Design and Implementation of a Resource Consumption Benchmarking System for Wastewater Treatment Plants

E. Doherty*, L. Fitzsimons**, B. Corcoran** and Y. Delaure**, E. Clifford*.

* Department of Civil Engineering, National University of Ireland, Galway, University Road, Newcastle, Co. Galway, Ireland
(E-mail: *edelle.doherty@gmail.com*; *eoghan.clifford@nuigalway.ie)*
** School of Mechanical and Manufacturing Engineering, Dublin City University, Glasnevin, Dublin 9, Ireland
(E-mail: *lorna.fitzsimons@dcu.ie;brian.corcoran@dcu.ie; yan.delaure@dcu.ie.*

Abstract
Energy and water are inextricably linked, and together they are the two of the most valuable global resources. Internationally, the links between the energy, wastewater and water sectors are attracting increasing attention. In the wastewater sector, pressures including increasingly stringent environmental regulations and greater volumes of wastewater being produced and treated are a major challenge. These challenges mean that, without intervention, wastewater treatment facilities will become more resource intensive and may increasingly exceed environmental requirements, such as discharge limits.

These issues are set against the backdrop, in many countries, of an emphasis on cost reduction and increased concerns regarding sustainability of the sector. Thus it is imperative that tools and methodologies are developed that allow the wastewater sector to measure resource efficiency, benchmark its performance in a standardised and efficient manner and identify cost-effective measures that can improve plant performance. This research presents a novel resource benchmarking system for wastewater treatment plants (WWTPs). This toolkit is designed to be easily implemented and effective in enabling benchmarking of WWTPs with varying capacity, technology, sampling frequency and management practices. The research considers both centralised and decentralised facilities (manned and unmanned) and investigates the challenges of benchmarking plants where routine monitoring is sporadic.

Keywords
Key performance indicators; benchmarking; wastewater treatment; energy; water; resource consumption

INTRODUCTION

Energy and water are the most important and valuable resources required to sustain a growing population and to ensure continued economic growth. Indeed the two are heavily intertwined – for example, wastewater treatment accounts for approximately 1% of the world's total energy consumption – equating to over 660 million m^3 of water a year being dissipated to generate the required energy for wastewater treatment alone (Metcalf & Eddy 2003, IEA 2012). These figures are set to rise and with a potential water and energy crisis occurring in the coming years, various reports have identified that methods of reducing energy and water consumption must be explored (US EPA 2012, IEA 2012).

Resource consumption is intensive in traditional wastewater treatment systems, with three main resources being identified as those of greatest concern; energy, chemicals and water. (US EPA 2010; WEF 2011). More importantly, energy and water production and usage are inextricably linked due to their heavy dependency on each other. This research, which is concerned with reducing resource consumption, focuses on developing key performance indicators for energy, chemicals and water.

Benchmarking resource efficiency

Benchmarking is an underutilised but potentially important element in performance improvement schemes. To be beneficial, the benchmarking process requires standardised, relevant and accurate information on resource consumption and WWTP performance analysis (Lindtner et al. 2008). Benchmarking can have various methodologies including key performance indicators (KPIs), exergy analysis and life cycle assessment (LCA). All of these methods offer viable solutions when energy consumption must be considered, as is the case with wastewater treatment.

Exergy analysis and LCA (when implemented correctly) can be effective in benchmarking WWTPs and can provide in-depth analysis of the facilities overall performance. However, they require significant background knowledge in order to be able to extract substantial and accurate results (Reap et al. 2008; De Gussem et al. 2011). In smaller and decentralised WWTPs the main personnel who operate the system may only be on-site intermittently and thus data availability may also be a limiting factor. Furthermore for any benchmarking system, the user will not fully interact with all the capabilities of the system if it is overly complex; therefore selecting a user-friendly system is the key to success. Particular attention is given to achieving KPI analysis for decentralised WWTPs as they can have poor data reporting capabilities and frequently, the lack of an experienced operator (US EPA 2003).

This research proposes the use of KPIs as a mechanism to achieving resource benchmarking. 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). Numerous KPI based systems have already been developed for wastewater treatment, including the IWA Wastewater KPI application (Matos et al 2003) and IBNET's Benchmarking tool (Danilenko & van den Berg 2010). Both of these systems include a broad spectrum of KPIs for wastewater treatment (including staffing numbers, number of sick days per year etc.) in order to give a complete view of a wastewater treatment plant in terms of its performance.

