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Assessing the feasibility of a water treatment plant quality index

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ABSTRACT

This paper focuses on the development of a quality index applied to conventional water treatment plants (WTPQI) with the objective of providing a more consistent way of evaluating performance and comparing different plants. The methodology, based on the Delphi method, relies on the same principles used at the beginning of the 1970s in the formulation of the Water Quality Index (WQI). Afterwards, the WTPQI was applied to ten different Brazilian conventional water treatment plants, with horizontal sedimentation basins and variable sizes (average flow rates range from 100–4,300 $L\,s^{-1}$) and the results pointed out its usefulness as an instrument for plant evaluation. A significant correlation between plant performance and the WTPQI values was confirmed based on the filtered water turbidity, mainly for the rainy season when the raw water quality becomes harder to reach compliance with the drinking water standards. Therefore, these results open up the perspective of the use of the WTPQI as a reliable tool for the management of water supply systems.

Key words | Delphi method application, water treatment plant evaluation, water treatment plant index

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INTRODUCTION

Water treatment plant evaluation

The intervening factors on the performance of water treatment plants basically refer to (i) the suitability of the raw water characteristics for the treatment process, (ii) the ratio between the inflow rate and the water treatment plant capability and, probably the most important, (iii) the operational accuracy. Furthermore, the global evaluation of a plant must consider the finished water quality, which is strongly related to the dosage and the type of coagulant, the filter runs and the possibility of short circuits, among other factors. However, some factors are intangible. For example, how is it possible to ensure the adequacy of some coagulant, and its respective dosage and coagulation pH, for a specific natural water flowing into a specific water treatment plant?

This multiplicity of factors has brought many difficulties to the professionals' attempt to set up a reliable hierarchy among them. This hierarchy would define more accurately the priorities for water supply system managers in terms of operation and/or enlargement of water treatment plants. Consequently, the water treatment plants' evaluation has frequently been performed based only on the compliance with drinking water standards.

In this context, the option of a quality index was justified by the use of easily available data related to the physical characteristics and the operational routine of the plant. It will allow a better comprehension by the population (such as the Water Quality Index (WQI) does) because, in many situations, the professionals responsible for the application of financial resources do not have a clear knowledge about the water treatment processes. The mentioned public comprehension will help the use of the Water Treatment Plant Quality Index (WTPQI) as a tool for enhancing people's consciousness towards the good

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performance of water treatment plants, and minimizing, in a second instance, the outbreak risks through drinking water.

Besides these factors, an index will serve as a more accurate identifier of operational failures and as a comparing quantity among different conventional plants. In the latter case, an index will be useful for prioritizing the financial resources for expanding old plants as well as building new ones.

The index development

Informing the population on data and on parameters of water treatment plants is not an easy task. However, this is not a question restricted to this specific area. There have been many efforts attempting to synthesize in a single value the meaning of a dataset.

Brown *et al.* (1970) employed the Delphi method to develop the WQI based on the opinions of 142 water quality specialists. This research was composed of three questionnaires. In the first, a list with 35 randomly selected parameters was sent to the specialists. For each parameter, the respondents had to choose among three options: *included*, *not included* and *undecided*. It was possible to include other parameters that were absent in this first list. The respondents had to assign values from 1 to 5 for each parameter selected as *included*.

The results of this first round were sent to the respondents with the second questionnaire, thus allowing the respondents to compare their responses and, occasionally, re-evaluate them. A list including the 15 most important parameters was also requested from the respondents. In the third questionnaire, for each one of the nine selected parameters, the respondent had to draw a curve which, in his/her judgment, depicted the best way to represent the influence of this parameter in water quality. The nine average curves employed to define the WQI were a combination of the responses of all respondents. Among 142 specialists invited in the first round, 94 (66%) returned the first questionnaire in time to take part in the second round and, from this group, 82% completed and returned the second questionnaire.

