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Design and Implementation of a Resource Consumption Benchmarking Methodology Cognisant of Data Accuracy for Irish Wastewater Treatment Plants

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Abstract

Wastewater treatment plants (WWTPs) typically operate continually and are subject to a number of pressures (e.g. population changes, varying influent due to storm water, more stringent environmental regulation etc.), making the implementation of resource efficiencies uniquely challenging. These challenges mean that, without intervention, WWTPs will become more resource intensive as they strive to meet environmental regulations. These challenges are set against the backdrop, in many countries, of an emphasis on cost reduction and increased concerns regarding the economic sustainability of the sector. Thus it is imperative that tools and methodologies are developed that allow the wastewater sector to measure resource efficiency and benchmark performance in a standardised and efficient manner. This can identify cost-effective measures that can improve WWTP performance.

Measured data in WWTPs often contains errors that can greatly reduce the benefits of various performance assessment techniques. Existing benchmarking systems can offer detailed analysis of many aspects of wastewater treatment; however, these systems do not offer a means of assessing the accuracy of the data used for benchmarking. Furthermore, many benchmarking systems lack key performance indicators that focus on resource consumption and regulation performance. This paper presents a unique benchmarking methodology for WWTPs which addresses these challenges; enabling stakeholders to (i) benchmark a wide variety of WWTPs in an efficient and standardised manner (ii) identify data accuracy issues, (iii) isolate where and how resources are consumed in a WWTP and (iv) identify potential resource consumption mitigation measures. The methodology is implemented in a toolkit which is designed to be easily executed and effective in enabling benchmarking of WWTPs with varying capacity, technology, sampling frequency, data accuracy and management practices.

Keywords

Key Performance Indicators; Benchmarking; Wastewater Treatment; Data Accuracy; Data Availability.

1 Introduction

A clear link between energy usage, predicted future energy usage and environmental regulation is present (Danish et al., 2011; Fitzsimons et al., 2016; Puig et al., 2008). As environmental regulations become more stringent, increased pressure is placed on WWTPs to enhance performance; often resulting in increased energy and chemical consumption (Puig et al., 2008) With a potential water and energy crisis occurring in the coming years, various reports have identified that methods of assessing and reducing energy, chemical and water consumption must be explored (United States Environmental Protection Agency 2012, International Energy Agency 2012).

Wastewater treatment performance benchmarking has showed to be an effective means of comparing WWTPs and drawing conclusions of general validity (Benedetti et al., 2006; Cabrera et al., 2016; Guo et al., 2012; Puig et al., 2008). Benchmarking can involve assessments using key performance indicators (KPIs), energy audits, exergy analysis and life cycle assessment (LCA). When applied at each stage/process of a WWTP, energy auditing can enable the identification of where energy can be conserved (Henriques and Catarino, 2016). Exergy analysis (Fitzsimons et al., 2016; Shao and Chen, 2015) and LCA (Lorenzo-Toja et al., 2015; Risch et al., 2014) can be effective tools in benchmarking WWTPs and can provide in-depth analysis of resource consumption throughout a WWTP. However, they require significant background knowledge to obtain substantial and accurate results (De Gussem et al., 2011; Reap et al., 2008). In addition to this, exergy analysis and LCA do not account for the performance of the WWTP in terms of meeting environmental regulations, which is the most critical metric required for assessing WWTP performance.

With a clear connection evident between resource consumption and WWTP performance, there is a need for benchmarking methodology which can adequately assess resource consumption (energy, chemicals and water) in tandem with WWTP performance. The authors of this paper have previously published papers on exergy analysis and LCA methods for WWTP performance benchmarking. This study details the novel use of KPIs and data accuracy assessments for benchmarking purposes, previously unpublished in the context of WWTP performance benchmarking.

Key Performance Indicators (KPIs) are simple calculations that provide information which can define the effectiveness and efficiency of processes and systems, in a highly defined manner (Möller et al., 2012). KPIs have long been recognised as an efficient mechanism for conducting both process benchmarking (Lindtner et al., 2008; Torregrossa et al., 2016). Numerous KPI based benchmarking toolkits and KPI databases have already been developed for process benchmarking in the wastewater treatment sector (Table 1).

Table 1. Existing KPI benchmarking systems

Country	Reference	System Name	Remarks
Germany	(Bertzbach et al., 2012; Franz et al., 2015; Möller et al., 2012)	Aquabench	Focuses on plant and network performance. System has been applied by over 600 WWTP operators.
Austria	(Lindtner et al., 2008; Starkl et al., 2007)	Austrian Benchmarking System	Focuses on process performance. Uses mass balances for data error detection. Reports annual KPIs.
Finland	(Seppälä, 2015)	VENLA	Provides 2 levels of benchmarking; basic (free) and advanced. Regulatory data can be uploaded from, and downloaded to VENLA.
Sweden	(Balmér and Hellström, 2012; Seppälä, 2015)	VAAS	Provides 3 levels of benchmarking; early Level 1 (metric), Level 2 (process) and current Level 1 which is a compromise between early level 1 and level 2.
Denmark	(Seppälä, 2015)	DANVA	Process and metric benchmarking system used by 137 water companies.
Norway	(Seppälä, 2015)	BedreVANN	Provides 2 levels of benchmarking (simplified and advanced). Advanced level requires more data input and provides detailed cost analysis.
Ireland	(Gordon and McCann, 2015)		Extensive KPI database. Does not provide toolkit/software.
United Kingdom	(Environment Agency, 2001)	OfWat	KPIs used for regulatory and public reporting purposes. Focuses on serviceability of assets.
Luxembourg	(Torregrossa et al., 2016)	EOS	55 KPIs in database. Focuses on energy consumption and process performance. Reports daily KPIs.

China	(Li and Han, 2015)	IMS	Focuses on all aspects of plant performance (quality of service, human resources etc.) Web-based service for data collection and error checking.
Portugal	(Quadros et al., 2010)	PAS	108 KPIs in database. Focuses on resource consumption and WWTP monitoring.
Worldwide	(Danilenko and van den Berg, 2010)	IBNET	Focuses on operational, technical and financial aspects of WWTPs. Includes data collection toolkit and a continuously updated database of WWTP performance.
Spain	(Matos et al., 2003)	SIGMA Lite Wastewater	KPI system based on IWA indicators which focuses on KPIs used routinely at WWTP management level.

The KPIs utilised in these studies are typically well defined and can be seen across a number of the benchmarking systems in Table 1, particularly the KPI databases in the IBNET and SIGMA Lite Wastewater systems (Danilenko and van den Berg, 2010; Matos et al., 2003). Many benchmarking systems assess various aspects of plant performance; however, few systems concentrate solely on WWTP performance in tandem with resource consumption. Some benchmarking systems, such as Aquabench, offer users the ability to tailor their approach to benchmarking by focusing on a key area of interest on a case by case basis (Aquabench, 2017). However, this approach can reduce the comparability of results across WWTPs by enabling the user to focus solely on issues specific to that WWTP.