Challenges with Benchmarking Systems

A number of problems have been identified with current benchmarking tools. Previous KPI and benchmarking systems have included numerous, if not every aspect of wastewater treatment (e.g. human resources, personnel training etc.). However, broad, all-inclusive boundaries such as those identified in these systems can act as a hindrance. Expansive KPI analysis on multiple aspects of wastewater treatment is an intensive and time consuming process in terms of data collection and analysis. As mentioned previously, the resource benchmarking system developed in this research focuses solely on the energy, chemical and water consumption. This is primarily due to the principle that full KPI analysis on a small number of critical areas can offer more potential for accurate benchmarking than superficial analysis on a vast number of wastewater treatment areas.

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 by the Environmental Protection Agency (EPA) stipulate conditions for a WWTP in the form of a discharge license). Such licences may require effluents to be analysed on a monthly, fortnightly or weekly basis. This irregular sampling frequency leads to data availability problems. In many situations this data may be the only performance data available for the WWTP.

Other challenges regarding benchmarking can include (i) limited flow information, (ii) the lack of energy and water metering, (iii) limited automated data collection procedures, (iv) the lack of a permanent operator, particularly in decentralised WWTPs and (v) significant variations in processes and technologies.

To address these problems, the proposed KPI toolkit, KPICalc, has been designed to be flexible in its adaption to any WWTP configuration. KPICalc is designed to handle various data availabilities in WWTPs where reporting frequency range from daily to monthly while offering users the ability to view data in a layered fashion. Macro KPI analysis is displayed through monthly KPI averages, however toolkit users requiring more in-depth analysis can acquire data based on daily averages. Through data analysis, this research also identifies the ideal frequency of data required to achieve confidence in the KPIs output by the toolkit (based on the fact that more frequent data delivers more accurate KPIs).

Previous systems require the user to manually identify KPIs which they would like to utilise. In terms of benchmarking, this feature can be troublesome as it is often difficult to identify WWTPs which utilise similar sets of KPIs (KPI analysis similarity is a key requirement of benchmarking). To rectify these benchmarking issues, the user is asked to provide critical information on their WWTP's setup including discharge requirements and available data streams. From this information, the toolkit, named KPIAdvisor, will identify the KPIs which can be utilised in the benchmarking exercise. Furthermore, the toolkit can identify other WWTPs with similar characteristics that are also involved in the benchmarking process, thus facilitating ready comparisons.

Resource Benchmarking System Architecture

Overall description

The resource benchmarking system can be broken into two main elements; the preliminary WWTP survey toolkit, KPIAdvisor, and the KPI analysis toolkit, KPICalc. These toolkits both have a pre-defined list of outcomes which are utilised in the benchmarking process and have been primarily designed with the user in mind. KPICalc employs 54 KPIs which encapsulate the plant's performance in terms of discharged effluent quality, resource consumption and associated costs. These KPIs have been split into 5 categories; (i) wastewater and sludge data, (ii) regulatory compliance, (iii) contaminant removal rates, (iv) chemical and mains water consumption and (v) energy usage for WWTP and pump house. A schematic of the entire resource benchmarking system is shown in Figure 1.

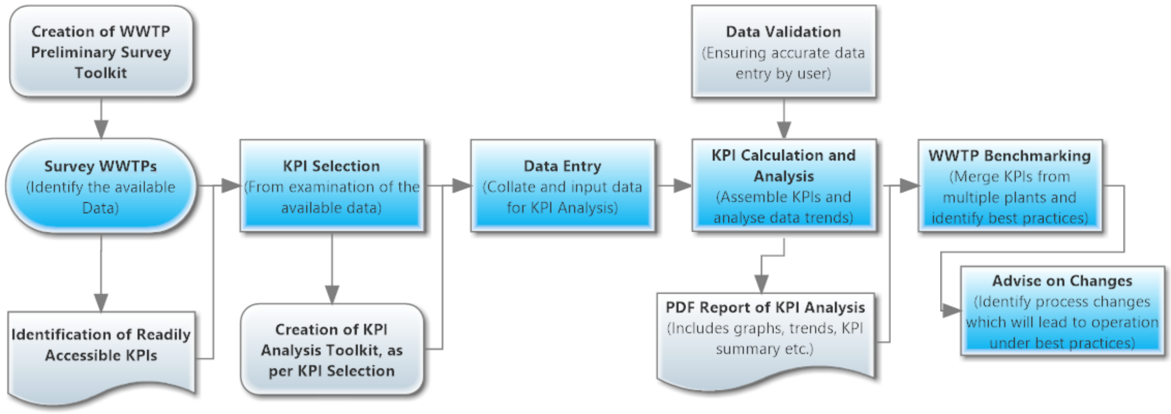

Figure 1. A basic overview to the benchmarking and KPI system

Key Performance Indicator Advisor (KPIAdvisor)