Based on this methodology, Nagels *et al.* (2001) proposed an index system to assess the recreation water quality in New Zealand. Also, they used the Delphi method to summarize the judgment of 18 specialists from consulting engineering, environmental management companies, research institutes and universities. The research was composed of two phases. The first, with four questionnaires, had the objective of defining the list of parameters that would be included in the index. In the second phase, with three questionnaires, the respondents were asked to draw the curves for each parameter as a function of its relevance to the recreation water quality. Finally, the respondents were asked about their agreement with the final curves.

In a similar context, Taylor & Ryder (2003) utilized the Delphi method to define a management plan of 25 multiple-use reservoirs. This information concerned basically the necessary water levels to guarantee the survival of fish. Questionnaires were elaborated for each reservoir and were sent to 26 specialists. The number of respondents by reservoir varied from 2 to 8. The same specialist was allowed to answer questionnaires related to more than one reservoir. The first questionnaire had questions about a list of the more vulnerable species and the period that each species was particularly sensitive to the variations of the reservoir level. In the second questionnaire, the specialists re-valuated their responses by contrasting it with the opinion of the entire group. A return of 85% was achieved, along with a high convergence of opinions, for all reservoirs.

The information collected constituted a significant component of the development of a support decision model for reservoir management. The research showed the applicability of the Delphi method to deal with several pieces of information related to the management of complex environmental questions. The innovation of this research was the final definition of the index. Distinctive to the WQI, the weights were not established for each parameter and the index of a specific water source was the lowest value extracted from these curves. The justification was based on the fact that an aggregation of many individual scores could hide a low value of a specific water quality parameter.

OBJECTIVE

According to these concepts, this paper proposes a WTPQI as a tool for the water supply system administrations to evaluate the water treatment plant performance and to make more precise comparisons among different plants. Additionally, the paper proposes:

(i) to list the intervening parameters on the performance of water treatment plants;
(ii) to define a hierarchy for these parameters according to their role in the plant performance;
(iii) to validate the WTPQI based on the operational daily data of ten conventional water treatment plants with different sizes;
(iv) to define the best formulation for the WTPQI between the sum and product forms.

METHODS

The present work can be defined as applied research and its scope was restricted by the conventional water treatment plants which have coagulation, flocculation, sedimentation, filtration and disinfection steps with horizontal sedimentation basins. These plants have to be able to treat typical raw water in order to produce filtered water turbidity lower than 0.5 NTU and an effluent with the absence of total coliform, in compliance with the Brazilian Drinking Water Standards. The conventional water treatment process has been used for surface waters all over the world and, particularly in Brazil, more than 3,000 plants have been supplying more than half of the Brazilian population (a total of about 190 million people).

The methodology to formulate the WTPQI was similar to the one used to develop the WQI. In such a way, after the establishment of all parameters, and respective weights and grading criteria, two different formulations were defined, in terms of the sum and product forms:

$$\mathrm{WTPQI} = \sum_{i=1}^{N}\left(\sum_{j=1}^{n} WjQj\right)_i \quad (1)$$

$$\mathrm{WTPQI} = \prod_{i=1}^{N}\left(\prod_{j=1}^{n} Q_j^{Wj}\right)_i \quad (2)$$

in which:

Wj: weight rated to each parameter established by the specialist judgment;
Qj: score obtained by a specific water treatment plant for each parameter selected according to the developed criterion;
j: each parameter included in the index;
i: each group of parameters to comprise the index such as rapid mix, flocculation, sedimentation, filtration, disinfection, and operational factors;
n: number of parameters included in the index;
N: total number of groups of parameters that will constitute the index.

The methodology for the development of the WTPQI was divided into three phases, i.e. opinion research, definition of the grading criteria and the index validation.

