Basis for the development of sustainable optimisation indicators for activated sludge wastewater treatment plants in the Republic of Ireland

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ABSTRACT

This paper describes the basis of a stakeholder-based sustainable optimisation indicator (SOI) system to be developed for small-to-medium sized activated sludge (AS) wastewater treatment plants (WwTPs) in the Republic of Ireland (ROI). Key technical publications relating to best practice plant operation, performance audits and optimisation, and indicator and benchmarking systems for wastewater services are identified. Optimisation studies were developed at a number of Irish AS WwTPs and key findings are presented. A national AS WwTP manager/operator survey was carried out to verify the applied operational findings and identify the key operator stakeholder requirements for this proposed SOI system. It was found that most plants require more consistent operational data-based decision-making, monitoring and communication structures to facilitate optimised, sustainable and continuous performance improvement. The applied optimisation and stakeholder consultation phases form the basis of the proposed stakeholder-based SOI system. This system will allow for continuous monitoring and rating of plant performance, facilitate optimised operation and encourage the prioritisation of performance improvement through tracking key operational metrics. Plant optimisation has become a major focus due to the transfer of all ROI water services to a national water utility from individual local authorities and the implementation of the EU Water Framework Directive.

Key words | activated sludge, optimisation, performance indicators, wastewater

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INTRODUCTION

Overview of research study

The aim of this research study is the formulation of a practical stakeholder-based sustainable optimisation indicator (SOI) system for small-to-medium sized activated sludge (AS) wastewater treatment plants (WwTPs), focused on the Republic of Ireland (ROI) but applicable to other regions. The proposed SOI system shall provide a robust and flexible framework for monitoring and rating the optimisation and sustainable performance of AS WwTPs for plant managers/operators, which also meets the needs and concerns of a wide range of stakeholders including regulatory bodies and customers. This paper describes how the key plant operational stakeholder factors and issues were determined that contribute to the development of the overall SOI system.

A total of 48 AS WwTPs ranging in size from a design population equivalent (PE) of 150 up to larger plants with a design PE of 1.7 million in ROI were reviewed, and a select number were assessed in detail as part of the applied operational research phase of this study. This was facilitated by the instigation of research collaborations with local authorities and private plant operation contractors to inform the development of comprehensive plant optimisation studies. Plant optimisation comprises continuous process operational and management performance assessment and improvement while potentially reducing treatment cost and achieving consistent and/or improved environmental performance. The aim was to evaluate the current status of WwTP management systems, operations and maintenance and to identify the current key process operational and management decision-making processes. It was deemed

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necessary to examine the role of plant management/operations staff in detail because it has been shown that more consistent and optimised performance can be provided with a competent, dedicated and diligent plant manager/operator utilising an effective and efficient operating regime (Wheeler 2008). To extend the applied optimisation study findings, a questionnaire was formulated and circulated to plant managers/operators nationwide to evaluate their role in relation to effective and efficient plant management. A comprehensive literature review of current plant optimisation methods, performance evaluation and operational indicator systems was compiled to aid the development and substantiate the requirements of the proposed SOI system.

Wastewater services in Republic of Ireland

According to the 2011 census, ROI had a total population consisting of 4,588,252 people but with only seven urban councils of over 50,000 population (CSO 2012) and a large number of decentralised rural and small urban communities of less than 1,000 population. The Irish Urban Waste Water Treatment Regulations 2001–2010 (DECLG 2001) and the 1991 Urban Waste Water Treatment Directive (OJEC 1991) set the framework for provision of wastewater collection systems and treatment plants, the monitoring of wastewater discharges and to specify limits for certain effluent parameters. The European Union Water Framework Directive (OJEC 2000) has set member states the objective of achieving good ecological status in all surface and groundwater bodies by 2015 through catchment-based river basin management plans as opposed to local authority boundaries.