KPIAdvisor has been designed as a short excel-based toolkit. It has a concise, user-friendly interface which prompts the user to enter a number of key details regarding the WWTP. The user, often the WWTP manager, can complete the survey in minutes by ticking boxes along with other simple user inputs. Some of the key details required include:

1. Population equivalent (PE) of the WWTP;
2. Identification of the various treatment processes used on-site;
3. EPA discharge license requirements for various effluent contaminant concentrations;
4. Chemicals used as part of the wastewater treatment process and their cost per unit;
5. List of any energy consumption monitoring taking place on-site.

Behind this easy-to-use interface, a number of hidden logic levels gather the information entered by the user and compare it to the information or data required for each of the KPIs involved in the resource benchmarking system. From this comparison, KPIAdvisor will identify the KPIs which can potentially be implemented in a WWTP.

As an output of KPIAdvisor, a list of available KPIs for benchmarking the plant in question will be reported to the user and then utilised further in the setup of KPICalc. The development of this small toolkit came about from stakeholder meetings. These meetings strongly identified the need for a tool that could determine which KPIs could be measured, in a standardised manner, for a particular WWTP, based on the available data.

Key Performance Indicator Calculator (KPICalc)

To make KPICalc as autonomous as possible, the toolkit architecture encompasses various processing features, data analysis and validation. This validation takes place with minimal user input by identifying and flagging incorrect values based on acceptable data ranges, which are included within the toolkit architecture. As outlined previously, WWT is a highly variable process, with numerous variables such as influent flow volumes, contaminant concentrations, weather effects etc. Therefore, the logic behind the toolkit accounts for a wide variety of factors which could affect data validity (Figure 2).