The issue of data accuracy in WWTP benchmarking and modelling has become prominent in research in recent years (Martin and Vanrolleghem, 2014; Torregrossa et al., 2016), however, few methods of improving data accuracy have been applied in operational benchmarking systems that are suited to WWTPs with decreased data availability. Some existing benchmarking systems offer data error detection through the use of mass balances or statistical analysis methods, although these methods typically require large amounts of often unavailable data. A number of benchmarking systems retrieve data from regulatory data reporting systems, potentially reducing the occurrence of data errors (Seppälä, 2015). In order to enhance the applicability and accuracy of the data used by Aquabench, this system provides consultation services on the appropriate data collection measures for a WWTP via online resources (Aquabench, 2017).

ENERWATER, a European Union wide project which commenced in 2015, is developing a standardised methodology for the continuous assessment and benchmarking of energy consumption in WWTPs (Longo et al., 2016). ENERWATER has utilised user questionnaires to gathering information on WWTP characteristics and main energy consumers and identified usability as a crucial aspect of benchmarking (ENERWATER, 2016).

1.1 Benchmarking system applicability challenges

The number of KPIs applied during benchmarking should be kept to a minimum; this ensures a focused approach to benchmarking and also to prevent users from becoming inundated with KPI data requirements (Parmenter, 2015; Peterson, 2006). The processes employed in a WWTP can vary greatly, resulting in the need for KPIs to be selected on a case-by-case basis to ensure those not applicable to a particular WWTP are not included in the benchmarking process. The lack of a standardised approach for KPI selection (e.g. by permitting users to manually select the KPIs to be analysed) can potentially reduce the relevance of the benchmarking process. This can result from biased personal motivations and a lack of a clear understanding of benchmarking objectives (Alegre et al., 2009). KPIs should be selected using a standardised framework to ensure that WWTPs, in so far as is possible, can be usefully analysed and compared. This ensures that areas of efficiency/inefficiency in particular WWTPs are identified relative to their peers.

1.2 Data availability in wastewater treatment plants

To be beneficial, WWTP benchmarking requires standardised, relevant and accurate information (Lindtner et al., 2008). However, data availability and data accuracy can restrict the success of WWTP benchmarking in an undetected yet substantial manner (Puig et al., 2008). Torregrossa et al. (2016) detail a lack of wastewater quality data as the main obstacle of achieving satisfactory operation of KPIs. The lack of data management can often be the key limiting factor for benchmarking and this is especially the case in both decentralised and small-scale WWTPs; typically those treating for population equivalents (PEs) less than 2000 (Beltrán et al., 2012; O'Reilly et al., 2012; Torregrossa et al., 2016). WWTPs that present poor data reporting capabilities may also lack experienced operators, which may further limit data availability (United States EPA, 2003).

Wastewater treatment is a highly complex process and it is intensely regulated both internationally and nationally, normally by state regulatory agencies (e.g. in Ireland the

Environmental Protection Agency (EPA) stipulate conditions for a WWTP in the form of a discharge license). Such licences may require influent and effluent to be analysed at intervals varying from a number of times per year to one sample per month. Frequently, data which is required for regulatory purposes may be the only performance data available (Puig et al., 2008), potentially hindering the success of benchmarking. As a consequence of poor data management, the feasibility of a benchmarking system must be assessed prior to investing resources.

1.3 Data accuracy in wastewater treatment plants

In addition to assessing data availability, it is necessary to assess the accuracy of available data; in many cases the identification of reliable data sources constitutes the challenge in WWTP benchmarking (Matos et al., 2003). Many WWTPs may record process data (e.g. influent and effluent flow volumes) however, if regular calibration and maintenance records are limited, the resulting data has a high probability of being erroneous. In addition, these errors may remain undetected for some time in the case where the data is not regularly assessed and utilised.

The accuracy of process data in WWTPs can be a significant barrier to benchmarking. Internationally, the issue of data availability and data accuracy is prominent. Poor data quality will limit the meaningfulness of WWTP model predictions; a limitation which is also highly applicable to WWTP benchmarking Rieger et al. (2010). Such data limitations can be linked to capital and operational cost requirements. For example the lack of influent data is frequently due the high cost (in terms of workload and financial resources) required for gathering such datasets (Martin & Vanrolleghem, 2014).

1.3.1 Data accuracy assessment methods

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Mass balances (e.g. COD, nitrogen and phosphorus) form the basis of linear relations which adequately describe systems such as wastewater treatment and can be used as a method of error detection and data reconciliation (first introduced by Van der Hijden et al., (1994a, 1994b, 1994c) in the context of fermentation processes). Identification of data errors can also be achieved through the application of various upcoming technologies including fuzzy logic and artificial neural networks (ANNs) which are capable of learning complex nonlinear relationships which exist in biological wastewater treatment (Vijayaraghavan and Jayalakshmi, 2015; Yoo, 2003). In addition to these technologies, many data inaccuracy detection methods rely on the use of statistical analysis to facilitate fault detection (Yin et al., 2016, 2015). *Table* 2 details research and application of these methods to detect data accuracy issues in the

Commented [ED2]: Reviewer 1: response to comment 2 wastewater sector and related disciplines. In some studies, data accuracy issues can be indirectly assessed through the use of data prediction.

Table 2. Summary of research on methods for data accuracy assessment.

Objectives	Assessment Methodology	Study type	Reference
Modelling study on a method for gross error detection and data reconciliation	Mass balances and data reconciliation using statistical hypothesis testing	Municipal WWTPs	Meijer et al. (2002, 2001)
Design of a data evaluation methodology for WWTPs	Mass balances and data reconciliation using statistical hypothesis testing and conservation principles	Municipal WWTP	Puig et al. (2008)
Study on the soft-sensing estimation of WWTP effluent concentrations	Optimised neural network and principal component analyses	Municipal WWTP and GPS-X simulation	Fernandez de Canete et al. (2016)
Study on improving daily flow prediction	Artificial neural networks, moving average analysis, singular spectrum analysis and wavelet multi-resolution analysis.	Watersheds	Wu et al. (2009)
Design of a hybrid model for daily rainfall prediction	Artificial neural networks and support vector regression	Watersheds	Chau and Wu (2010)
Study on modelling and monitoring of WWTPs including data fault detection	Principal component analysis and fuzzy methods	Industrial WWTP	Yoo, (2003)
Design of a fault diagnosis framework for wastewater processes with incomplete data	Auto associative neural networks and auto-regressive and moving average models	Municipal WWTP	Xiao et al. (2017)

Although many of the studies in Table 2 have been applied to WWTPs for the purpose of validation, it is uncommon to find these methods in operational WWTPs due to the workload and infrastructure required. Additionally, these methods often require additional measures, such as statistical analysis methods (as seen in *Table* 2) in order to assess data accuracy issues. Mass balance methods for data error detection typically requires less statistical analysis methods than ANNs however, these methods are often unfeasible due to influent, effluent and inter-process data requirements (Meijer et al., 2002), which are often unavailable.

1.4 Data issues in Irish wastewater treatment plants

Figure 1 provides an example of data collection or management issues in an Irish context. In 2013, 16% of audited WWTPs did not provide a flow meter where required. In addition to this, of the WWTPs audited which did provide a flow meter, 9% of these WWTPs did not calibrate the flow meter to an appropriate standard. Collectively, this adds up to a large number of audited WWTPs being unable to collect reliable and accurate flow data, which is vital for

WWTP management purposes, due to a lack of regulatory compliance and poor flow meter management.