Ireland has a diverse wastewater treatment infrastructure asset portfolio providing for a relatively large number and range of spatially disparate urban agglomerations. The EPA (2012) report outlined that 538 urban areas in ROI are subject to the wastewater discharge licensing process (i.e. areas with a PE greater than 500). Secondary treatment was provided at 432 of these urban areas in 2010, of which 58% of plants achieved the required effluent quality and sampling standards. Of the 106 urban areas that did not have secondary treatment in place, 38 did not receive any treatment or only basic preliminary treatment prior to discharge. It was noted that only 46% of these 538 urban areas achieved the effluent quality and sampling standards. In addition, there are in excess of 500 WwTPs in Ireland with a size of less than 500 PE that operate under a certificate of authorisation and are not eligible to be licensed.

A total of 34 city and county councils were responsible for the provision of water and wastewater services in ROI up to 31 December 2013. Design–Build–Operate–Maintain contracts have increased in popularity whereby private contractors perform the design, build, operate and/or maintain function on behalf of local authorities. Water services in ROI cost in excess of €1.2 billion in 2010, of which €715 million was operational costs (DECLG 2012). EPA (2012) cites inadequate capacity or the poor performance of the treatment plant as the main reasons for non-compliance. It indicates that, in order to deliver value for money from wastewater infrastructure investment, a step change in expertise is required in the operation of these national assets. A fundamental weakness with the ROI water services model is identified as the variability of service to the customer, the environment and other key stakeholders due to the absence of consistent policies, processes and standards, and variable standards of performance (DECLG 2012). A national public water utility, Irish Water, was established as a statutory body to take over the operational and capital delivery functions of all municipal water services from 1 January 2014, with the 34 local authorities carrying out their water and wastewater services functions under service level agreements.

Optimisation and performance indicator systems for wastewater services

The United States Environmental Protection Agency (US EPA 1984) Composite Correction Programme (CCP) and the Water Environment Association of Ontario (WEAO 2010) *Optimisation Guidance Manual for Sewage Works* both outline guidance frameworks for improving WwTP performance. Similar to the comprehensive performance evaluation' phase of the CCP, WEAO (2010) includes a 'sewage treatment plant self-assessment report' which allows a WwTP owner/operator to evaluate the performance and limitations of a WwTP to determine if the implementation of an optimisation programme might be beneficial. It has been identified that potential exists to tap the full capacity (often beyond design values) of existing WwTPs in Ireland and beyond with the implementation of effective utility management and operational control (Wheeler 2008). The opportunity for improved plant performance and compliance levels in ROI resulting from the consistent application of effective process controls as part of a comprehensive plant optimisation programme is highlighted by Wheeler (2008). Plant optimisation requires managers/operators to have multidisciplinary personal attributes from both a technical and organisational perspective and that recording and analysis of reliable plant operational data is important for effective data-based process control decisions (Wheeler 2009).

Performance indicators (PIs) developed by the Six-Cities Group (Stahre & Adamsson 2002) in Scandinavian countries began in 1995 and were considered by Matos *et al*. (2003) as a standardised reference language for making consistent system comparisons. A *Manual of Best Practice* by Matos *et al*. (2003) presents a framework of performance indicators for wastewater services. The Austrian Benchmarking System for WwTPs, whose indicators are to a large extent in agreement with Matos *et al*. (2003), was developed from 1999 to 2004 and concentrates on process benchmarking to compare WwTP performance with benchmarks to allow an optimisation and cost reduction potential to be derived (Lindtner *et al*. 2008). The Austrian system is restricted to process performance indicators whereas the International Water Association system (Matos *et al*. 2003) is related to the performance of processes and of utility management (Kroiss & Lindtner 2005). The relevance of quality staff was emphasised where it was reported that excellent treatment efficiency often coincided with low operational costs (Lindtner *et al*. 2008). Water and wastewater associations from Germany, Austria, Switzerland and the Netherlands developed a common basis for a number of performance indicators to allow performance comparisons to be made via an internet-based benchmarking platform for data management and information transfer (Lindtner *et al*. 2008). Cabrera *et al*. (2011) report on the European Benchmarking Co-operation which covers some 45 water utilities. It was reported that workshops became an inherent component of benchmarking to enhance best practice (Lindtner 2004). The IWA Specialist Group on Benchmarking strongly recommends abandoning the use of the terms 'metric benchmarking' and 'process benchmarking' for the terms 'performance assessment' and 'performance improvement' (Cabrera *et al*. 2011).