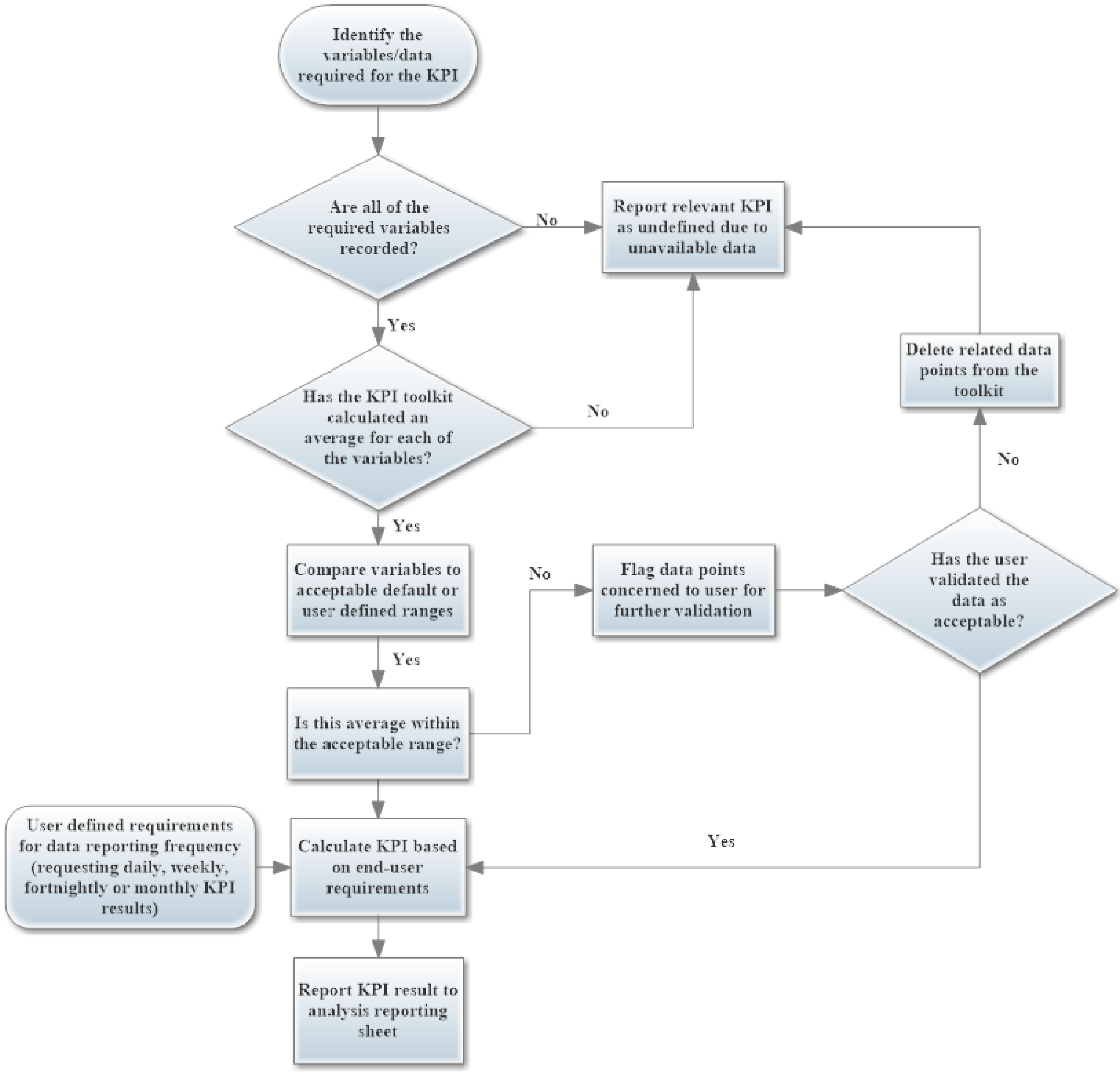

Figure 2. Decision making process involved for each KPI calculation

Shown in the above figure, this research identified a number of key steps for validating data as part of the decision making process.

1. Identify missing data points;

Identification of available and unavailable data allows the toolkit to be flexible in terms of the frequency of data supplied to the toolkit. Once missing data is identified KPICalc will either warn the user of the discrepancy or overlook the missing data if it is not important.

2. Identify incorrect data;

In the event that data is input to KPICalc incorrectly or is identified as being considerably out of range, it will be flagged and presented to the user to either be corrected or removed. An example of incorrect data would include the manual input of a negative concentration value for effluent constituents such as nitrogen, phosphorus etc.

3. Report whether the frequency of data is adequate or otherwise for accurate KPI calculation.

Frequency of data input into KPICalc will significantly affect the system's accuracy. This is explained in further detail in the testing and validation section.

A *Reporting Dashboard* displays the most relevant data. KPICalc allows for deeper data analysis and can rank KPIs in terms of a wastewater treatment plant's effectiveness and its performance trends. This is displayed in Figure 3.