Opinion research

Opinion research was carried out to select the intervening parameters to be included in the WTPQI, with their respective weights. A panel of 18 professionals with expertise in water treatment was chosen at this stage, and 16 completed and returned both questionnaires. The panel was composed by experts responsible for research, design and operation of water treatment plants, involving universities, sanitation companies and consulting engineering from six Brazilian states, located in the two most developed and densely inhabited regions. Additionally, most members of the panel have got PhDs in sanitary engineering with an emphasis in water treatment.

This research was constituted in two different phases, according to the Delphi method characteristics. Initially, a preliminary list of 22 intervening parameters in water treatment was drawn up, as shown in Table 1.

The first part of the questionnaire presented an introduction explaining all phases of the research and showing to the participant their role in it. The second part contained the instructions for correctly filling in the questionnaire. Finally, the third part was constituted by the preliminary list of the parameters (Table 1) to which the respondent should assign one of the following categories: *included*, *not included* and *undecided*. Also, he/she could suggest additional parameters absent in the first list. After his/her judgment, the respondent should attribute a grade (up to 100) only to those parameters marked *included* according to their relevance to water treatment.

Table 1 | Parameters included in the first questionnaire

G_{RM}	Rapid mix velocity gradient	V_T	Flow-through velocity
T_{RM}	Rapid mix detention time	Q_L	Weir loading rate
Jtest	Routine realization of the jar test	*Tfilt*	Filtration rate
Gf	Flocculation velocity gradient	*Fr*	Filter run
Tf	Flocculation time	*Exp*	Filter bed expansion
Gp	Velocity gradient through the ports of flocculator	*Vupf*	Upflow water wash velocity
Nc	Number of the compartments of the flocculator	*Lair*	Washing with auxiliary air scour
Gps	Velocity gradient through the ports of sedimentation basin	*Lwater*	Washing with auxiliary surface water system
Vc	Average velocity in the flocculated water channel	*Tc*	Detention time in the clearwell
Gb	Velocity gradient through the inlet baffle of sedimentation basin	*Nch*	Number of compartments of the clearwell
Vs	Settling velocity (sedimentation surface loading rate)	*IL*	Instruction level of the operational staff

At the end of the first phase, a report was written with a numerical summary of the responses of all participants. This report contained as well the inclusion percentage of each parameter, the average, the median, the mode, the first and third quartiles, and an abstract of the commentaries, the participant's responses and a column to review their initial responses. Following the analysis of the entire group's opinion, the respondents were asked to review their responses.

The parameters included in the index were divided into six groups according to the steps of the conventional water treatment processes such as rapid mix, flocculation, sedimentation, filtration, disinfection and operational quality. Anchored in the weights rated for the parameters by the panel, the weight of each group was determined as a function of treatment effectiveness. The main reason for the separation into groups was the possibility of summarizing a complete index considering the weights of each step of the water treatment. In such a way, it would be possible to identify which group is responsible for the eventual low grading of the plant.

Development of the grading criteria

After the definition of the parameters included in the index and their respective weights, the next phase was to establish the grading criteria for each parameter based on the suitable limits or intervals set up by the technical literature and by the Brazilian Technical Standards Association (1990).

Validation of the WTPQI

The final phase was composed of a comparative study among the final value provided by the index and the filtered water turbidity data, both related to a specific plant. The scope of this last phase was to choose the final formulation of the index, either sum or product, and to verify the index validation. In other words, the scope was to define whether or not the water treatment plant assigned to a high WTPQI would present a good performance based on the filtered water turbidity.

Although some parameters of the WTPQI are not related to filtered water turbidity, in many circumstances the protozoa removal is associated with the number of particles of plant effluent and this parameter is usually monitored in practically all Brazilian water treatment plants. Furthermore, this same parameter was applied as a performance indicator to 10-year data, involving 75 water treatment plants in Pennsylvania (USA). The main conclusion of this research pointed out the noticeable relevance of an intangible factor, the operational staff commitment so as to ensure the high finished water quality (Lusardi & Consonery 1999).