Quadros *et al*. (2010) identify the importance of a performance assessment system (PAS) as a method for cost-effective and sustainable management of wastewater services. This PAS system specifically addresses the performance assessment of urban WwTPs. It comprises 'overall performance assessment' which is intended to support technical management decisions and is based on performance indicators, and 'operational performance assessment' which consists of performance indices for a detailed assessment of each unit operation or plant process. Silva *et al*. (2012) report on the second generation of PI systems developed for water and WwTPs as a result of a national field-test (PASt21) coordinated by the National Civil Engineering Laboratory in Portugal. A study by Balmér (2010) into the current status of PIs and benchmarking of WwTPs found that the IWA *Manual of Best Practice* was not detailed enough for the operator level. The Swedish Water and Wastewater Association has created PIs for operator level related to use of resources and factors that can be influenced by the operator (Balmér & Hellström 2012). It has been reported that the rational management of urban water infrastructure is fundamental for service sustainability and to the economy of societies (Alegre 2010).

Rationale for the development of a SOI system

The applied research phase of this study has identified the requirement for a system which allows the operational performance of AS WwTPs of varying characteristics to be monitored by relevant stakeholders. It was identified that this could be achieved by quantitative and qualitative assessment of key factors relating to the operation and management of AS WwTPs. It is recognised that diverse stakeholder groups with varying levels of technical knowledge will require performance information to be reported at different levels of detail. The proposed system, based on performance indicators, requires a comprehensive set of technical plant operation and management type indicators which would allow tracking of performance and identification of particular areas that need improvement. It is also recognised that plant managers/operators have a key role in controlling plant performance that will ultimately have associated social, economic and environmental effects and impacts on a range of stakeholders. The development of a sustainable and performance-based indicator system that involves and considers the views and attitudes of relevant stakeholders, including policy-makers, regulators, environmental groups and customers, is required to evaluate AS WwTP performance. The development of a structured plant operational performance evaluation system requires performance gaps to be identified and should result in an increased focus on optimising plant performance.

METHODOLOGY

Plant optimisation study

The applied optimisation studies for this project were adapted from a number of sources including US EPA

(1984), Wheeler (2008, 2009) and WEAO (2010), and consisted of a historical data analysis, in-depth plant operational audits, the implementation of improved operating regimes, process control adjustments and performance improvements at a number of AS WwTPs in Ireland. The applied optimisation research work involved working with the plant operators/managers on-site in order to develop a comprehensive understanding of the operating and management methodologies used on a daily basis, as well as to allow the researcher to develop an understanding of the practical plant operating characteristics and constraints while considering effective and efficient plant operations. WwTP organisational and operational structures were identified through consultation with plant operations and management staff. Plant personnel were also consulted relating to operational data-based decision-making and monitoring regimes. The purpose of this consultation was to determine the responsibilities and knowledge of the various operation and management personnel and hence their level of accountability for effective and efficient plant operation.

A key component of each applied optimisation study was to investigate the plant operational data management practices and the associated level of data-based decision-making in place. To overcome deficiencies in plant data management practices, user friendly data management spreadsheets were developed based on the technical, operational, organisational, environmental and economic plant performance factors identified. These spreadsheets were developed to allow key operational data input and automatic plotting and updating of trend graphs for process monitoring and evaluation. Each spreadsheet was adapted to specific plant requirements but developed based on the same framework with a view to ensuring that only key information was recorded and monitored by the plant operator. It was important to strike a balance with regard to data management, as incorporating too much or too little information could prevent effective identification of plant operational cause and effect relationships to allow the correct process control adjustments to be implemented. Specific elements incorporated into the spreadsheets included trend graphs for key process and quality parameters, action levels and a traffic-light system to assist the plant manager/operator in making prompt data-based operational decisions based on current and historic parametric trends. Data-based process control adjustments were implemented at each plant in a stepwise manner while taking economic, environmental, operation and maintenance factors into consideration. The plant optimisation studies also included verification that implemented process control changes and revamped operational philosophies were successful in improving performance. Training and identification of training needs of key personnel, relating to effective monitoring, sampling, process control adjustments, data-based decision-making and analysis of cause and effect relationships, were an integral part of each optimisation study.