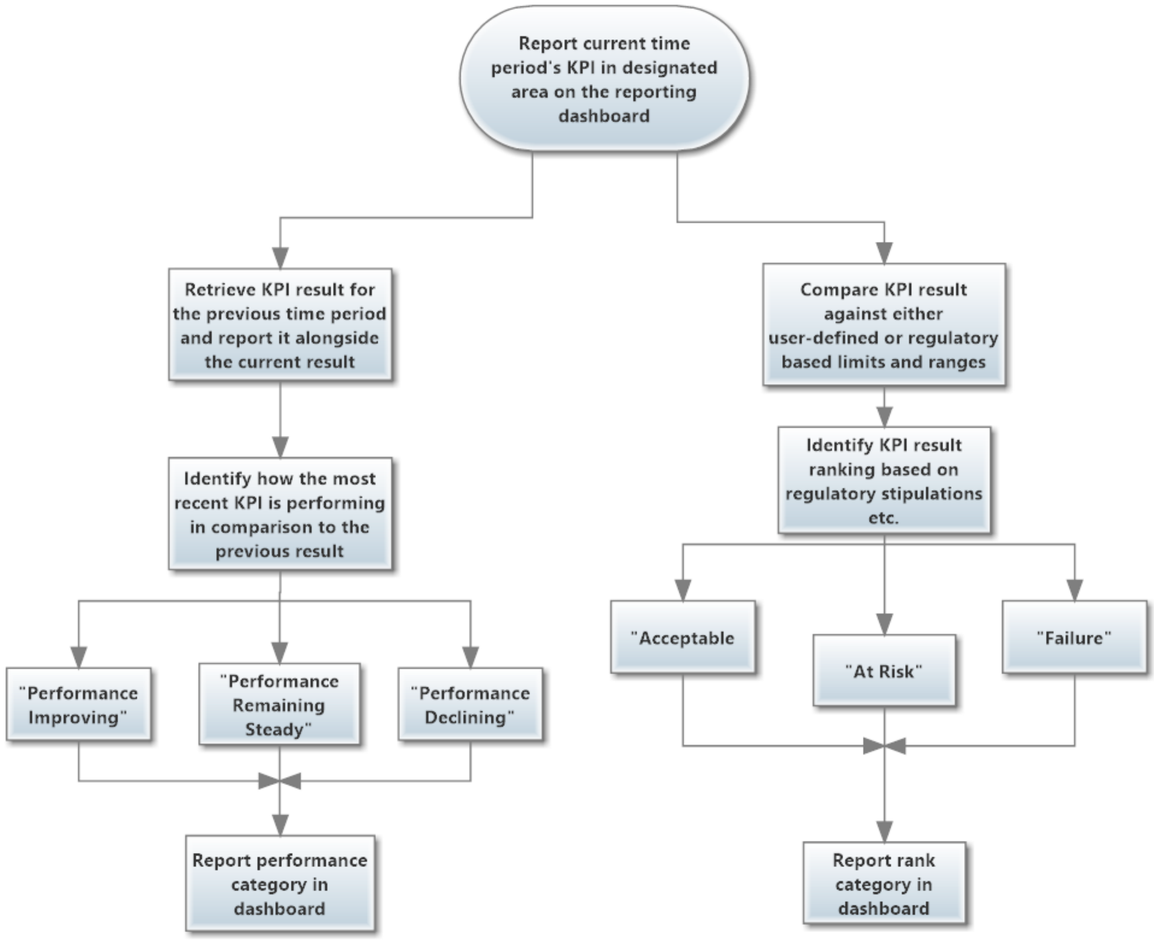

Figure 3. Architecture of the *Reporting Dashboard* system in KPICalc for each KPI

Testing and validation

Both KPIAdvisor and KPICalc have undergone alpha and beta testing in a number of Irish WWTPs. Alpha testing is an in-house testing phase undertaken by the toolkit developer in order to identify potential problems. The toolkit then proceeded to beta testing which involved using key stakeholders to test the system. Feedback, in particular from end-users, was crucial to the development of the system.

WWTPs Selection for Testing

In order to efficiently complete alpha testing on the toolkits, a number of Irish WWTPs were carefully selected with the intention of encompassing the various combinations of WWTPs which operate in Ireland. This step was important to ensure the toolkits' applicability across a range of WWTP sizes and types. Key Stakeholders including the Irish Environmental Protection Agency (EPA) government regulatory bodies and international advisors with a regulatory background and Irish WWTP operators, were involved in this WWTP selection process. These stakeholders identified a number of WWTP characteristics which have the potential to be troublesome in terms of data availability and sampling frequency. Key characteristics that impact on data availability include:

- centralised or decentralised WWTPs;
- large, medium or small-scale WWTPs in terms of population equivalent (PE);
- manned or un-manned WWPTs;
- discharge licence requirements;
- WWTPs capable of on-site sludge treatment.

With these critical characteristics in mind, WWTPs (a sample of which are detailed in Table 1), were selected due to their varied characteristics in order to provide an indication of the flexibility of the toolkits.

Table 1. Sample characteristics of the treatment plants selected for KPI analysis testing

WWTP	WWTPs A and B	WWTP C	WWTP D
Population Equivalent (PE)	20,000 – 30,000 PE	600 PE	300 PE
Treatment Technology	Activated sludge & chemical phosphorus removal	Activated sludge	Biofilm-based batch treatment system
Plant Type	Municipal	Municipal	Municipal and research facility
Location	Centralised	Decentralised	Decentralised
Operational Personnel	Manned	Unmanned	Unmanned
Discharge licence reporting requirements	Monthly	Monthly	N/A
Sludge Treatment	Yes	No	No

Data Validation

Load and regression testing is used as a means of data validation. It identifies the optimal frequency of data while detecting any bugs in the system which could lead to erroneous results. In terms of data validation, this research is focused on quantifying the operational costs behind extensive data collection versus the cost incurred from incorrect analysis resulting from an unacceptable frequency of data collection.