With this objective, the developed index, in both forms, was applied to ten conventional water treatment plants of the two most important Brazilian states with an average flow rate ranging from 100–4,300 $L\,s^{-1}$. These plants were selected according to the availability and the reliability of the monitoring data provided by the respective operational staffs. For all plants selected, the filtered water turbidity monitoring was carried out on the combined filter effluent according to the Brazilian Drinking Water Standards.

The comparison between the WTPQI and the filtered water turbidity was performed based on six months' data (three months of the drought season and three months of the rainy season). The following values were calculated for each season, according to the Brazilian and American Drinking Water Standards:

- percentage of time operation in which the plant produced filtered water turbidity ≤ 0.5 NTU;
- percentage of time operation in which the plant produced filtered water turbidity ≤ 0.3 NTU;
- percentage of time operation in which the plant produced filtered water turbidity ≤ 0.1 NTU;
- value lower than 95% of the filtered water turbidity values.

In this sequence, scatter plots with the WTPQI on the horizontal axis and one of the previous values on the vertical axis were developed for each season and each plant. For verifying whether or not the WTPQI was correlated to the filtered water turbidity values, linear and nonlinear correlation coefficients were calculated. This analysis focused on assessing whether or not the reduction of the WTPQI was followed by higher filtered water turbidity levels.

RESULTS AND DISCUSSION

Definition of the weights for each parameter

A return of 89% of 18 questionnaires was achieved in the first round of the research. During this phase, the questionnaires were printed and mailed to the respondents. In the second phase, the return was 94% and the questionnaires were sent by electronic mail due to a clear preference of several respondents for this method.

The justifications and comments related to the first questionnaire were sent to the respondents in the second round, with the objective of showing their opinions to other participants. No parameter listed in the first questionnaire (Table 1) was dismissed and, among the parameters suggested by the respondents, none was inserted in the second round because the necessary information about them was not available or the parameter was very subjective. For example, some suggestions were proposed related to the general situation of the laboratory, the plant versatility, among others. Besides that, no new parameters had been suggested by more than three respondents.

As mentioned earlier, the respondents were instructed to assign values from 0 to 100 only for the selected parameters marked *included*. This rating system was chosen in order to make easier the procedure of filling in the questionnaires because, otherwise, in the case of the participant being asked to distribute 100 points among the parameters, the procedure would be slow and the absence rate would increase. However, in the context of this research, it was relevant to account for the relative importance of each parameter and the weight assigned by the respondent in proportion to the total points distributed by him/her. Therefore, the final score of each parameter was divided by the total points distributed by the respondent, thus summing up to 100. The relative importance of each parameter in terms of global performance of the water treatment plants is depicted in Figure 1.

By observing the vertical bars shown in Figure 1, it is possible to relate the highest ranges among the responses to the most significant parameters, emphasizing the agreement of the respondents concerning their relevance, in spite of a clear disagreement in terms of the weight to be assigned. According to the panel, the filtration rate (*Tfilt*) is the most relevant parameter, accounting for about 9% of the performance, thus agreeing with the tendency of the national and international water drinking standards to

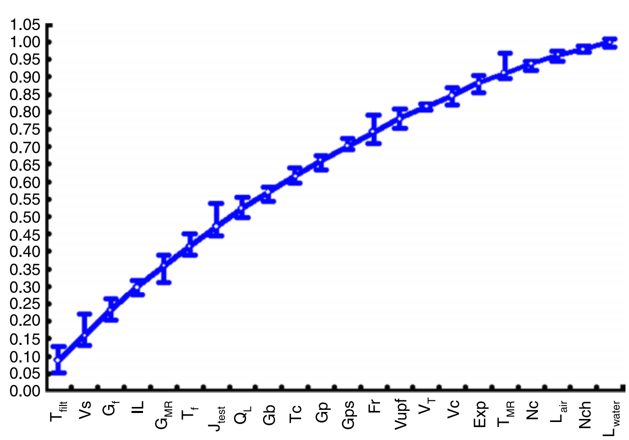

Figure 1 | Accumulated median of the weights for each parameter.

