Drinking water treatment plant assessment through performance indicators

P. Vieira, H. Alegre, M. J. Rosa and H. Lucas

ABSTRACT

Performance assessment (PA) of urban infrastructure services, mainly in the case of water systems, is becoming a major issue worldwide. Therefore, in the last decade, the need for a clear definition of management objectives of water services and the subsequent need to monitor goals achievement have led to the development of some initiatives to tackle the evaluation of the efficiency of those services, their main aim being the definition of systems of performance indicators. However, these PA systems are strongly oriented by a management/economic perspective and technical aspects have often been ignored. In addition, none of them has specifically addressed the drinking water treatment.

This paper presents a proposal for a PI system that applies to drinking water treatment facilities as a part of a standardised methodology for performance assessment. In total, *ca*. 80 PI have been defined and classified according to seven evaluation domains, namely: treated water quality; plant reliability; use of natural resources and raw materials; by-products management; safety; human resources; and, economical and financial resources.

Key words | drinking water, indicators, performance, treatment plant

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INTRODUCTION

Performance assessment (PA) of urban infrastructure services, mainly in the case of water systems, is becoming a major issue worldwide. In many countries, including Portugal, competition is low due to the monopolistic character of the water sector but the growing public awareness for environmental and cost issues related to water, together with the emerging trend for services privatization, has questioned this type of approach and provided incentive for efficiency improvement in water companies. Therefore, in the last decade, the need for a clear definition of management objectives of water services and the subsequent need to monitor goals achievement have led to the development of some initiatives to tackle the evaluation of the efficiency of those services, their main aim being the definition of systems of performance indicators.

A performance indicator (PI) is a quantitative measure of the effectiveness (extent to which the targeted objectives are achieved) and efficiency (extent to which resources of a water utility are utilised optimally to produce a service) of a specific aspect of the service delivered by a water supplier. Performance indicators are typically expressed as ratios between variables that may be commensurate (e.g. %) or non-commensurate (e.g. $\$/m^3$) (Alegre *et al.* 2006).

The most relevant PI systems developed for supply systems and for wastewater systems were those promoted by the International Water Association (IWA) (Alegre *et al.* 2000, 2006; Matos *et al.* 2003) and by the World Bank (World Bank 1999, 2006), but several others can be named, such as the "Six Scandinavian Cities Group" (Stahre & Adamsson 2002), the program QualServe from AWWA (Crotty 2003), the UK Ofwat scheme (Ofwat 2004) and a series of national projects that were modified versions of the IWA system.

In the drinking water sector, performance assessment has been carried out in the areas of drinking water production,

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storage and distribution. In these areas, several aspects for performance evaluation have been identified, varying from country to country, from utility to utility and depending on the specific objectives and on the different stakeholders involved in each case. In general, these aspects can be grouped in the following categories: economy and finance, technology, human resources and company organisation, quality of service (including quality of product) and environment. Correspondingly, the PI developed also fall in the same categories. The majority of existing PI systems has a strong component of economic and financial PI (e.g. Stahre & Adamsson 2002; Alegre *et al.* 2006; World Bank 2006) that usually correspond to common used ratios relating to profits, capital costs, investments, running costs, leverage, profitability and water tariffs. Financial agents, such as the World Bank, rely on this type of PI to assess investment priorities, select and follow-up investment projects (World Bank 2006). Technology related PI assess aspects of operation, maintenance and rehabilitation of facilities, water quality monitoring and water losses (Stahre & Adamsson 2002; Crotty 2003; Alegre *et al.* 2006).

The optimisation of human and organisational resources of the water utility is evaluated through organisational and personnel PI covering aspects such as availability, qualification, training, health and safety. These PI were considered by IWA (Alegre *et al.* 2006).

Of extreme importance for water suppliers, and also for regulators of the water industry, are the quality of service and quality of product PI due to the fact that these are directly health-related issues often with clear legislated restrictions. IWA, Worldbank and Ofwat (UK regulator) systems assess compliance of drinking water quality and the latter also focus on customer satisfaction, reliability and availability of the service provided by water utilities.

Environmental PI are considered by Crotty (2003), Alegre *et al.* (2006) to assess environmental impacts caused by water systems, water resources use and energy consumption.