Analysis on the Varying Frequencies of Data Collection

Testing involved collecting required KPI data from WWTPs on a highly frequent basis and then applying the data, in various broken-down data frequencies to KPICalc toolkits to identify favourable and unfavourable data loading conditions in terms of producing accurate KPI analysis reports. A schematic shown above in Figure 4 provides a basic detailing of this testing phase.

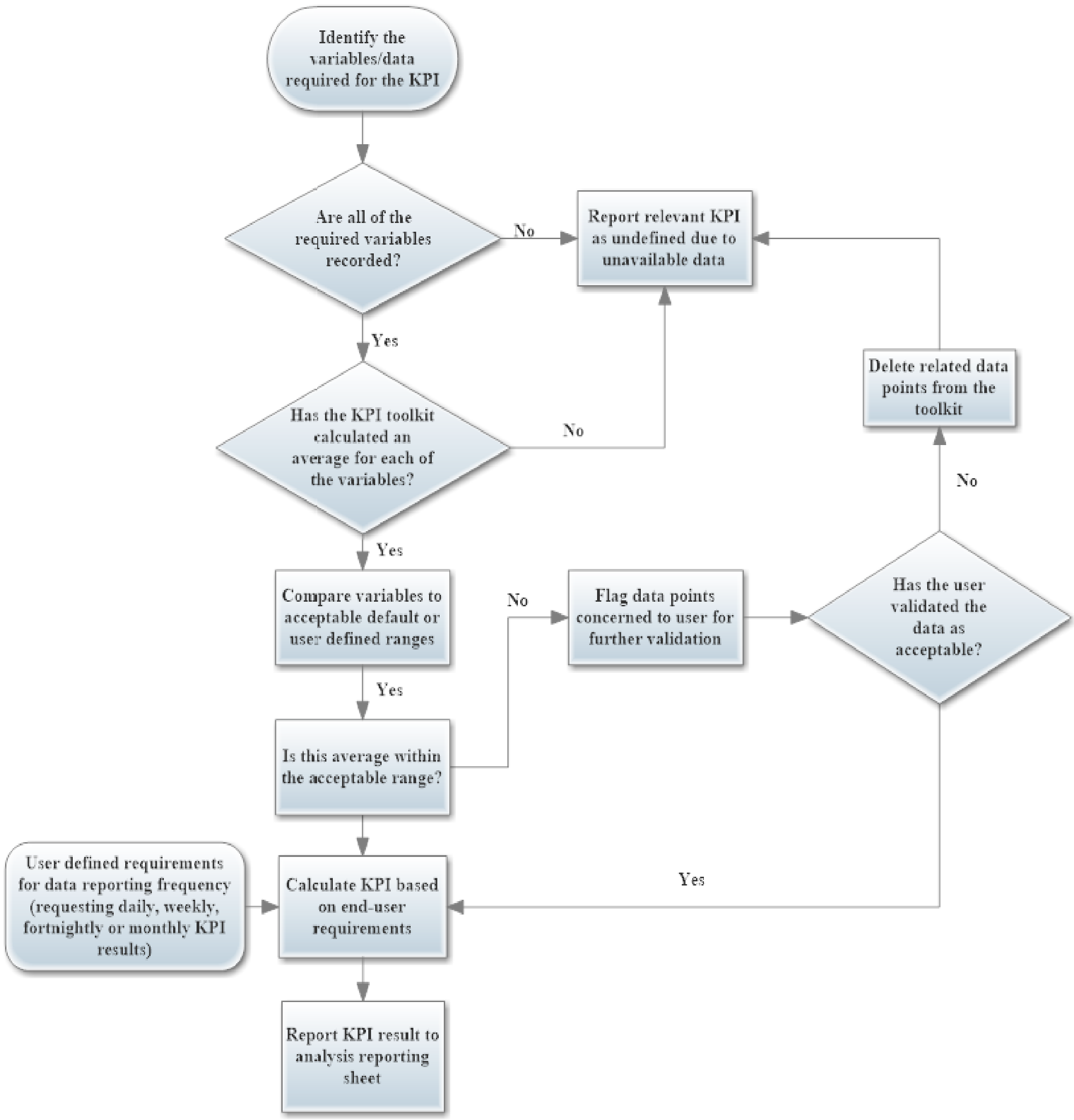

Figure 4. Methodology of load and regression testing

Testing which has taken place on one of the pre-selected WWTPs has identified a number of key factors which can affect the validity of data collected at different frequencies. Prior to testing it was hypothesised that a higher frequency of data (i.e. daily sampling) would result in more accurate KPI analysis than a lower frequency of data (i.e. monthly sampling).