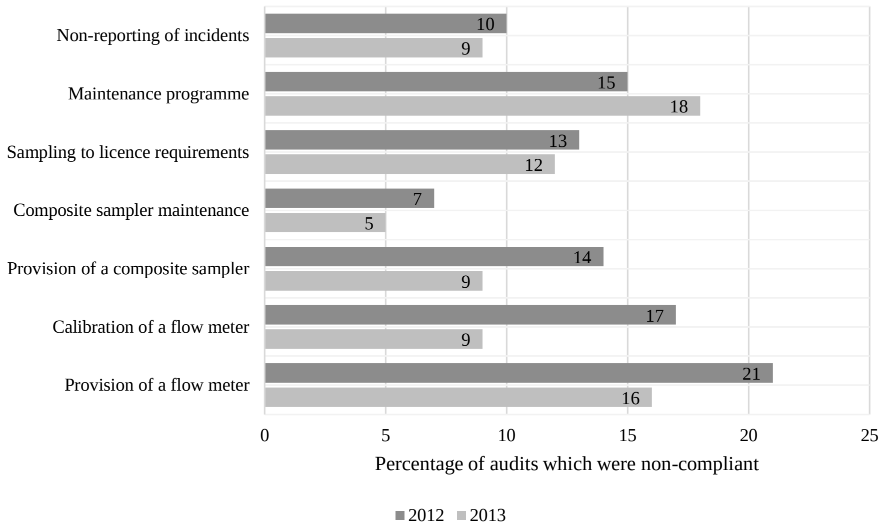

Figure 1. Non-compliance results from EPA audits of Irish WWTPs (EPA, 2013).

1.5 Research gaps and objectives

A number of existing challenges surrounding WWTP benchmarking can be addressed through the development of a novel methodology. These include; (i) provision of KPIs focusing on resource consumption, (ii) standardisation of KPI selection across WWTPs so comparison between WWTPs is possible, (iii) accounting for potential data inaccuracies within the benchmarking toolkit, and (iv) analysis of WWTP compliance with environmental regulations as a key output.

This paper presents a benchmarking methodology, KPICalc, that addresses the highlighted challenges, including automated KPI selection based on the data available in a WWTP (removing the user bias associated with manual selection). Mass balances provide the ideal solution to gross error detection in datasets however, they are not feasible in WWTPs with limited data availability. Thus KPICalc utilises user-perceived data accuracy ratings (Figure 2) as a means of gross error detection when mass balances are not feasible. This study also presents a series of newly-developed resource consumption KPIs to overcome the difficulty of monitoring resource consumption using the limited KPIs previously in existence.

2 Developed benchmarking methodology

KPICalc is applied, in this study, through the use of Microsoft Excel as a working platform as the software exhibited the data entry, calculation, graphing and coding capabilities required to implement and test the methodology. An overview of the methodology is presented in Figure 2. It is noted that many alternatives exist which are capable of implementing KPICalc and these are discussed in the conclusions.

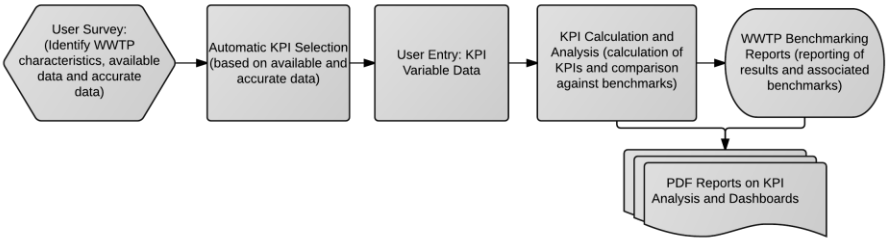

Figure 2. A basic overview of KPICalc.

2.1 Key performance indicator database

KPICalc is suitable for application to various KPI databases, however for the purpose of this study, the methodology is applied to a KPI database which focuses on resource consumption in terms of energy, chemicals and water in conjunction with an overview of WWTP performance (in terms of removal capacities and effluent discharge requirements). The KPI database contains 45 KPIs that encapsulate the WWTP performance in terms of discharged effluent quality, chemical, energy and water consumption along with associated costs (Appendix 1). These KPIs are either adopted directly, or adapted from existing benchmarking systems or developed to address gaps which are not covered by pre-existing KPIs and this is annotated in Appendix 1. The advantages of applying KPICalc to this KPI database are three-fold; (i) it facilitates the testing of the KPICalc, (ii) it offers an opportunity to discuss the advantages of adopting KPICalc and (iii) it presents of the newly developed resource consumption KPIs and discusses their use in WWTP benchmarking.

Similar KPIs have been grouped into categories, for ease of access during benchmarking: (i) Influent volumes, treated volumes and water consumption data, (ii) regulatory compliance, (iii) contaminant removal rates, (iv) chemical consumption and (v) energy usage for both the treatment plant and pump house. These categories (detailed in Appendix 1), offer the advantage of enhanced toolkit usability, as they provide clear display of KPI results throughout KPICalc.

2.2 KPICalc benchmarking methodology

Figure 3 details the framework behind KPICalc; modules which require user input are shown in bold, with automated processes shaded grey. Modules with a similar aim are grouped together (detailed on the left hand side of the process chart) and these are discussed in the following subsections.

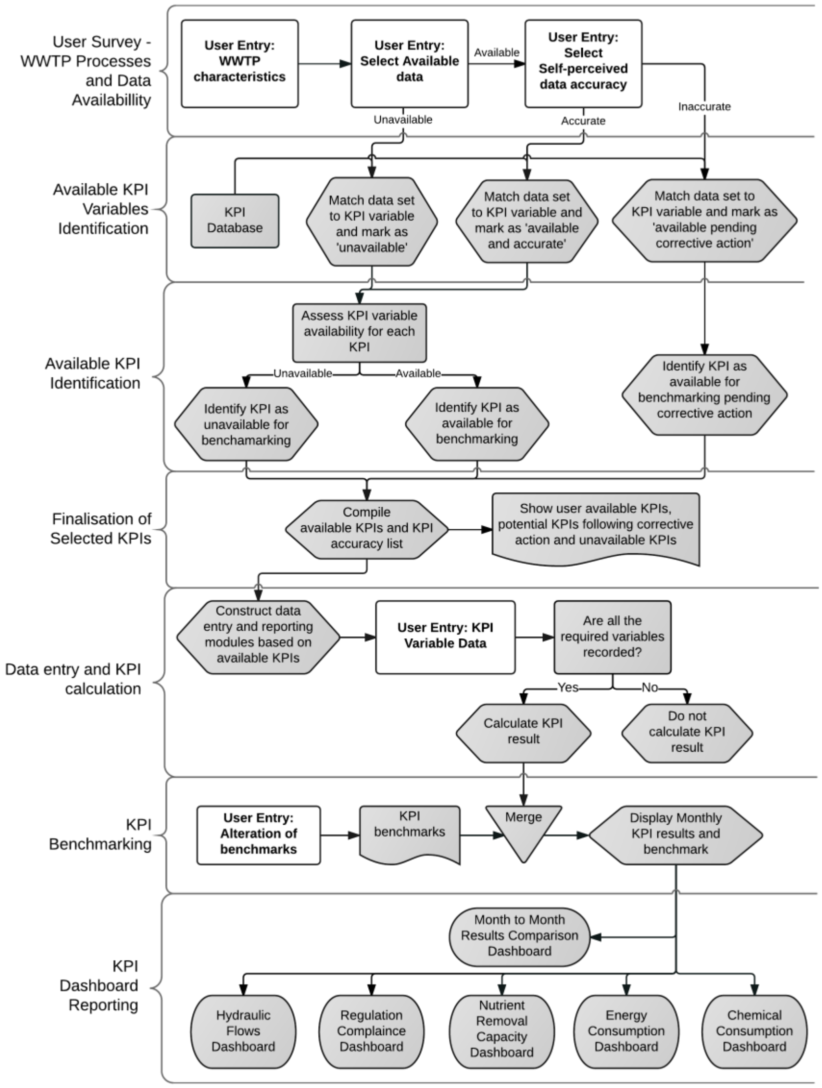

Figure 3. KPICalc framework.