From a process point of view, a water treatment plant (WTP) is similar to a chemical industry because, in both cases, raw materials are transformed in a final product through technological means. Another similarity is the quality control that the final product has to be submitted to. Standardised performance assessment through performance indicators is also currently practised in the chemical industry in the scope of Responsible Care initiative (ICCA 2005). This voluntary programme is based on 16 core PI and 11 optional PI that cover the following aspects: workers health and safety (fatalities and injuries resulting from working accidents), pollution prevention (emissions to air, discharges to water and hazardous waste), use of resources (energy and water), response to emergency situations, final product distribution (transport incidents). At present, industries in 52 countries (representing 90% of world chemical production) have implemented this PI system.

As can be seen from the state of the art, the research carried out worldwide so far has focused in producing indicators for a broad set of areas, for example environment, technology, economy, quality of service. However, these PA systems (PAS) are strongly oriented for a management perspective, and technical aspects have often been ignored. In addition, none of them has specifically addressed the drinking water treatment, key component of a water supply system. Actually, they only assess water quality related performance in terms of the "number of analysis complying with legislation". The most common problems faced today in drinking water treatment plants are non-optimised use of chemicals, operation of units processes, sludge production and energy consumption. In spite of this, the traditional approach for WTP efficiency evaluation is almost always based solely on legislation compliance of the treated water. A clear need therefore exists for research to focus on detailing PAS for treatment plants.

This paper presents a proposal for a PI system that specifically applies to drinking water treatment facilities as part of a standardised methodology for WTP performance assessment.

METHODOLOGIES FOR PI DEFINITION AND IMPLEMENTATION

Methodology for PI definition

The overall methodology followed in the definition of PI for WTP is depicted in Figure 1. As will be explained later, this methodology refers to the development of the PI system for general use and differs from the methodology to be followed

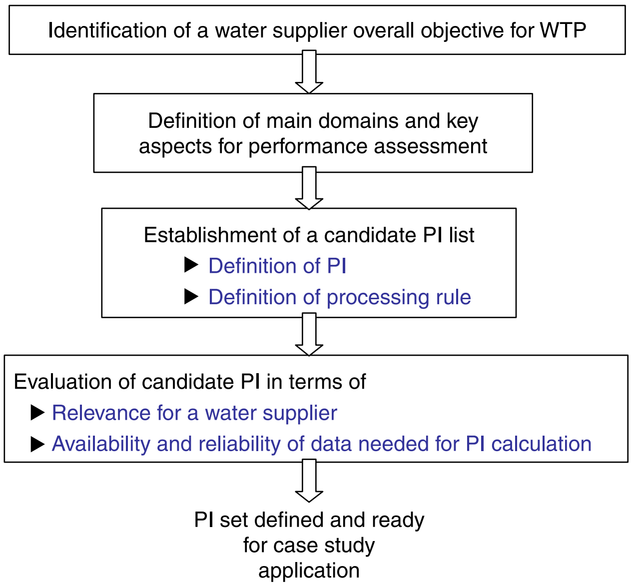

Figure 1 | Methodology for PI definition.

by any specific water supplier willing to use and implement the PI system in its own WTP.

The definition of PI was initially based on the overall objective identified as common to most WTP. This objective consists of producing water with efficiency and effectiveness, i.e. the WTP should produce water with adequate quality for human consumption, while making an efficient use of available resources (natural resources, technological resources, human resources, economical and financial resources) and causing the minimum environmental impact. Therefore, the following seven main domains with relation to which performance of a WTP should be assessed have been identified:

- treated water quality;
- plant reliability;
- use of natural resources and raw materials (water, energy, chemicals and others);
- by-products management;
- safety;
- human resources;
- economical and financial resources.

For each of the above mentioned evaluation domains, key performance aspects have been identified, as well as performance indicators that best translate each aspect into a quantitative measure. A first candidate list of PI was created and analysed, taking into consideration aspects such as PI relevance for a water supplier and availability of reliable data for their determination. PI for which data is not usually obtained during the regular operation of a WTP–and it is forecasted that the implementation of procedures for periodic data collection will not be cost effective–were not further considered. PI for WTP defined in this work comply with the general requirements already considered by the existing PI systems for water supply (Ofwat 2004; Alegre *et al.* 2006; World Bank 2006): to represent relevant aspects of the water supplier performance, to have a clear definition and unambiguous meaning, to have a simple processing rule, to give results easily verifiable, to be applicable to different types of water suppliers (e.g. different dimension or development stage), to be independent from each other, to be comparable with legal or other type of target values, to be suited for the final end-user, to require means to obtain raw data that are easily affordable.