Plant manager/operator questionnaire

A research questionnaire was formulated consisting of 25 relevant questions and circulated to key plant management and operations personnel within local authorities and private operation contractors for a wide range of plant types and PE from April to June 2013. The purpose of this questionnaire was to evaluate the role of plant managers and pose questions in relation to their qualifications, experience, level of workload, operational communication structures, and the priority placed on calculating, measuring and monitoring key operational parameters. In addition to the potential use of specific questionnaire results for SOI formulation, the questionnaire has allowed key respondents to be identified that are willing to participate in the technical plant manager/operator stakeholder group consultation phase for the final stage of SOI development. A spreadsheet was circulated to local authority sanitary services departments to identify the organisational reporting structure, plant characteristics and level of on-line monitoring and controls installed at each plant to provide a data set of plant types and variation. Purposive and snowball sampling techniques were used to solicit plant manager/operator participation.

Development of SOI system

The SOI system being developed is intended to incorporate the audit-based operational evaluation, optimisation, and correction procedures commonly used in North American systems (e.g. WEAO 2010) and be complementary to IWA and other European wastewater services performance and improvement indicator systems as reported by Matos *et al.* (2003) and Quadros *et al.* (2010) and others, based on a sustainable framework. This literature review will be used in conjunction with findings from comprehensive plant optimisation studies developed and implemented as part of this research study, plant manager/operator questionnaire data, local authority organisational structure spreadsheets and feedback from technical plant manager/operator stakeholders to contribute to the development of a comprehensive SOI system for AS WwTPs in ROI. The next phase of this research study involves consultation with all WwTP operation stakeholder groups including regulators, policy-makers, customers, organisations and experts to ensure that those who can affect or be affected by the operation of a WwTP are included in the consultation for SOI system formulation. The proposed SOI system will provide a holistic measurement/rating of plant performance using indicators that will be combined with a subsequent applied plant operational evaluation to determine plant optimisation/improvement potential.

RESULTS AND DISCUSSION

Plant optimisation studies

Applied plant operation and optimisation research identified a lack of focus on the consistent and continuous optimisation of existing treatment assets and no holistic operational performance assessment framework or guidelines. It found that plant managers typically adopt a reactive plant operation approach which is not conducive in achieving consistent or improved economic and environmental performance. This applied research phase was a critical element in the SOI operational performance assessment framework development process as it provided a unique insight into the operating characteristics and constraints for a range of small-to-medium sized municipal AS WwTPs in Ireland. It allowed key AS WwTP performance assessment parameters to be identified which will contribute to indicator development. Significant findings from plant operation and optimisation studies are summarised as follows.