The KPICalc framework was developed with key input from stakeholders, including (i) members of the Irish Environment Protection Agency (EPA) and the Irish Department of Communications, Climate Change and the Environment, (iii) the national water utility and (iv) WWTP managers and consulting engineers. The key issues identified by stakeholders included (i) a lack of a standardised approach to KPI selection, (ii) the need for a benchmarking methodology to fully encapsulate WWTP performance and resource consumption, particularly in the area of energy consumption, and (iii) the need for a means of distinguishing between KPIs which could be measured, for any particular WWTP, and KPIs which could not be calculated due to the accuracy and frequency of available data. In the event of conflicting feedbacks, these group meetings provided the opportunity to apply any recommended changes or inputs to the methodology, via the toolkit in real time (where possible) and to observe the effect which the changes had on the usability of the toolkit and the reported results.

2.3 User survey on wastewater treatment plant characteristics, data availability and data accuracy

Initially the end-user (engineer, facility manager etc.) completes a short survey which enables the automatic selection of KPIs to be used for the remainder of KPICalc. This survey, which can be completed in minutes, asks users to identify WWTP characteristics, data sources which are readily available. Some of the key details requested in the survey include; (i) Population equivalent (PE) of the WWTP (based on hydraulic or organic load); (ii) flow data availability, (iii) various treatment processes used on-site from a predefined list, with the option to add additional information if desired, (iv) enforced regulatory discharge licence requirements for effluent contaminant concentrations (v), chemicals used as part of the wastewater treatment process and their unit cost and (vi) energy consumption monitoring actively taking place on-site.

During identification of available data sources, the user is required to rate their self-perceived accuracy of this data source. Where feasible, users can utilise the methods listed in Table 2 to help with this process; these are referenced for the user in the quick start manual included with the benchmarking methodology. These methods are referred to as advanced methods due to the level of data, user expertise and infrastructure required for successful implementation. Where these methods are not feasible, users can self-perceive the accuracy of a dataset based on personal judgement and experience. This user-perceived method of assessing data accuracy in

KPICalc is not without its limitations and challenges. Requiring users to rate data accuracy based on their knowledge of the data and the monitoring equipment can be subjective (e.g. personal bias, variances in user's knowledge of data accuracy principles etc.). Irrespective of this, the user-perceived accuracy assessment step in the methodology provides an insight into the degree of data accuracy issues present in a WWTP by highlighting the number of KPIs which cannot be included in benchmarking due to data accuracy issues. This incentivises the user to correct these data accuracy issues, which in itself, is an improvement in WWTP performance. Alternately, the user-perceived accuracy ratings act as a high-level data error detection system when coupled with the inclusion of inaccurate KPI results in the KPI reporting modules.

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2.3.1 Selection of a point scale for user-perceived accuracy rating

Originally, a 3-point system (accurate, moderately accurate and inaccurate) was recommended, however, during testing by stakeholders it was identified that KPICalc users felt apprehensive of perceiving data sources as moderately accurate without detailed knowledge of the degree of inaccuracy. When benchmarking under the 3-point rating system; users avoided identifying data as moderately accurate and opted for inaccurate, resulting in the exclusion KPIs. As a result, the user-perceived system was reduced to a 2-point rating system (accurate and inaccurate) where KPIs are only calculated from accurate data sources.

2.4 KPICalc customisation

Once the survey is complete, KPI variables are identified as available/unavailable and accurate/inaccurate and are matched to corresponding KPIs. Each KPIs is then defined as available, unavailable or available pending corrective action (Table 3). These results are shown to users once the survey is complete. Where a KPI is identified as available pending corrective action, the KPI variables requiring corrective action are displayed and a link detailing the variables is provided.

Table 3. KPI availability and accuracy result groups

KPI Group	Description
Available and Accurate	KPIs available for benchmarking due to the availability of the required data and the high accuracy these data are expected to have by the user
Available Pending Corrective Action	KPIs require the accuracy of one or more variables to be corrected prior to their implementation

Unavailable	KPIs are not applicable to the aspects of wastewater treatment present in the WWTP

A key benefit of these outputs is the list of KPIs which cannot be utilised in the benchmarking system due to data inaccuracies. This list incentivises users such as WWTP managers and engineers to correct any data inaccuracies prior to commencing benchmarking, offering an advantage over other benchmarking methodologies which do not take data accuracy into account. In the case where data accuracy can be improved, KPICalc prompts the user to implement any corrective actions and also to correct the user-perceived accuracy in the original survey which will increase the number of available KPIs.

2.5 Data entry and key performance indicator calculation

The customised (based on the aforementioned survey) data entry module for WWTP data enables users to enter data as frequently as is desired or available. Historical data entry is also facilitated. KPIs are automatically calculated by KPICalc based on data availability, if a data point required for KPI calculation is unavailable, the KPI is not calculated or reported. Identification of missing data allows KPICalc to streamline KPI reporting. By default, KPICalc will only calculate KPIs based on data sources identified as accurate by the user. To use KPICalc to detect high level errors in datasets, the user can opt for KPICalc to calculate and report KPIs based on inaccurate data (as previously noted by the user), enabling gross error detection when viewing result reports.

2.6 Key performance indicator benchmarking

Following KPI calculation, targets are used to track the performance of the facility with regard to a particular KPI (Figure 4). KPICalc identifies results deemed “acceptable” where a KPI has met a desired target, “at risk” where a KPI is close to not meeting a desired target and “failed” when the KPI fails to meet the target. These targets can be changed by the user as they will typically vary depending on specific discharge licence requirements, wastewater pumping requirements, technological advancements, etc.