The PI proposed in the present work follow the concepts and overall philosophy of IWA PI for water supply systems and they have been designed to be used as a complement to that system that details the component of the water treatment plant. The IWA system has been developed and extensively field tested since 1997 (69 water utilities from all the world in the scope of an international project and others in the scope of national projects in many countries) and is already a reference in the water industry with its directory of ca. 170 indicators. In order that end-users point of view is addressed, the WTP PI system has been developed in close cooperation with a Portuguese water utility (Águas do Algarve, S.A.).

Methodology for PI system implementation by an end-user

Although the starting point for the PI definition was the overall objective for a WTP, the final PI system was conceived and is structured to be as universal as possible so that it is applicable to any treatment plant and is useful for any water supplier regardless of its particular objectives. The set of PI presented here can be seen as a comprehensive portfolio of indicators that will be totally or only partially implemented in each specific situation. For this process of implementation of the WTP PI system, the water supplier

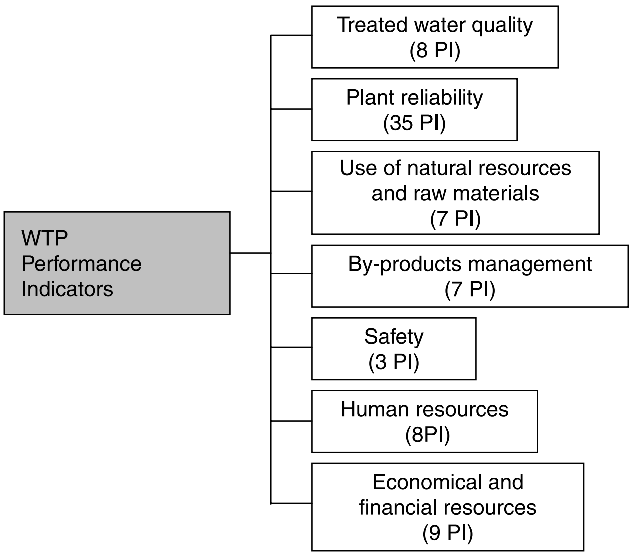

Figure 2 | Performance Indicators framework for drinking water treatment plants.

will have to: (i) clearly identify its own objectives; (ii) select PI from the complete PI set that are adequate to evaluate the achievement of the objectives; (iii) assess data availability for PI calculation; (iv) in those cases where data needed is not available but the PI is considered to be important for performance assessment, study (considering the cost benefit balance) the possibility to obtain additional data on a regular basis; (v) calculate PI and interpret the results.

RESULTS—THE PI SYSTEM FOR WTP

In total, ca. 80 PI have been defined and classified in seven categories corresponding to the seven evaluation domains (Figure 2). Detailed characterisation of each PI (objective, definition, processing rule, units of measurement, data required, results analysis, etc.) has been made elsewhere (Vieira *et al.* 2007). The structure of the PI system is presented in Tables 1–7.

Domain 'treated water quality' evaluates performance in terms of compliance with criteria established by the water utility for the water at the exit of the WTP and in terms of the WTP ability to produce water that has an adequate quality at the consumption point. Key aspects for performance assessment considered in this domain are the following: compliance with criteria for the water at the outlet of the WTP; maintenance of water quality in the distribution system after treatment. When analysing results in terms of the latter aspect, it should be kept in mind that a poor performance is not necessarily assigned to a poor performance of the WTP but may be due to problems occurring in the downstream distribution system. Eight PI assess all these aspects (Table 1).

Category 'plant reliability' evaluates performance in terms of WTP technological robustness (technology shall not fail and has to assure that the adequate contaminant removal efficiency is maintained over time) and in terms of flexibility of the WTP to respond to variations that occur in raw water. The 35 PI in this domain (Table 2) translate aspects such as: water source utilisation degree; infrastructure capacity; chemicals supply; continuity of operation; optimisation of chemicals dosage as a function of raw water characteristics; automation degree of the plant; process monitoring (online or not); alternative chemicals dosing; feasibility of accurate measure of chemicals dosages; existence of a periodic procedure of equipment inspection

Table 1 | PI from the evaluation domain 'treated water quality'

