater Treatment Plant, Galway County Council, Tuam, Co. Galway – personal communication, February 2010.

US EPA, 1990. National sewage sludge survey: availability of information and data, and anticipated impacts of proposed regulations, proposed rule. Title 40 of the Code of Federal Regulations, Part 503. *Federal Register* **55:** 47210–47238.

US EPA, 1991. Title 40 of the Code of Federal Regulations, Part 258: Solid waste disposal facility criteria. *Federal Register* **56:** 1–16.

US EPA, 1993. Title 40 of the Code of Federal Regulations, Part 503: The standards for the use or disposal of sewage sludge. *Federal Register* **58:** 9248–9404.

US EPA, 2002. *Onsite Wastewater Treatment Systems Manual.* Office of Water. EPA/625/R-00/008. US EPA. Pennsylvania Avenue, Washington, USA.

US EPA, 2007. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2005.* US EPA. Pennsylvania Avenue, Washington, USA.

van den Bergh, J.C.J.M. and van der Straaten, J. (Eds), 1994. *Towards Sustainable Development, Concepts, Methods, and Policy*. International Society for Ecological Economics. Island Press, Washington DC and Covelo California, USA. ISBN 1-55963-349-2.

Van Harrevald, A.P., 2003. O*dour Regulation and the History of Odour Measurement in Europe. Odour Measurement Review*. Ministry of the Environment, Government of Japan, Japan.

Van Harreveld, A.P., Jones, N. and Stoaling, M., 2001. *Odour Impacts and Odour Emission Control Measures for Intensive Agriculture.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. ISBN 1-84095-075-7.

Werther, J. and Ogada, T., 1999. Sewage sludge combustion. *Progress in Energy and Combustion Science* **25:** 55–116.

WHO, 1993. *Guidelines for Drinking-Water Quality.* Second Edition. World Health Organisation, Geneva, Switzerland.

Yang, O., Wang, S., Yang, A., Guo, J. and Bo, F., 2007. Advanced nitrogen removal using pilot-scale with intelligent control systems built on three layer network. *Environmental Science Engineering, China* **1(1):** 33–38.

Zhan, X.M., Rodgers, M. and O'Reilly, E., 2005. Biofilm growth and characteristics in an alternating pumped sequencing batch biofilm reactor (APSBBR). *Water Research* **40:** 817–825.

Acronyms and Annotations

ABS	Acrylonitrile butadiene styrene
API	American Petroleum Institute
ASF-BR	Air-suction flow biofilm reactor
BOD	Biochemical oxygen demand
BOD_5	5-Day biochemical oxygen demand
$cBOD_5$	Carbonaceous BOD_5
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COD_f	Filtered COD
COD_t	Total COD
CPI	Corrugated Plate Interceptor
DO	Dissolved oxygen
DS	Dry solids
EC	European Commission
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EQS	Environmental quality standard
EROM	European Reference Odour Mass
ERTDI	Environmental Research Technological Development and Innovation
EU	European Union
EU UWWTD	European Union Urban Waste Water Treatment Directive
FOG	Fats, oils and grease
GSI	Geological Survey of Ireland
H_2S	Hydrogen sulphide
HFBR	Horizontal flow biofilm reactor
HMI	Human machine interface
HSA	Health and Safety Authority
IGV	Interim guideline value
IWA	International Water Association
MLSS	Mixed liquor suspended solids
MRMC	Mobile remote monitoring and control system

N_2O	Nitrous oxide
NH_3	Ammonia
NH_4-N	Ammonium-nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NUI	National University of Ireland
ORP	Oxidation–reduction potential
PAH	Polyaromatic hydrocarbon
PAO	Phosphorus accumulating organism
PE	Population equivalent
PFBR	Pumped flow biofilm reactor
PLC	Programmable logic controller
PO_4-P	Orthophosphate-phosphorus
PS	Phase study
PSCS	Project supervisor, construction stage
PSDS	Project supervisor, design stage
SBBR	Sequencing batch biofilm reactor
SBR	Sequencing batch reactor
SMART	Self-monitoring, analysis and reporting technology
SO_2	Sulphur dioxide
SRT	Solids retention time
SS	Suspended solids
TN	Total nitrogen
TN_f	Filtered TN
TSPA	Top surface plan area
TWWTP	Tuam Wastewater Treatment Plant
UV	Ultraviolet
VMBR	Vertically moving biofilm reactor
VOC	Volatile organic compound
WFD	Water Framework Directive
WHO	World Health Organisation
WRF	Water Research Facility
WWTP	Wastewater treatment plant

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.
- Scardadh dramhuisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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SSTI Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government