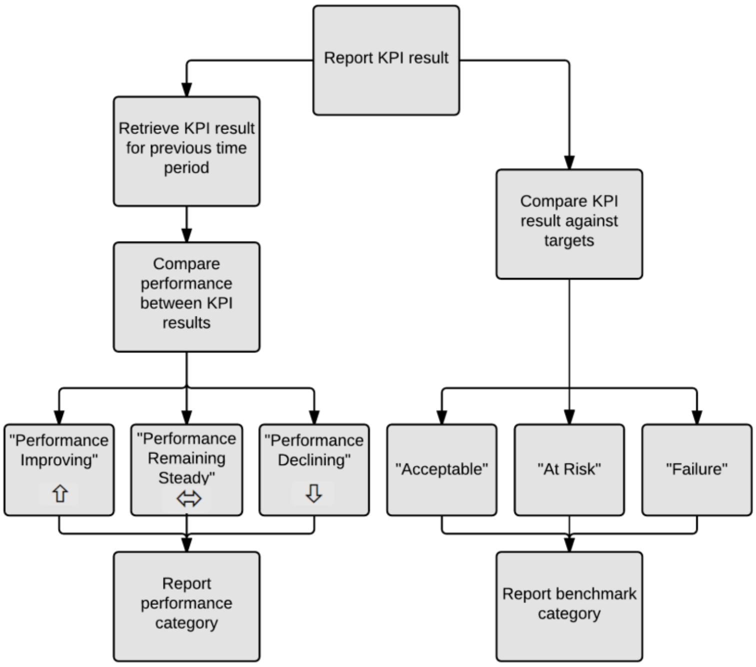


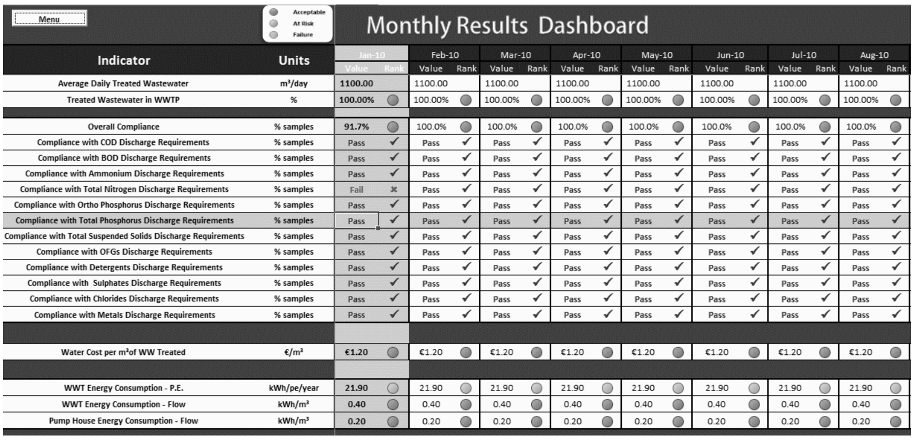
Figure 4. Architecture of the KPI target reporting system

2.7 Key performance indicator reporting dashboards

KPICalc offers reporting dashboards (detailed in Table 4) which provide the user with various colour-coded means of viewing outputs from KPICalc. These include month-by-month comparison dashboards, graphs and tables (an example of which is shown in Figure 5).

Table 4. Dashboard Functions in KPICalc.

Dashboard	Function
Weekly KPI Report	Reporting of weekly KPI results in a tabular format
Monthly KPI Report	Reporting of monthly KPI results and rankings in a tabular format
Monthly Comparison Dashboard	Comparison of KPI results and rankings over any two months selected by the user
Hydraulic Flows Dashboard	Provision of KPI results and graphs focusing on KPIs relating to hydraulic flows
Regulation Compliance Dashboard	Provision of KPI results and graphs focusing on KPIs relating to both compliance testing and in-house testing of influent and effluent wastewaters
Nutrient Removal Dashboard	Provision of KPI results and graphs focusing on KPIs relating to the nutrient removal achieved in the WWTP
Energy Consumption Dashboard	Provision of KPI results and graphs focusing on KPIs relating to energy usage both in the WWTP and pump houses
Chemical Consumption Dashboard	Provision of KPI results and graphs focusing on KPIs relating to chemical consumption and cost



Menu

Acceptable
At Risk
Failure

Monthly Results Dashboard

Indicator	Units	Jan-10		Feb-10		Mar-10		Apr-10		May-10		Jun-10		Jul-10		Aug-10	
		Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
Average Daily Treated Wastewater	m^3/day	1100.00		1100.00		1100.00		1100.00		1100.00		1100.00		1100.00		1100.00	
Treated Wastewater in WWTP	%	100.00%		100.00%		100.00%		100.00%		100.00%		100.00%		100.00%		100.00%	
Overall Compliance	% samples	91.7%		100.0%		100.0%		100.0%		100.0%		100.0%		100.0%		100.0%	
Compliance with COD Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with BOD Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Ammonium Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Total Nitrogen Discharge Requirements	% samples	Fail	✗	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Ortho Phosphorus Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Total Phosphorus Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Total Suspended Solids Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with OFGs Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Detergents Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Sulphates Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Chlorides Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Metals Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Water Cost per m^3 of WW Treated	€/m^3	€1.20		€1.20		€1.20		€1.20		€1.20		€1.20		€1.20		€1.20	
WWT Energy Consumption - P.E.	kWh/pe/year	21.90		21.90		21.90		21.90		21.90		21.90		21.90		21.90	
WWT Energy Consumption - Flow	kWh/m^3	0.40		0.40		0.40		0.40		0.40		0.40		0.40		0.40	
Pump House Energy Consumption - Flow	kWh/m^3	0.20		0.20		0.20		0.20		0.20		0.20		0.20		0.20	

Figure 5. Monthly Results Dashboard Screenshot

A reporting dashboard is available for each of the 5 KPI categories, providing a means of focusing on results from one aspect of WWTP performance (e.g. energy usage). This is achieved through the use of rolling tables and graphs. The details presented in the graphs can be toggled on or off through the use of the checkboxes at the left of the graph.

3 Application of KPICalc and discussion

3.1 Wastewater treatment plant selection

KPICalc was piloted at a number of Irish WWTPs of varying design capacities and processes chosen in consultation with stakeholders (Table 5). The design capacity is reported in using population equivalent (PE). PE is a measurement of organic biodegradable load where 1PE is defined in the Wastewater Discharge (Authorisation) Regulations, (2007) as the organic biodegradable load having a five-day biochemical oxygen demand (BOD_5) of 60g of oxygen per day, where the load is calculated on the basis of average weekly load entering the WWTP during the year, excluding situations such as heavy rain incidents.

Table 5. WWTPs selected for KPICalc piloting

Characteristic	WWTPs A, B and C	WWTP D	WWTP E
Population Equivalent (PE)	15,000 – 30,000 PE	2,500 PE	350 PE
Treatment Technology	Activated sludge & chemical phosphorus removal	Activated sludge & chemical phosphorus removal	Biofilm-based batch treatment system
Plant Type	Municipal	Municipal	Municipal and research facility
Location	Centralised	Centralised	Decentralised

Operational Personnel	Manned	Manned	Unmanned
Discharge licence reporting requirements	Monthly	Monthly	N/A
Sludge Treatment	Yes	Yes	No

3.2 KPICalc piloting

KPICalc piloting incorporated between 3 weeks and 3 months of daily data in each WWTP. For the purpose of discussing the key findings, KPI calculation results presented in this paper (Table 5) are limited to the average result for each KPI in each WWTP, over the duration of the piloting period, in conjunction with the KPI's user perceived accuracy rating (portrayed using a marker system with '✓'markers identifying KPIs calculated from data sources perceived as accurate and '×' markers which identify KPIs that are based on user-perceived data inaccuracies. By default, KPICalc will not calculate results for inaccurate KPIs; for piloting purposes, users opted to calculate inaccurate KPIs to assess if the perceived accuracy rating could be useful in detecting data inaccuracies within the benchmarking methodology. KPIs which were not applicable to all of the WWTPs are excluded from Table 5; the full database of KPIs is shown in Appendix 1.