Performance aspect to be evaluated	No. of PI	PI example [units]
Compliance with water quality criteria at the exit of the WTP	3	WQ1–Compliance of water analysis [%] = (no. of treated water analysis complying with criteria defined by water supplier/no. of analysis performed) × 100
Maintenance of water quality in the distribution system	5	WQ4–WTP storage tanks cleaning [%/year] = ((volume of treated water storage tank cells that have been cleaned × 365/assessment period)/volume of treated water storage tank cells) × 100
		WQ5–Water quality at distribution system consumption points that have low chlorine concentration [mg/L] = Average of the 10% lowest values of free chlorine recorded in the distribution network

Table 2 | PI from the evaluation domain 'WTP reliability'

Performance aspect to be evaluated	No. of PI	PI example [units]
Water source utilisation adequacy	1	ER1–Water source utilisation [%/year] = ((volume of water at the entrance of the WTP × 365/assessment period)/total annual abstraction capacity of the source) × 100
Infrastructure capacity	12	ER2–Raw water storage capacity [day] = (volume of WTP raw water storage tanks × assessment period)/volume of water at the entrance of the WTP
		ER4–WTP utilisation [%] = volume of treated water/maximum WTP capacity
		ER8–Dosage capacity for chemicals (maximum doses) [%] = (maximum chemical flow used/maximum flow of the metering pump) × 100
Chemicals supply adequacy	1*	ER10–Chemicals supply [day] = stored quantity of chemical/chemical consumption
Continuity of operation	1	ER11–Daily period of WTP operation [h/day] = total of hours that the WTP operates/assessment period
Chemicals dosage optimisation	1	ER12–Adjustment of chemicals dosage to raw water quality variation [no./year] = no. of jar tests performed × 365/assessment period
Automation degree	4	ER13–Online water quality monitoring [no./UPO] = no. of sampling points with online water quality monitoring/(no. of UPO of the WTP + 1)
		ER16–Sludge discharge from settlers [%] = no. of settlers that have automatic sludge discharge/no. of settlers
Process monitoring	2	ER17–Water quality monitoring [no./UPO] = no. of sampling points for water quality monitoring/(no. of UPO of the WTP + 1)
Alternative chemicals dosing	1	ER19–Possibility of dosing alternative chemicals [−] = no. of dosing systems for chemicals not used in a regular basis/no. of dosing systems for chemicals used regularly during WTP operation
Feasibility of accurate measure of chemicals dosages	2	ER20–Chemicals dosing systems with changeable set point [%] = (no. of chemicals dosing systems with changeable set point/no. of chemicals dosing systems) × 100
Equipment inspection	4	ER22–Pump inspection [no./pump/year] = (no. of pumps inspections × 365/assessment period)/no. of pumps)
		ER23–Emergency equipment inspection [%/year] = ((sum of the nominal power of the emergency equipment subjected to inspection × 365/assessment period)/total nominal power of the emergency equipment) × 100
Filter inspection	1	ER26–Filter media inspection [no./filter/year] = (no. of filter inspections × 365/assessment period)/no. of filters) × 100
Equipment calibration	4	ER27–Flow meters calibration [no./meter/year] = (no. of flow meters calibrations × 365/assessment period)/no. of flow meters
		ER30–Online water quality meters calibration [no./meter/year] = (no. of online water quality meters calibrations × 365/assessment period)/no. of online water quality meters
Failures	3	ER31–Average time to solve a failure [h/failure] = total time spent to solve failures that led to treatment process interruptions > 30 min./no. of failures that led to treatment process interruptions > 30 min.
Reliability of energy supply system	2	ER34–Interruptions of WTP operation due to energy failure [h/year] = (no. of hours that the WTP was out of service or was operated with emergency energy supply, due to failure in the electricity supply × 365)/assessment period
		ER35–Energy autonomy [%] = (power of the emergency electric generator/total power of the equipment at the WTP) × 100

*Determined individually for each of the chemicals used at the WTP.
UPO: Unit process/operation.

