Applying reliability analysis to evaluate water treatment plants

ABSTRACT
The aim of this study was to demonstrate the applicability of reliability analysis to a water treatment plant (WTP). Data from daily monitoring of raw and finished water quality from a direct filtration WTP covered the parameters of turbidity, apparent colour, pH, aluminium, chlorine and fluoride, from December 2007 to August 2011. Data analysis included descriptive statistics and adherence tests to normal, log-normal, rectangular, exponential and gamma distributions. A reliability analysis was conducted in three steps: (i) estimation of mean values for monitored parameters based on the established percentage of compliance and comparison with observed mean; (ii) estimation of expected percentage of compliance based on observed mean values and comparison with the observed percentages; and (iii) evaluation of the applicability of reliability analysis to parameters with upper and lower limits. When the comparison between estimated and observed percentages of compliance was made, reliability analysis led to inaccurate results for parameters whose observed percentage of compliance remained below 90%. For parameters whose observed percentage of compliance tended to fullness, deviations were not observed. It is believed that such a conclusion can be extrapolated to estimated mean values: most accurate results are obtained for parameters that have percentages of compliance near 100%.

INTRODUCTION
Performance evaluation
Performance evaluation has been recognized as a way to introduce competitive pressures in markets (Corton 2003). The use of a measure of performance forces the search for more efficient management and improvement in relation to other companies. In addition, performance evaluation can still be seen as a necessity deriving from technical aspects inherent to operation of water treatment plants (WTP). The increased demand for water, the deterioration of natural water quality and the establishment of more restrictive progressive targets for drinking water quality usually require the enlargement and modification of WTP.

The performance evaluation before and after such changes can indicate the level of effectiveness and success (or failure) resulting from these actions.
However, due to the numerous variables involved in the processes it is not easy to evaluate the performance of WTP. The variation of raw water quality and performance of one stage of treatment can affect performance of the following steps, making the evaluation of WTP a more complex problem. The evaluation can be done either by processes, considering each stage of the WTP, or by system, analyzing only the influent and effluent. The first way is recommended to be used by service providers, especially for treatment control, while the global analysis is used by regulatory, normative and legislative agencies.
**Water quality targets**

The World Health Organization (WHO) has as one of its initiatives the development of guidelines relating to drinking water. The guide published by WHO (2001) aims to support the establishment of drinking water standards, good practices of operation for water supply systems and the development and implementation of strategies to manage health risks in many countries (WHO 2004). Another organization is the United States Environmental Protection Agency (USEPA), which sets standards for drinking water considering the health risks associated with each contaminant followed by recommended treatment technologies. Further, USEPA compiles data on water quality, providing public information, technical assistance and inspection of water quality control programmes (USEPA 2004).

In order to protect public health, legislation that set standards for drinking water quality are becoming increasingly strict. In Brazil, drinking water standards are established by Regulation 2914/2011 (Brazil 2011), with physicochemical and organoleptic features resulting in 85 water quality parameters, a number that has increased over the years as shown in Figure 1.

This Regulation establishes the maximum of 0.5 NTU for turbidity with progressive goals: 25% of compliance in the first year, 50% in the second, 75% in the third and 95% in the fourth year after its promulgation. However, the authors believe that a large majority of WTP in Brazil is not ready to meet these more rigorous standards recently established. The limit values and bands for some parameters of finished water quality are shown in Table 1.

The establishment of limits followed by percentages of compliance requires detailed knowledge of the behaviour of these parameters. WTP should be designed to accommodate the variability of natural water quality to ensure that the targets will be met during a given period of time. The use of probabilistic methods to establish standards is a realistic and practical approach from an operational viewpoint (Oliveira & von Sperling 2008). As an example, the standard of turbidity after filtration established by the cited Regulation 2914 is defined by absolute values accompanied by percentages of compliance which sets progressive targets applied from the end of 2012. In this context, tools such as reliability analysis assume importance, since they can greatly contribute to performance evaluation of WTP.

**Reliability analysis**

WTP can be evaluated from three main aspects: reliability, robustness and resilience. Reliability is the probability that a WTP meets the drinking water standards or self-imposed threshold targets over a specific period of time. Robustness can be defined as the plant capacity to produce high quality finished water, meeting the drinking water standards, despite the raw water quality and operational conditions. Resilience is the speed at which a WTP returns to its former performance (producing high quality finished water) after a failure usually due to a sudden worsening of raw water quality or an operational problem, for example, an interruption of coagulant dosing (Zhang et al. 2012).