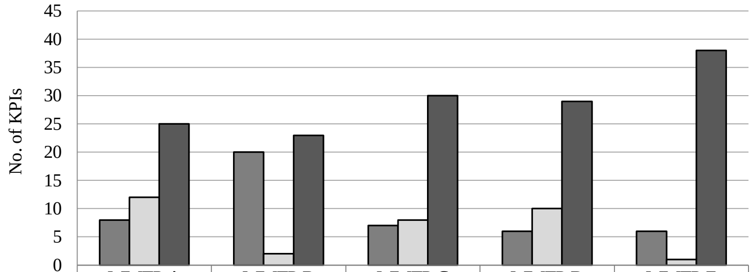
Table 6. Key results from KPICalc testing

Key Performance Indicator	**Units**	**WWTP A**		**WWTP B**		**WWTP C**		**WWTP D**		**WWTP E**	
		Available	**KPI**	**Available**	**KPI**	**Available**	**KPI**	**Available**	**KPI**	**Available**	**KPI**
Design Capacity	% utilised	✗	20	✓	82	✗	166	✗	156	✓	68
Treated Wastewater	% total influent	✗	100	✓	100	✗	100	✗	100	✓	100
Volume of Storm Overflow	% total influent	✓	0	✓	0	✓	0	✗	0	✓	0
Sludge Production in WWTP	kg/m^3 wastewater treated	✗	0.50	✗	0.01	✗	0.94	✗	0.11		
Overall Compliance with Discharge Requirements	% samples	✓	100	✓	63	✓	80	✓	90		
COD Discharge Compliance	% samples	✓	100	✓	95	✓	100	✓	100		
BOD Discharge Compliance	% samples	✓	100	✓	71	✓	100	✓	100		
Ammonium Discharge Compliance	% samples	✓	100	✓	27			✓	100		
Total Nitrogen Discharge Compliance	% samples	✓	100	✓	56	✓	0				
Orthophosphate Discharge Compliance Requirements	% samples	✓	100	✓	13			✓	50		
Total Phosphorus Discharge Compliance Requirements	% samples			✓	87	✓	100				
Total Suspended Solids Discharge Compliance Requirements	% samples	✓	100	✓	91	✓	100	✓	100		
BOD Removal Rate	% removal	✗	90	✓	92			✗	98		
Nitrogen Removal Rate	% removal	✗	33	✓	69	✗	47				
Phosphorus Removal Rate	% removal			✓	88						
Mains Water Volume Consumed	litres/m^3			✓	59					✗	43
Wastewater Reuse*	%	✗	0.14								
Ferric Sulphate Utilised	kg/m^3	✗	0.06	✗	0.7			✗	0.06		
WWTP Energy Consumption per PE	kWh/PE/year	✗	11.7	✓	20.0	✗	16.3	✗	20.2	✓	15.02
WWTP Energy Consumption per Unit Flow	kWh/m^3	✗	0.2	✓	0.3	✗	0.3	✗	0.4	✓	0.2
WWTP Energy Consumption per Unit BOD Removed	kWh/kg BOD	✗	1.0	✓	1.8	✗	1.5	✗	2.1	✓	1.7
WWTP Energy Consumption per Unit Nitrogen Removed	kWh/kg Nitrogen	✗	21.1	✓	12.4	✗	44.3				
WWTP Energy Consumption per Unit Ammonium Removed	kWh/kg Ammonium	✗	11.0					✗	16.7		
WWTP Energy Consumption per Unit Phosphorus Removed	kWh/kg Phosphorus			✓	0.05						

*Wastewater Reuse is defined as the reuse of final effluent for on-site purposes such as tank cleaning, belt press cleaning etc.

3.3 KPI variable availability and accuracy

A considerable number of KPIs were identified as inaccurate due to inaccurate data sources (Table 5). Figure 6 highlights data availability and data accuracy results from each WWTP, including KPIs found to be not applicable. The majority of inaccuracies were reported in flow data, sludge production data and water and chemical consumption data. These common inaccuracy issues are discussed further in the following sections.



	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E
Accurate	8	20	7	6	6
Inaccurate	12	2	8	10	1
Not Applicable	25	23	30	29	38

Figure 6. Data availability and accuracy results

3.4 Advantages of KPICalc customisation

A large percentage of KPIs in each WWTP were identified as not applicable mostly due to the varying compliance requirements which a WWTP can be subject to (Appendix 1). The advantages of KPICalc customisation can be seen when discussing the exclusion of inaccurate or not applicable KPIs. Without the ability of KPICalc to customise itself to the WWTP which it is applied to, the user would be presented with KPIs and associated reporting modules which were either not applicable to the WWTP in question, or inaccurate.

Exclusion of these not applicable or inaccurate KPIs overcomes the challenge cited in literature by Parmenter (2015) and Peterson (2006) of users becoming inundated with KPIs and hence lacking a focused approach to benchmarking.

3.5 Flow data accuracy

The importance of available and accurate flow data is reflected in KPICalc where 32 of the 45 KPIs require flow data. The remaining KPIs in the database, fall under the regulatory compliance category where typical concentration-based measurements of pollutants are required (Appendix 1).

The majority of inaccurate KPIs excluded from the respective benchmarking methodologies in the test WWTPs were due to inaccurate flow monitoring data. WWTPs A, C, and D were found to have inaccurate flow data (Figure 7). In each WWTP, the number of KPIs which are inaccurate due to flow data issues alone, equals or exceeds the number of accurate KPIs. This is in line with previously mentioned regulatory audits in Ireland (EPA, 2013), that noted 21% of WWTPs failed to provide flow meter measurements, and 17% failed to maintain calibration of flow meters.

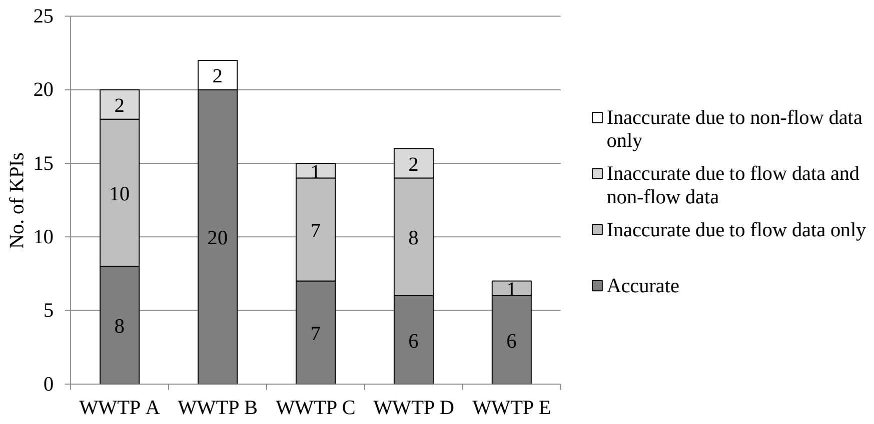


Figure 7. Breakdown of KPI inaccuracies identified by KPICalc

This study, similarly to Puig et al., (2008) found that in general regulatory data was the primary performance data available. The WWTPs used in this study are legally required to have regulatory wastewater samples analysed in an accredited and external lab. As a result, the data is readily available and highly accurate (note all regulatory compliance KPIs are identified as accurate). In a slight contrast to this requirement, Irish WWTPs are legally required to report their average daily hydraulic loading (based on influent flow). Calculated average hydraulic loadings often lack the ability to identify flow data issues due to their broad application across a year of flow data.