Table 3 | PI from the evaluation domain 'Use of natural resources and raw materials'

Performance aspect to be evaluated	No. of PI	PI example [units]
Water consumption	2	RU1–Efficiency of water use at the WTP [%] = (volume of treated water/volume of water at the entrance of the WTP) × 100
Energy consumption	1	RU3–Energy consumption [kWh/m^3] = Energy consumption/volume of treated water
Chemicals consumption	3	RU5–Consumption of coagulants and flocculants [kg/m^3] = Total consumption of coagulants and flocculants/volume of treated water
Filter media consumption	1	RU7–Filter media refill [%/year] = ((quantity of filter media used for refill × 365/assessment period)/quantity of filter media of all filters) × 100

Table 4 | PI from the evaluation domain 'By-products management'

Performance aspect to be evaluated	No. of PI	PI example [units]
Waste production	3	BP1–Quantity of sludge generated [kg/(m^3.NTU)] = Quantity of sludge generated/(volume of water at the entrance of the WTP × raw water turbidity)
		BP2–Quality of sludge [% w/w] = Dry weight of produced sludge
Waste management	4	BP4–Final disposal of sludge [%] = (quantity of sludge subjected to valorisation/quantity of sludge generated) × 100
		BP5–Destination of waste that can be regenerated [%] = (quantity of exhausted waste that is regenerated/quantity of exhausted waste that can be regenerated) × 100
		BP7–Process wastewater without treatment that is discharged in the environment [m^3 wastewater/m^3 treated water] = volume of process wastewater discharged in the environment/volume of treated water

Table 5 | PI from the evaluation domain 'safety'

Performance aspect to be evaluated	No. of PI	PI example [units]
Chemicals spillage	1	S1–Chemicals spillage [kg/m^3] = Quantity of chemicals spilled/volume of treated water
Working accidents	2	S2–Working accidents [no./employee/year] = (no. of working accidents × 365/assessment period)/no. of full time equivalent employees of the WTP
		S3–Emergency response [h/emergency] = Total time elapsed between emergency detection and its resolution/no. of emergency situations

and calibration; existence of adequate resources for failures correction; failures occurrence and reliability of the WTP energy supply system.

'Use of natural resources and raw materials' indicators (Table 3) evaluate performance in terms of efficiency of use of WTP inputs: water, energy, chemicals and filter media.

The amount of process treatment by-products and the adequacy of corresponding management practices can have significant negative environmental impacts and are therefore assessed by seven PI from the category 'by-products management' (Table 4). Some by-products considered are process wastewater, sludge, filter media, exhausted ion exchange resins and granular activated carbon.

Category 'safety' evaluates, through three PI, the performance in terms of plant safety and environmental safety (Table 5). Key aspects are the occurrence of chemicals spillage, working accidents with WTP employees and the existence of means that allow a short response time when facing emergency situations.

Aspects such as the availability of personnel, the adequacy of personnel qualification and training, absenteeism and overtime work are assessed by eight 'human resources' PI (Table 6).

Table 6 | PI from the evaluation domain 'human resources'

Performance aspect to be evaluated	No. of PI	PI example [units]
Resources availability	1	Pe1–WTP personnel [no./m^3] = no. of full time equivalent employees of the WTP/volume of treated water
Personnel qualification	2	Pe2–Personnel with a university degree [%] = (no. of WTP employees with a university degree/no. of full time equivalent employees of the WTP) × 100
Personnel training	2	Pe4–Total training time [h/employee/year] = (no. of WTP employees training hours × 365/assessment period)/no. of full time equivalent employees of the WTP
Absenteeism	2	Pe6–Absenteeism [day/employee/year] = (no. of days of absenteeism of WTP employees × 365/assessment period)/no. of full time equivalent employees of the WTP
Overtime working	1	Pe7–Overtime work [%] = (hours of overtime work of the WTP employees/total hours of regular work of the WTP employees) × 100

Table 7 | PI from the evaluation domain 'economical and financial resources'

Type of cost	No. of PI	PI example [units]
Total costs	1	Fi1–Unit total costs [euro/m^3] = (running costs + capital costs)/volume of treated water
		Fi1 a–Unit running costs [euro/m^3] = Running costs/volume of treated water
		Fi1 b–Unit capital costs [euro/m^3] = Capital costs/volume of treated water
Composition of running costs per type of costs	5	Fi2–Internal manpower costs [%] = (internal manpower costs/running costs) × 100
		Fi3–Chemicals costs [%] = (chemicals costs/running costs) × 100
		Fi4–Electrical energy costs [%] = (electrical energy costs/running costs) × 100
		Fi5–Costs with transport, valorisation and final disposal of by-products [%] = (costs with transport, valorisation and final disposal of by-products/running costs) × 100
		Fi6–External services costs [%] = (external services costs/running costs) × 100
Composition of running costs per main technical function activity	3	Fi7–Operation costs [%] = (operation costs/running costs) × 100
		Fi8–Maintenance costs [%] = (maintenance costs/running costs) × 100
		Fi9–Analytical control costs [%] = (analytical control costs/running costs) × 100

Finally, 'financial resources' indicators (Table 7) are related to total annual costs; unit running costs; unit capital costs; manpower costs ratio; chemicals costs ratio; energy costs ratio; waste management costs; external services costs ratio; operation costs ratio; maintenance costs ratio and water quality monitoring costs ratio.