Table 2 | Final weights of the 19 parameters

Group	Parameter	Weight	Group	Parameter	Weight
Rapid mix	G_{RM}	0.06	Filtration	*Tfilt*	0.09
	T_{RM}	0.03		*Fr*	0.04
Flocculation	*Gf–Tf*	0.14		*Exp/Vupf*	0.04
	Gp	0.04		*Laux*	0.03
	Nc	0.03	Disinfection	*Tc*	0.05
	Vc	0.03		*Nch*	0.02
Sedimentation	*Gps*	0.04	Operation	*Jtest*	0.07
	Gb	0.05		*IL*	0.06
	Vs	0.08			
	V_L	0.04			
	Q_L	0.06			

reduce, as mentioned in *Methods*, the filtered water turbidity and its role in protozoa removal. According to the respondents, the settling velocity or surface loading rare (*Vs*) and the flocculation velocity gradient (*Gf*), with the filtration rate, were responsible for 23% of the plant efficiency.

Based on these results, the weights for determination of the WTPQI would have to be defined. In this context, the best way to reduce scatter in the results was evaluated. Perhaps other rounds could help reach a higher convergence. Nevertheless, this was not an option due to the time that would be expended in a new round. Moreover, it should be noted that there was little change expressed in the second questionnaire and several respondents did not modify their scores. So, two important decisions were taken to define the final weights: (i) to avoid the influence of extreme points, the median was chosen as the best measurement of the group opinion and (ii) to include all parameters by multiplying their weights by the inclusion rate of each parameter. In this way, the weights were kept for the parameters with 100% inclusion rate, while the other parameters had theirs reduced.

For the development of the grading criteria some parameters were unified. As an example, the *Lair* and *Lwater* parameters were transformed in only one parameter named *Laux* (auxiliary wash), the weight of which was defined as the median of the weights assigned to both. The same procedure was defined for the group of *Exp* and *Vupf* parameters because the inclusion of both would be overrating the same aspect related to the bed filter wash. Finally, the last transformation was to divide each weight by the total score. In such a way, all weights summed up to 1.00. The final weight of each parameter is shown in Table 2.

Development of the grading criteria

After the definition of weights for each parameter the grading criteria were established. In reality, this definition is a substitution of the mentioned curves drawn by the respondents for the WQI. In this phase, the parameters were divided into six groups: *Rapid Mix, Flocculation, Sedimentation, Filtration, Disinfection* and *Operation.*

Then, for example, the simplest criterion was defined for the parameter *Jtest* that was evaluated for each water treatment plant whether the jar test was routinely done or

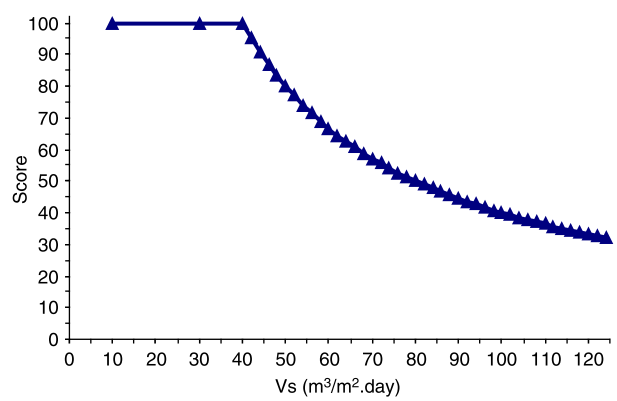

Figure 2 | Grading criterion for the *Settling velocity* (*Vs*).