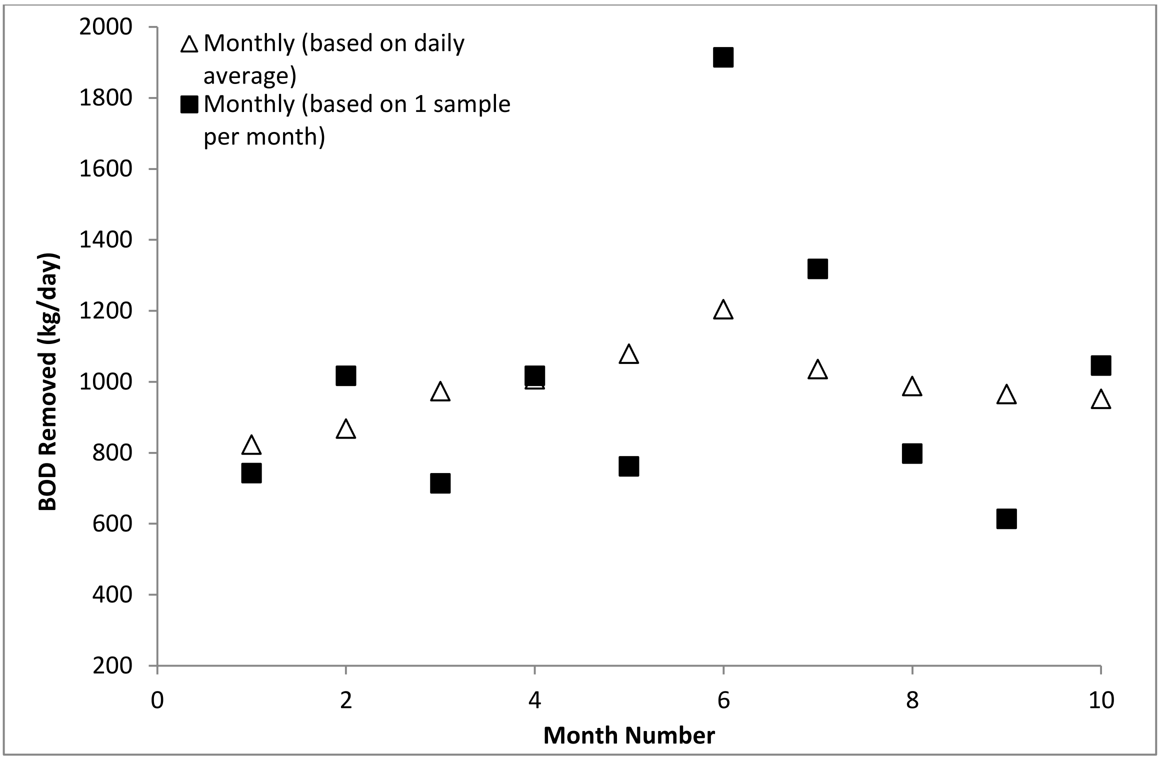

Figure 5. Graphed results from load and regression testing

Figure 5 shows results obtained from load and regression testing focused on one critical KPI, the Biological Oxygen Demand (BOD) removal rate. A monthly KPI result, such as this, can be calculated from either a single set of BOD samples per month, or BOD samples taken as frequent as one set per day.

As seen in the graph, a monthly KPI calculated form daily averages is shown to be of greater accuracy than KPIs calculated from a single sample per month. This is proven, quite simply, from the small deviation in monthly KPIs calculated on daily averages in comparison to the wide deviation between KPI results calculated using one monthly sample. However, it must also be noted that daily data collection is both costly and time consuming; therefore the advantages of undertaking daily data collection must be considered. A greater accuracy in KPI calculations may not offset the added cost and time required.

Further Findings for Data Validation

From load and regression testing, a number of key findings have come from this stage of testing including:

1. This research identified a major benefit to using load testing as a means of continuous commissioning of the toolkit once it is in place in a WWTP.

Through adopting a short period of intensive monitoring and KPI analysis, a WWTP manager or operator can gain extensive knowledge into a WWTP's performance on a macro level. This in-depth knowledge will allow for well-informed process optimisation measures to be realised and implemented. Also, continuous commissioning can be used as a method of reassessing a plants performance after process optimisation, offering a best practice to assessing its efficacy.