The calculation of PI is made for a time period previously defined, for example one year (other time frames can be chosen by the water supplier according to his management needs). This period is called 'assessment period' in the PI processing rules presented in the above tables. The variables required for PI determination can also refer to the same time period as the PI they will be used for (e.g. volume of treated water) or can be assessed for a reference date (e.g. number of employees) that, usually, corresponds to the last day of the assessment period.

As the performance of an individual plant may be dependent on the specific context of its activity, it was defined which context and explanatory information (information not used to calculate the indicators but that allows a correct interpretation of indicators and a fair comparison between different plants) should be collected (e.g. characteristics of raw water).

In the scope of this project, an Excel® spreadsheet application has been developed for automatic calculation of all variables from raw input data (screenshot in Figure 3a, in

(a) (b)

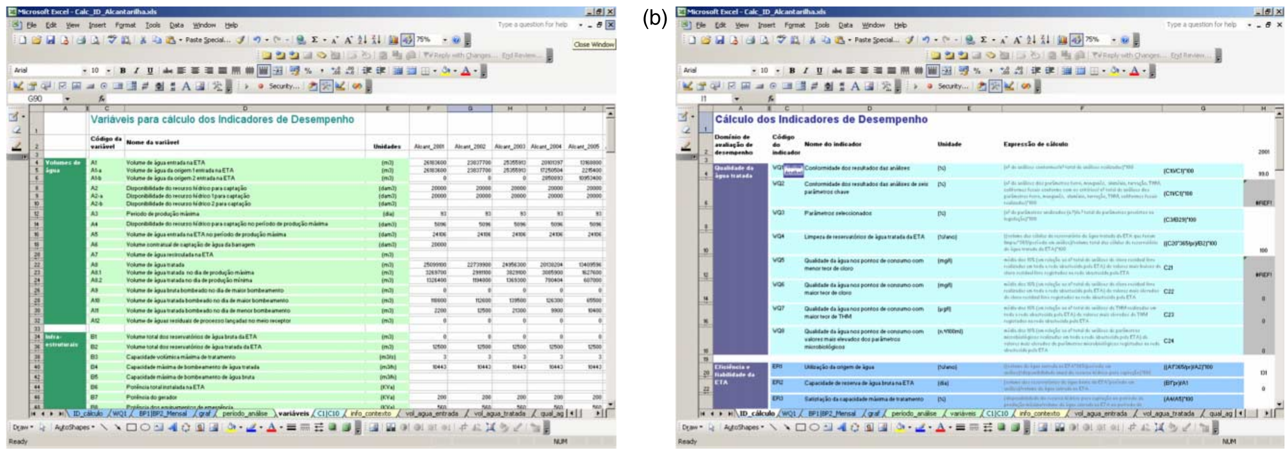

Figure 3 | Screenshots of the tool for PI calculation for WTP (PI_WTP_CALC.xls).

Portuguese) and of all PI from variables (screenshot in Figure 3b, in Portuguese). Charts of different types with PI results are also automatically generated.

CONCLUDING REMARKS

In this paper, a PI system for drinking water treatment plants was presented. These PI provide, in a systematic way, objective and quantifiable measures of the performance of a WTP. Furthermore, allow for comparisons between undertakings in the scope of benchmarking initiatives. PI are intended to asses the actual condition of the plant based on historical records and, due to its level of aggregation, are to be used more at a management level of the WTP. As this level of detail is not suitable to support decision at the technical level, an operational performance assessment system is being developed by the authors covering the aspects of overall and unit processes/operations efficiencies and their relation with operating conditions. The final Performance Assessment System for WTP will be formed by those two components: overall performance assessment (OvPA) and operational performance assessment (OpPA). To test its applicability and feasibility, OvPA has already been tested in full scale case studies that are four drinking water treatment plants from Águas do Algarve, S.A. The outcome from this field test has been presented in Vieira *et al.* (2008) and served as a basis for a refinement of the PI system. Application and validation of this revised PI to further selected case studies from other water suppliers is planned. Selected case studies will have different types of water sources, different treatment schemes, plant capacity, etc.

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