Table 3 | Partial example of the WTPQI determination for one of the ten plants sampled

Group	Parameter	Daily data median	Score (Qj)	Weights (Wi)	Weights × score ($Wi \times Qj$)	Score^{weight} (Qj^{Wi})	Score by group (sum.)	Score by group (prod.)
Rapid mix	G_{MR} (s^{-1})	1,341	100	0.06	6.00	1.32	9.00	1.52
	T_{MR} (s)	0.40	100	0.03	3.00	1.15		
Flocculation	G_F (s^{-1})	35.2	30	0.14	4.20	1.61	9.04	2.09
	T_F (s)	836						
	Type of flocculator	Hydraulic						
	Gp (s^{-1})	55.11	1	0.04	0.04	1.00		
	Nc	5	60	0.03	1.80	1.13		
	Vc ($m.s^{-1}$)	0.29	100	0.03	3.00	1.15		
Sedimentation	Gps (s^{-1})	19.3	100	0.04	4.00	1.20	25.24	3.40
	Gb (s^{-1})	8.2	100	0.05	5.00	1.26		
	Vs ($m^3\,m^{-2}\,d^{-1}$)	43.5	80	0.08	6.40	1.42		
	V_L ($cm\,s^{-1}$)	0.26	100	0.04	4.00	1.20		
	Q_L (L/s.m)	1.64	100	0.06	6.00	1.32		
Filtration	$Tfil$ ($m^3\,m^{-2}\,d^{-1}$)	279.7	100	0.09	9.0	1.51	17.03	2.17
	Filter run ($m^3\,m^{-2}$ run filter^{-1})	475.3	100	0.04	4.0	1.20		
	Washwater volume ($m^3\,m^{-2}$ filter^{-1})	6.06						
	$Exp/Vupf$	32	100	0.04	4.0	1.20		
	$Laux$	None	1	0.03	0.03	1		
Disinfection	Residual chlorine ($mg.L^{-1}$)	0.87	10	0.05	0.5	1.12	1.5	1.21
	Tc (min)	1.47						
	Disinfection pH	$\leq$7.0						
	Nch	1	50	0.02	1	1.08		
Operation	IL	Graduated	100	0.07	7.00	1.38	13	1.82
	$Jtest$	Routinely	100	0.06	6.00	1.32		
WTPQI							74.8	51.6

Table 4 | Coefficients of linear correlation (*R*) and determination (R^2) for both forms of WTPQI

		Rainy season					Dry season				
Filtered water turbidity (NTU)		≤0.1	≤0.3	≤0.5	≤0.7	95%	≤0.1	≤0.3	≤ 0.5	≤0.7	95%
WTPQI sum	*R*	0.37	0.55	0.80	0.85	−0.62	−0.05	0.33	0.47	0.48	−0.50
	R^2	0.14	0.30	**0.63**	**0.73**	0.38	0.00	0.11	0.22	0.23	0.25
	p	0.37	0.16	**0.02**	**0.01**	0.10	0.90	0.39	0.21	0.20	0.17
WTPQI product	*R*	0.56	0.85	0.73	0.69	−0.86	0.38	0.21	0.25	0.24	−0.23
	R^2	0.31	**0.73**	**0.53**	0.48	**0.74**	0.14	0.04	0.06	0.06	0.05
	p	0.15	**0.01**	**0.04**	0.06	**0.01**	0.31	0.60	0.51	0.53	0.55

not. In this context, this score of a plant for this specific parameter will be 100 or zero because it is impossible to ensure how well done the jar test has been carried out.

Concerning the hydraulic parameters, in order to be brief, among 16 parameters, only the *Settling Velocity* (from the group *Sedimentation*) will be explained. Its grading criterion was defined based on the ratio Vs'/Vs, considering *Vs* the actual settling velocity of a specific plant and Vs' the highest settling velocity set up by the Brazilian Technical Standards Association (40 $m^3\ m^{-2}\ d^{-1}$ or 2.78 $cm\ min^{-1}$). From the design rate, a progressive increase of 5% was established with a respective reduction of the score as shown in Figure 2. In this way, the plants with their sedimentation basins operating with settling velocities lower than 40 $m^3\ m^{-2}\ d^{-1}$ received the maximum score (100).