3.5.1 Gross error detection in flow data

Due to the inclusion of inaccurate KPIs in the calculation and reporting modules of KPICalc, it was possible to detect gross data errors during result analysis. For example, analysis of the

KPI results for design capacity utilisation (Table 5) indicated WWTPs A, C and D may have been significantly over/under loaded based on influent data and the design capacity of the WWTP. These results supported the user-perceived inaccurate ratings given at the start of the benchmarking process for the influent flow data in 3 of the pilot WWTPs. On further investigation, flow data issues were diagnosed using mass balance checks. It should be noted however that the completion of mass balance checks on the flow data in each WWTP required intensive data collection over a number of days.

In WWTP A, a large balance residual was found to be the result of inaccuracies in the influent flow meter (ultrasonic level meter and flow measurement channel). The automated screening process was defective and powered off for the duration of the study (influent flow diverted to manual screening just 2-3 meters downstream from the flow monitoring channel). Although these screens were raked frequently, regular screen blockages occurred which artificially increased the height of water in the flow measurement channel, causing the ultrasonic level meter to over-read flow rates. The influent flow meter was found to be out of calibration in WWTP C. The influent flow meter in WWTP D was located downstream of the RAS return point, resulting in the influent flow meter reading both the influent and RAS.

3.6 Sludge production data accuracy

Due to the high cost of treating and transporting sludge, WWTP managers and operators aim to reduce the volume of waste sludge requiring further treatment, however, sludge volume data collected in WWTPs A, B, C and D was found to be both sporadic and inaccurate (Table 5). Sludge volume data in each WWTP was only available on an annual basis for each WWTP and for the purposes of this study, daily sludge production was assumed to be uniform throughout the duration of the study.

3.7 Chemical consumption data accuracy

KPICalc includes 14 KPIs which encompass a variety of chemicals used in WWTPs. In this study ferric sulphate featured as the only chemical utilised. Ferric sulphate is used in WWTPs for chemical phosphorus removal and typically utilises a drip-feed system for chemical addition. Drip-feed systems were not found to be frequently monitored and thus for WWTPs A, B and D, the daily chemical masses utilised were estimated based on the delivery dates of ferric sulphate and subsequent estimations of volume delivered. This estimation led to users identifying chemical consumption data as inaccurate.

3.8 Benchmarking with limited data availability

Implementing KPICalc is achievable even where limited data is available, however it is recommended that caution is exercised if benchmarking such facilities against other WWTPs or drawing significant conclusions from the exercise. For example, WWTP E is not required to operate meet regular ELV requirements (in Ireland this applies to WWTPs which a PE of less than 500). The limited levels of monitoring at WWTP E resulted in relatively few KPIs being reported (Figure 6). This reflects challenges previously identified regarding data management practices in small and decentralised WWTPs (Beltrán et al., 2012; O'Reilly et al., 2012).

Should the manager of a small-scale WWTP wish to benchmark against its peers, it is recommended that managers undertake a period of intensive wastewater testing and data collection for benchmarking purposes. This ensures that sufficient results are provided, enabling adequate conclusions to be drawn from benchmarking.

4 Conclusions

This study presents and tests a benchmarking methodology, KPICalc, designed to assess data accuracy and availability and analyse wastewater treatment performance and resource consumption. KPICalc addresses challenges identified in the literature associated with existing benchmarking methodologies including the effect of data inaccuracies on achieving meaningful benchmarking results. The novel aspects of KPICalc (and those which offer an advantage over existing methodologies) presented in this paper include:

1. Automated exclusion of KPIs which are unrelated to the processes utilised in the WWTP enabling (i) standardisation of benchmarking between WWTPs and (ii) automatic adaptation to user requirements;
2. Identification of KPIs that may be based on inaccurate data (through the use of the user-perceived data accuracy survey);
3. Gross data error detection through the use of user-perception and KPI reporting.

To critically analyse the developed methodology, KPICalc was tested in 5 WWTPs. The results from testing show the numerous advantages of assessing data availability and data accuracy when benchmarking WWTP performance. This study contributes to the current body of literature by applying a method of assessing data accuracy in WWTPs with limited data availability and highlights the advantages of such a methodology in a number of pilot WWTPs. Furthermore, KPICalc testing further highlighted the prominence of inaccurate process data which was echoed in the literature. Beyond the academic interests of this study, this study emphasises the negative effects of inaccurate process data from a WWTP management perspective and highlights the use of mass balances as a means of assessing data accuracy.

While this study and KPICalc does not offer fully-automated analysis of data accuracy issues, it offers an advancement in the use of user-perceived data accuracy ratings and KPI reporting for gross error detection. Future work for a WWTP benchmarking methodology may include more robust and automated methods of assessing data accuracy, capable of assessing data accuracy in real time and throughout the benchmarking exercise. Application of the methodology in a standalone software package capable of storing extensive databases, rather than Microsoft Excel (which was chosen for testing purposes) could provide a more stable platform with increased usability and automation. A separate methodology and toolkit which groups comparable WWTPs based on key characteristics is currently being developed. This tool will enable users to identify similar WWTPs which can be fairly benchmarked using KPICalc.

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Appendix 1. Key performance indicators utilised in the KPICalc

GROUP	KEY PERFORMANCE INDICATOR	UNITS	CALCULATION
FLOW	Design Capacity Utilised [6]	%	*(Weight of BOD per unit of influent wastewater/ volume of influent wastewater) / 0.06) / Design Capacity) x 100*
	Treated Wastewater in WWTP [1,2]	%	*(Volume of effluent wastewater / volume of influent wastewater) x 100*
	Volume of Storm Overflow [6]	%	*(Volume of storm overflow / volume of influent wastewater) x 100*
	Sludge Production in WWTP [1,2,4,5]	kg/m^3	*Volume of sludge produced on-site / volume of effluent wastewater*
REGULATORY COMPLIANCE	Overall Compliance with Discharge Requirements [1,2,4,5]	%	*(Total number of tests meeting discharge requirements / Total number of tests carried out) x 100*
	COD Compliance with Discharge Requirements [1,2,5]	%	*(Number of COD tests meeting discharge requirements / Number of COD tests carried out) x 100*
	BOD Compliance with Discharge Requirements [1,2,5]	%	*(Number of BOD tests meeting discharge requirements / Number of BOD tests carried out) x 100*
	Ammonium Compliance with Discharge Requirements [6]	%	*(Number of Ammonium tests meeting discharge requirements / Number of Ammonium tests carried out) x 100*
	Total Nitrogen Compliance with Discharge Requirements [1,2,5]	%	*(Number of Total Nitrogen tests meeting discharge requirements / Number of BOD tests carried out) x 100*
	Orthophosphate Compliance with Discharge Requirements [6]	%	*(Number of Orthophosphate tests meeting discharge requirements / Number of Orthophosphate tests carried out) x 100*
	Total Phosphorus Compliance with Discharge Requirements [1,2,5]	%	*(Number of Total Phosphorus tests meeting discharge requirements / Number of Total Phosphorus tests carried out) x 100*
	Total Suspended Solids Compliance with Discharge Requirements [1,2,5]	%	*(Number of Total Suspended Solids tests meeting discharge requirements / Number of Total Suspended Solids tests carried out) x 100*
	Oil, Fats and Grease Compliance with Discharge Requirements [6]	%	*(Number of Oil, Fats and Grease tests meeting discharge requirements / Number of Oil, Fats and Grease tests carried out) x 100*
	Detergents Compliance with Discharge Requirements ts [6]	%	*(Number of Detergents tests meeting discharge requirements / Number of Detergents tests carried out) x 100*
	Sulphate Compliance with Discharge Requirements [6]	%	*(Number of Sulphate tests meeting discharge requirements / Number of Sulphate tests carried out) x 100*
	Chlorides Compliance with Discharge Requirements [6]	%	*(Number of Chlorides tests meeting discharge requirements / Number of Chlorides tests carried out) x 100*
	Metals Compliance with Discharge Requirements [6]	%	*(Number of Metals tests meeting discharge requirements / Number of Metals tests carried out) x 100*