2. KPICalc has proven to remain stable in terms of its own operation in both manned and unmanned WWTPs where human interaction with the toolkit is minimal.

This stability is also noted for WWTPs of varying population equivalent and in small scale plants which do not have the same expansive process monitoring and data collection as large scale plants, which often collect data on a continuous basis.

3. Adopting a daily data collection regime would lead to highly accurate KPI analysis however; the incurred cost and amount of time which is required to complete intensive monitoring will generally offset the benefits of highly accurate KPI analysis.

In general terms, it is clear that the greater the frequency of data collection, the greater the chance of accurate KPI analysis. Testing has proven that the toolkit is capable of accurately achieving KPI analysis in WWTPs of varying characteristics.

Quantifying Usability of the Toolkit

Usability is a key element in any system that requires the user to input information and interact with a toolkits' processes. Ease of operation is paramount to the success of both KPIAdvisor and KPICalc. Feedback from stakeholders identified a number of key criteria for enhancing the usability (and thus impact) of benchmarking toolkits, including:

- the level of input and amount of time required to adapt a toolkit to suit the WWTP in which it's being applied;
- the ability of a system to competently assess data with minimal user input;
- ease of access to all relevant results, graphs and charts in a standardised format;
- influencing WWTP managers to fully adopt KPI analysis as an operational tool and also apply it to other WWTPs under their control.

To test KPICalc's level of usability, it was applied to the test WWTPs and also supplied to the key stakeholders. Stakeholders identified a number of features which they found highly beneficial – including:

1. The amount of operator training required for a user to become familiar with the user interface is minimal. This finding was connected to the means by which KPICalc is supplied (through a macro-enabled Microsoft Excel workbook).

2. Low levels of participation from the user is adequate for KPICalc to achieve acceptable and useful KPI results due to the high level of automation present in the KPI calculation and reporting stages.

3. Susceptibility to calculating incorrect KPIs based on incorrect data is reduced through semiautonomous data validation.

KPICalc cannot be completely autonomous due to the high-variability of wastewater treatment and the need for an expert opinion on the validity of certain groups of data. Stakeholders identified that the methods with which the toolkit validates data are beneficial as although it completes most validation automatically, data that falls outside of acceptable ranges is flagged for the user to assess manually, allowing the user to gain a more in-depth view of their WWTPs performance.

4. The layered nature of the toolkit's reporting section places operators in a highly favourable position.

Should a user require a general monthly KPI average, perhaps to include it in a report, the toolkit will automatically provide monthly averages. However, when the user requires in-depth analysis, as would be the case for decision making in terms of process control and optimisation measures, it is possible to view more detailed data analysis.

Discussion and Conclusions

This research paper has presented an approach to analyse wastewater treatment performance and resource consumption via benchmarking, and the use/development of relevant KPIs. The developed benchmarking toolkit can enable resource intensive WWTPs to reduce energy, chemical and water consumption to the minimum level required, in a practically viable manner. The novel resource benchmarking system (KPIAdvisor and KPICalc) developed in this research is:

1. Easily accessible, intelligent, and less time consuming to implement in comparison to other benchmarking systems.
2. Capable of being implemented in WWTPs of varying macro processes, population equivalent, staffing numbers and sampling frequencies.
3. Flexible in terms of the frequency of data collection it can handle, allowing WWTP managers to adopt periods of intensive monitoring in order to achieve continuous commissioning of a WWTP if desired.

The system also presents significant cost saving opportunities which could arise from reducing energy and water consumption. It also offers WWTPs a large incentive to opt into an international benchmarking scheme, which will assist in reducing the currently excessive global energy and water demand.

Future work on this KPICalc will involve increasing user-friendliness, data analysis reliability and a major reduction in human interaction requirements. Areas of future work include:

- Streamlining the KPI selection process to remove the requirement for selected KPIs from KPIAdvisor to be manually imported into KPICalc.

- Developing the toolkits as an add-on to pre-existing WWTP SCADA systems in order to remove the requirement for a user to manually input data and replace the process with a real-time data collection and KPI calculation add-on.

- Further beta testing on more WWTPS with varying macro processes and data reporting capabilities in order to obtain a more comprehensive view on the toolkits applicability to WWTPs.

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