- A major deficiency was identified as being a lack of reliable and robust data for process operation. Data management spreadsheets were found to be an effective tool to facilitate active process monitoring and data-based process control decisions as part of routine plant operations with a view to improving plant performance. This tool incorporated action levels linked to a colour-coded traffic-light system for final effluent compliance data. Trend graphs were used to monitor the main process (e.g. flow rate, mixed liquor suspended solids (MLSS), sludge volume index (SVI)) and quality (e.g. influent and effluent biochemical oxygen demand (BOD)) parameters. Removal efficiency graphs were used to track treatment performance for key discharge criteria (e.g. BOD, chemical oxygen demand, total suspended solids, total nitrogen and total phosphorus) against targets. This tool was deemed favourable by plant operators compared to existing systems that lacked useful data. It will ensure that baseline variables are available for indicator development and calculation.
- Training was provided to the plant operator during the studies in reliable sampling methodologies, data management and trend graph analysis, protocols for the physical implementation of process control changes (e.g. methodology for reducing aerobic phase duration) and subsequent analysis of cause and effect relationships. This empowered the plant operator to implement appropriate process control changes in a stepwise manner to sustainably optimise/improve plant performance.
- One such applied optimisation study at an 11,500 PE extended aeration fine-bubble diffused aeration AS WwTP resulted in aeration energy savings of circa 30%. This involved the stepwise reduction of aerobic phase duration while tracking key plant performance and discharge compliance data using a data management spreadsheet. The plant operator was trained in the implementation of process control adjustments and in the identification of associated cause and effect relationships. Additional dedicated time by the senior technical manager of the plant and specific operator mentoring assisted with this process. Treatment cost was reduced without compromising treatment performance. This optimisation study transformed operational data management from passive data recording to active data use.
- A study at a 4,000 PE oxidation ditch type AS WwTP with surface aeration found that more consistent environmental performance could be achieved by effective sludge mass control. A sludge core sampler was used to sample the secondary clarifier sludge blanket, and a desktop centrifuge with conical-bottomed centrifuge tubes was used for prompt and accurate determination of solids concentration similar to that reported by Wheeler (2009). This sludge mass control regime targeted a specific mean cell residence time (MCRT) and allowed the surplus sludge volume to be calculated in order to maintain the desired MCRT to ensure effective nitrification. Training was provided to the plant operator on the necessary process monitoring and control concepts (effective control of surplus/waste sludge pumping) associated with the revised operating regime. This study found that using the desktop centrifuge for estimation of process solids concentrations allowed more frequent determination of MLSS, therefore enabling more frequent calculation of SVI in conjunction with settled sludge volume (SSV) data as a measure of plant performance.

- Key process operational and treatment performance variables were identified that assist with performance evaluation of AS WwTPs. These variables include process flow rates, MCRT, food:micro-organism ratio, SSV, SVI, energy consumption, chemical use, pollutant removal rates, operator training hours and scheduled maintenance frequency. These variables contributed to the development of preliminary SOIs. The preliminary 'process monitoring and treatment efficiency' indicators assess sampling, testing and calculation frequency of key process and quality parameters, removal efficiencies and operator/manager time dedication to the plant. The 'operational asset management and maintenance' indicators assess treatment plant utilisation, inspection, maintenance and calibration regimes and asset failure rates. The 'operations and management personnel' category assesses the characteristics and number of operations and management personnel and operational training and mentoring hours received. Discharge compliance rates, pollution incidents and environmental loadings are assessed in the 'environmental' SOI category. The 'resource use' SOI category assesses elements such as performance relating to energy consumption per cubic metre of wastewater treated and chemical use.
- Other important operational factors were identified for inclusion in the proposed SOI system, including the societal/environmental impact of the plant and the availability of funding for on-going minor process operational and monitoring upgrades. The societal/environmental impact relating to nuisance due to plant operations is assessed using the complaint rate for noise, odour and visual impact.
- Applied optimisation studies have also allowed realistic/appropriate indicator assessment periods to be selected based on plant requirements, operating constraints and best practices. An example of this is that quality parameter (e.g. BOD) testing rates would be more appropriately measured on a monthly basis while equipment (e.g. flow meter) calibration rates would be more appropriately measured on an annual basis.

Applied optimisation research has shown that it is possible to improve AS WwTP economic and environmental performance using a holistic plant-wide optimisation approach that facilitates the plant operator to make appropriate data-based process control decisions in combination with appropriate process control training.

Local authority wastewater operations structure overview

A key finding from the organisational structure spreadsheets and subsequent interviews with local authority personnel was that the official reporting structure may differ from the actual plant operational reporting structure. In some local authorities, plant caretakers are managed and report to Area Supervisors on a regional sub-divisional basis but often communicate with an Executive Engineer regarding process control decisions and troubleshooting who in turn reports to a Senior Executive Engineer. In other local authorities, caretakers report for all matters to Executive Technicians who in turn report to a Senior Executive Engineer. Discussions with some caretakers found that they operated the plant without any technical input from the Senior Executive Engineer that they reported to directly. It is clear from this research study that the current disjointed local authority organisational and operational structure for sanitary services operations needs reform.