To determine a mean value of concentration which ensures that effluent concentration is below the target, according to a certain percentage of time, Niku et al. (1979) developed a method that relates the mean concentration of the parameter (design or desired value) to the target (required value), based on probabilistic analysis. This method has been widely used to evaluate the performance of waste WTP (Niku et al. 1981, 1982; Niku & Schroeder 1982).

![Figure 1](https://iwaponline.com/ws/article-pdf/14/4/634/415717/634.pdf)
Some aspects that must be observed in the use of reliability analysis are as follows:

- The method is highly sensitive to the distribution of values of the parameter analyzed (Niku et al. 1981), being suitable only for data that follow a log-normal distribution.

- Results tend to be most reliable when samplings are taken regularly and with relatively short intervals, providing data which ensure representativeness of the process. Thus, it is possible to assume that the percentage of samples that complies with the standard is equal to the fraction of time that the operation is satisfactory (level of reliability).

- The calculation of the required mean value to meet the desired level of reliability not always competes for values lower than the target. Low coefficients of variation (CV) associated with low percentage of compliance can lead to achievement of a coefficient of reliability (COR) greater than the unit and, therefore, required means greater than the targets.

- Once the reliability analysis relies on the probability of compliance to a maximum value, the compliance regarding minimum values cannot be ensured when the parameter under study has, at the same time, upper and lower limits.

### Objective

In this context, the main objective was to demonstrate the applicability of reliability analysis to a direct filtration WTP as a tool to complement the performance evaluation. The specific objectives were: (i) to estimate the mean values for some parameters based on the desired percentage of compliance and comparison with observed mean values, (ii) to estimate the expected percentage of compliance based on observed mean values and comparison with the observed

---

**Table 1 | Water quality standards established by Brazil, United States and WHO**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Brazil</th>
<th>United States</th>
<th>WHO$^{a,*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total coliforms</td>
<td>Absent in 100% of samples$^a$</td>
<td>Absent in 95% of samples (No. samples &gt; 40)$^j$ Present in just one sample (No. samples ≤ 40)$^j$</td>
<td>Absent in 100% of samples</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Maximum of 1.0 NTU$^b$ and 25% &lt; 0.5 NTU in 2013 50% &lt; 0.5 NTU in 2014 75% &lt; 0.5 NTU in 2015 95% &lt; 0.5 NTU in 2016</td>
<td>Maximum of 1.0 NTU$^j$ and 95% &lt; 0.3 NTU$^j$</td>
<td>Maximum of 5.0 NTU</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Between 0.2 mg L$^{-1c}$ and 2.0 mg L$^{-1d}$ Maximum of 5.0 mg L$^{-1e}$</td>
<td>Maximum of 4.0 mg L$^{-1j}$</td>
<td>Maximum of 5.0 mg L$^{-1}$</td>
</tr>
<tr>
<td>Apparent colour</td>
<td>Maximum of 15 HU$^e$</td>
<td>Maximum of 15 HU$^j$</td>
<td>Maximum of 15 HU</td>
</tr>
<tr>
<td>Fluoride</td>
<td>Between 0.7 mg L$^{-1f}$ and 1.0 mg L$^{-1}$ Maximum of 1.5 mg L$^{-1j}$</td>
<td>2.0 mg L$^{-1j}$ Maximum of 4.0 mg L$^{-1j}$</td>
<td>1.5 mg L$^{-1}$</td>
</tr>
<tr>
<td>pH</td>
<td>Between 6.0 and 9.5$^h$</td>
<td>Between 6.5 and 8.5$^j$</td>
<td>- $^j$</td>
</tr>
</tbody>
</table>

$^a$In the effluent of WTP, established in Annex I of Regulation 2914 (Brazil 2011).
$^b$Established in Annex III of Regulation 2914.
$^c$In the distribution network, established in Article 34 of Regulation 2914.
$^d$Recommendation in the second paragraph of Article 39 of Regulation 2914.
$^e$In the distribution network set out in Annex X of Regulation 2914.
$^f$Recommended range, Table 1 of Regulation 635 (Brazil 1975).
$^g$In the distribution network, established in Annex VII to Regulation 2914.
$^h$Range established in the first paragraph of Article 39 of Regulation 2914.
$^i$Primary Standard (National Primary Drinking Water Regulations) (USEPA 2009).
$^k$WHO (2011).
$^l$Not considered as hazardous to health at the levels commonly found in drinking water.
percentages, and (iii) to verify the applicability of reliability analysis to parameters with upper and lower limits.