[1] Matos et al., 2003, [2] ISO, [3] Danilenko and van den Berg, 2010, [4] Quadros et al., 2010, [5] Altered from original source, [6] Developed

Appendix 1. Key performance indicators utilised in the KPICalc (continued)

GROUP	KEY PERFORMANCE INDICATOR	UNITS	CALCULATION
REMOVAL CAPACITY	BOD Removal Rate [6]	*%*	*(1-((Weight of BOD present per unit of effluent wastewater x volume of effluent wastewater) / (weight of BOD present per unit of influent wastewater x volume of influent wastewater))) x 100*
	Nitrogen Removal Rate [6]	*%*	*(1-((Weight of Total Nitrogen present per unit of effluent wastewater x volume of effluent wastewater) / (weight of Total Nitrogen present per unit of influent wastewater x volume of influent wastewater))) x 100*
	Ammonium Removal Rate [6]	*%*	*(1-((Weight of Ammonium present per unit of effluent wastewater x volume of effluent wastewater) / (weight of Ammonium present per unit of influent wastewater x volume of influent wastewater))) x 100*
	Phosphorus Removal Rate [6]	*%*	*(1-((Weight of Total Phosphorus present per unit of effluent wastewater x volume of effluent wastewater) / (weight of Total Phosphorus present per unit of influent wastewater x volume of influent wastewater))) x 100*
WATER CONSUMPTION	Mains Water Volume Consumed [4,5]	*Litres/m³*	*Volume of mains water consumed on-site / volume of effluent wastewater*
	Mains Water Cost [6]	*€/m³*	*Cost of mains water consumed on-site / volume of effluent wastewater*
	Wastewater Reuse [6]	*%*	*(Volume of effluent reused / volume of effluent wastewater) x 100*
CHEMICAL CONSUMPTION	Calcium Carbonate Utilised [6]	*kg/m³*	*Weight calcium carbonate of utilised / volume of effluent wastewater*
	Calcium Hydroxide Utilised [6]	*kg/m³*	*Weight of calcium hydroxide utilised / volume of effluent wastewater*
	Calcium Oxide Utilised [6]	*kg/m³*	*Weight of calcium oxide utilised / volume of effluent wastewater*
	Sodium Bicarbonate Utilised [6]	*kg/m³*	*Weight of sodium bicarbonate utilised / volume of effluent wastewater*
	Sodium Carbonate (Soda Ash) Utilised [6]	*kg/m³*	*Weight of sodium carbonate (soda ash) utilised / volume of effluent wastewater*
	Sodium Hydroxide (Caustic Soda) Utilised [6]	*kg/m³*	*Weight of sodium hydroxide (caustic soda) utilised / volume of effluent wastewater*
	Alum Al(III) Utilised [6]	*kg/m³*	*Weight of alum Al(III) utilised / volume of effluent wastewater*
	Iron Fe(III) Utilised [6]	*kg/m³*	*Weight of iron Fe(III) utilised / volume of effluent wastewater*
	Ferric Chloride Utilised [6]	*kg/m³*	*Weight of ferric chloride utilised / volume of effluent wastewater*
	Aluminium Chloride Utilised [6]	*kg/m³*	*Weight of aluminium chloride utilised / volume of effluent wastewater*
	Polyaluminium Chloride Utilised [6]	*kg/m³*	*Weight of polyaluminium chloride utilised / volume of effluent wastewater*
	Polyiron Chloride Utilised [6]	*kg/m³*	*Weight of polyiron chloride utilised / volume of effluent wastewater*
	Alum Sulphate Utilised [6]	*kg/m³*	*Weight of alum Sulphate utilised / volume of effluent wastewater*
	Ferric Sulphate Utilised [6]	*kg/m³*	*Weight of ferric Sulphate utilised / volume of effluent wastewater*

(1) Matos et al., 2003, (2) ISO, (3) Danilenko and van den Berg, 2010, (4) Quadros et al., 2010, (5) Altered from original source, (6) Developed

Appendix 1. Key performance indicators utilised in the KPICalc (continued)

GROUP	KEY PERFORMANCE INDICATOR	UNITS	CALCULATION
ENERGY CONSUMPTION	WWTP Energy Consumption per PE [1,2]	*kWh/PE/ year*	*Energy consumed in both WWTP and pump house / (Volume of effluent wastewater / 0.15)*365*
	WWTP Energy Consumption per Unit Flow [4,5]	*kWh/m³*	*Energy consumed in both WWTP and pump house / volume of effluent wastewater)*
	WWTP Energy Consumption per Unit BOD Removed [6]	*kWh/kg BOD*	*Energy consumed in both WWTP and pump house / (weight of BOD present per unit of influent wastewater x volume of influent wastewater) - (weight of BOD present per unit of effluent wastewater x volume of effluent wastewater)*
	WWTP Energy Consumption per Unit Nitrogen Removed [6]	*kWh/kg N*	*Energy consumed in both WWTP and pump house / (weight of Total Nitrogen present per unit of influent wastewater x volume of influent wastewater) - (weight of Total Nitrogen present per unit of effluent wastewater x volume of effluent wastewater)*
	WWTP Energy Consumption per Unit Ammonium Removed [6]	*kWh/kg A*	*Energy consumed in both WWTP and pump house / (weight of Ammonium present per unit of influent wastewater x volume of influent wastewater) - (weight of Ammonium present per unit of effluent wastewater x volume of effluent wastewater)*
	WWTP Energy Consumption per Unit Phosphorus Removed [6]	*kWh/kg P*	*Energy consumed in both WWTP and pump house / (weight of Total Phosphorus present per unit of influent wastewater x volume of influent wastewater) - (weight of Total Phosphorus present per unit of effluent wastewater x volume of effluent wastewater)*
	Pump House Energy Consumption per Unit Flow [6]	*kWh/m³*	*Energy consumed in pump house / volume of influent wastewater*

[1] Matos et al., 2003, [2] ISO, [3] Danilenko and van den Berg, 2010, [4] Quadros et al., 2010, [5] Altered from original source, [6] Developed