Analysis of plant manager questionnaire results

The plant manager/operator questionnaire was circulated to 28 local authorities and 8 private plant operation contractors in ROI. The questionnaire response rate for local authorities was 70.4% while a 75% response rate was achieved from private plant operation contractors. A total of 43 responses were received of which 31 were from local authority personnel and 12 from private plant operation contractors. Valid respondents included personnel responsible for the operational decision-making and management of WwTPs typically including 'plant caretakers', 'plant managers' and 'senior executive engineers'. One question determined the level of importance that plant managers/operators placed on measuring and calculating key parameters for monitoring and controlling the operation of AS WwTPs as shown in Table 1. The key AS operational parameter MLSS and discharge compliance rated highest in importance. Less than 50% of respondents rate the measuring and monitoring of raw wastewater influent characteristics as very important, which is a concern because having this as an unknown would make performance assessment particularly difficult.

A total of 65% of respondents indicated that they had a 'high workload' associated with their role, while no respondents stated that they had a 'low workload'. A total of 63% of respondents indicated that their current level of workload was preventing them from having sufficient time to work on

Table 1 | Respondent level of importance on monitoring, measuring and calculating key parameters

	Unimportant (%)	Slightly important (%)	Important (%)	Very important (%)
MLSS concentration	0.00	0.00	25.58	74.42
Return sludge concentration	2.33	23.26	55.81	18.60
Waste/surplus sludge concentration	0.00	30.23	48.84	20.93
Settled sludge volume (SSV_{30})	0.00	11.63	46.51	41.86
Dissolved oxygen (hand-held)	2.33	4.65	46.51	46.51
Sludge return flow	0.00	13.95	65.12	20.93
Influent quality testing	0.00	9.30	41.86	48.84
Effluent quality testing	0.00	0.00	13.95	86.05
Sludge volume index	0.00	18.60	51.16	30.23
Mean cell residence time	2.33	23.26	46.51	27.91
Food:micro-organism ratio	0.00	18.60	48.84	32.56

improving the operational cost efficiency of the WwTPs that they manage/operate. Responses in relation to how the rhetorical statement 'Wastewater treatment plant managers/ operators spend more time recording and reporting plant data than using it for plant operation' reflected each of the respondents found that 21% indicated that it was 'very true of me', 37% indicated that it was 'somewhat true of me', 30% indicated that it was 'somewhat untrue of me' and 12% indicated that it was 'very untrue of me'. The spread of responses evident in Table 1 corresponds to the wide range of plant technology, practices and monitoring equipment available at each plant. The questionnaire results contribute to the next phase of plant manager/operator stakeholder group consultation to determine additional comprehensive information through surveys and interviews which will be used in conjunction with results from the wider stakeholder consultation to contribute to the formulation of the candidate SOI set.

CONCLUSIONS

This study identifies the need for reform in the ROI wastewater sector and has verified the distinct requirement for continuous operational performance assessment and optimisation of existing AS WwTPs. Applied operation and optimisation studies identified available performance improvement potential at existing AS WwTPs in Ireland. This can be achieved through the implementation of effective sampling, monitoring and data management regimes combined with technical training and the implementation of process control protocols that allow the operator to make data-based process control decisions and identify the associated cause and effect relationships. Consistent and/ or improved environmental performance and reduced treatment cost are the fundamental by-products of a successful optimisation study. Currently there is no measurement system or set of protocols in place in Ireland for evaluating AS WwTP operational performance that would encourage plant owners to refocus attention on and ensure accountability for effective and efficient operation and management of existing AS WwTPs while improving economic, environmental and societal performance factors relevant to a range of stakeholders. Applied research and plant manager/operator surveys have allowed key operational performance assessment parameters to be identified that have contributed to the formulation of preliminary SOIs. The SOI system will allow the assessment of key plant operational indicators over time and provide the baseline information for benchmarking of plant operational performance. It has the potential to facilitate reform by promoting continuous performance evaluation and improvement and becoming an inherent tool to ensure sustainably operated AS WwTPs nationwide.

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