Application of the WTPQI

Finally, after the definition of the weights and the grading criteria, the final phase of the research was to apply the WTPQI, in both forms (Equations (1) and (2)), to the ten water treatment plants. An example of the determination of the WTPQI is presented in Table 3.

The results presented in Table 3 confirm the supremacy of the WTPQI sum and allow us to see that the score of *Vs* (80) was obtained based on the grading criterion illustrated in Figure 2.

After the WTPQI determination, the main point was the final choice between the product or sum forms for the WTPQI equation. The distinction between both equations was focused on the possibility of a plant with a low grade, for a specific parameter, has its final score more significantly affected when the product form is utilized. Plants with a more uniform grading among the parameters tend to keep the final score approximately unchanged for both formulations. The main question is: is only a parameter with a low score able to justify the option for the product form of the WTPQI equation?

For a better comparison among the obtained values, the coefficients are shown in Table 4, highlighting the more significant results (R^2 and *p* value) and also including the correlation with the percentage below 0.7 NTU, as an intermediary value between the maximum level (1.0 NTU) and the recommended level (0.5 NTU) by the Brazilian Drinking Water Standards.

Certainly, the WTPQI role is more crucial during the rainy season, when usually the plant limitations, physical and operational, become more evident due to the raw water quality. In this context, it is possible to observe that the product form yielded more significant results for the filtered water turbidity percentage lower than 0.1 and lower than 0.3 NTU, and the value higher than 95% of turbidity data. The number of parameters involved in the WTPQI and the use of a single water quality parameter (filtered water turbidity) indicate the significant magnitude of coefficients of determination explaining up to 74% of its variance. Also, the number of plants (10) does not weaken the feasibility of the index mainly due to, as mentioned in *Methods*, the reliability of operational data and the physical characteristics of these plants.

On the other hand, the sum form has showed more significance for the percentage lower than 0.5 and lower than 0.7 NTU. In the dry season, despite the better results with the sum form, the WTPQI values were correlated with higher *p* values. However, this fact does not restrict its application in actual scale due to the decrease of the relevance of the plant operation at this period of the year because, usually, it is easier to comply with the limits set up by the drinking water standards as a result of the better raw water quality.

Finally, considering the parameters listed in Table 2, it is important to consider two out of three parameters not related to the inflow rate and the physical characteristics of the plant: *Jar test* and *Instruction level*. In a subjacent way, these parameters are strongly associated with some important operational variables such as the suitable type of coagulant, the optimum coagulation pH and the coagulant dosage or the use of a coagulant aid or filter aid (usually a synthetic organic polymer). However, in a broad point of view, it is practically infeasible to previously evaluate the adequacy of the coagulation conditions due to the distinct raw water characteristics but a plant with a higher WTPQI probably is able to produce a highest finished water quality all through the year.

CONCLUSIONS

Focusing on the parameters' hierarchy, the questionnaires demonstrated an evident consensus about the higher relevance of some parameters in water treatment effectiveness. According to the clear tendency of the national and international standards, which has been progressively emphasizing the reduction of the filtered water turbidity as a reliable way to optimize protozoa removal, the filtration rate was chosen by the panel as the most relevant parameter.

The correlations confirmed the principles established for the grading criteria for the 19 parameters and the WTPQI product appeared as a good indicator to inform the plant's hierarchy. Despite the modest number of water treatment plants (10), the reliability of the dataset and the significant correlation coefficients pointed out a tendency of the plants that yield good filtered water quality to usually present high WTPQI values. This tendency is clearer, mainly for the WTPQI product, when more restrictive standards were established, and for the rainy season when the raw water quality makes the compliance with the drinking water standards harder. Nevertheless, for plants with higher scores in all parameters, the final WTPQI is approximately the same for both formulations. Therefore, the WTPQI product may be a useful tool for the water supply system administration to accurately identify the operational failures if, in a water treatment plant, a higher WTPQI is associated with a poorer filtered water quality.

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