**METHODS**

**Object of study**

The WTP studied started operation in 1986 and employs direct filtration with pre-flocculation. The design flow rate is 6.00 m$^3$/s$^{-1}$ and the mean flow rate in 2011 was 4.44 m$^3$/s$^{-1}$. Due to the raw water quality, coagulated water flows sometimes directly to the filters. The chemicals used are aluminum sulfate and anionic polymer (coagulation), chlorine gas (disinfection), hexafluorosilicic acid (fluoridation) and lime (pH adjustment). Filter backwashing is carried out with air and water and the washing water outflow is practically negligible due to the recirculation of the effluent from the wastewater treatment unit, at a rate of less than 5% of the inflow rate.

**Parameters of finished water quality**

Data collection comprised the mean daily records of turbidity, apparent colour, pH and free chlorine, aluminum and fluoride residuals relative to the period December 2006 to August 2011. The analysis of parameters was performed according to recommendations of the *Standard Methods for the Examination of Water and Wastewater* (APHA et al. 1998). Monitoring of filtered water turbidity was carried out using a continuous flow turbidimeter.

The descriptive statistics of the parameters (mean, median, minimum, maximum, standard deviation and coefficient of variation) were determined and presented in tables and box-plot graphs. As the adopted method is suitable only for data that follow log-normal distribution and is extremely sensitive to the distribution function of the parameters (Niku et al. 1981), the Kolmogorov–Smirnov test was used to verify adherence to normal, log-normal, gamma, exponential and rectangular distributions at the significance level of 5%. For the case in which the parameter fitted more than one distribution or none, histograms were used to select the best fit by visual comparison.

**Application of reliability analysis**

Reliability analysis takes account of the variability of the parameters of finished water quality inherent to the operation of the WTP. The COR allows the performance target ($X_T$) to be related with a required mean value ($X_R$), according to Equation (1). The calculation of the variable COR was carried out using Equation (2). Considering a WTP that should produce effluent with apparent colour below 15 HU ($X_T$) for 95% of the time (reliability level or percentage of compliance), and relating to the CV of 90%, the reliability analysis will result in a COR of 0.38. So the mean value of the apparent colour in finished water should be equal to 5.7 HU ($0.38 \times 15$) in order that the target is met for a desired percentage.

$$X_R = \text{COR} \cdot X_T$$

$$\text{COR} = \sqrt{(CV^2 + 1)} \cdot \exp \left[-Z_{(1-\alpha)} \cdot \sqrt{\ln (CV^2 + 1)} \right]$$

in which $X_R$: mean value required; COR: coefficient of reliability; $X_T$: performance target; CV: coefficient of variation; $\alpha$: probability of failure (unmet target); $Z_{(1-\alpha)}$: reduced central normal variable corresponding to the probability of compliance. It takes the values of 2.326 ($Z_{99\%}$), 1.645 ($Z_{95\%}$), 0.674 ($Z_{75\%}$), zero ($Z_{50\%}$) and $-0.674$ ($Z_{25\%}$).

In the first stage, estimated mean values were compared with the observed mean values. The limit values ($X_T$) for application of reliability analysis were 1.0 and 0.5 NTU for turbidity, 15 HU for apparent colour; 6.0 to 9.5 for pH; 0.2 mg L$^{-1}$ for aluminum, 2.0 mg L$^{-1}$ for chlorine, and 1.5 mg L$^{-1}$ for fluoride. The reliability levels used were 50, 75, 95 and 99%. In the second step the reverse procedure was carried out: from the observed mean the expected percentage of compliance was determined through Equation (3), and this was compared with the observed percentage of compliance

$$Z_{(1-\alpha)} = -\frac{\ln \left(\frac{\text{COR} \cdot \frac{1}{\sqrt{(CV^2 + 1)}}}{\text{COR} \cdot \frac{1}{\sqrt{(CV^2 + 1)}}} \right)}{\sqrt{\ln (CV^2 + 1)}}$$
Although some parameters such as pH, free chlorine and fluoride are not suitable for reliability analysis due to the two limits of compliance, upper and lower, they were included in the reliability analysis in order to observe what losses their inclusion could lead to in the evaluation. Deviations were measured by differences between the estimated and observed percentages of compliance.

RESULTS AND DISCUSSION

Evaluation of finished water quality

The descriptive statistics are presented in Table 2 and Figure 2. The raw water quality presents compatibility with the technology of direct filtration, as observed by the low turbidity and apparent colour. Despite the peaks of turbidity and colour achieved, 35.95 NTU and 50.67 HU, respectively, the occurrence of extreme values was rare. The pH was the most stable parameter, as shown by the amplitude (6.12 to 7.46) and the coefficient of variation (8%). In general, the water quality presented can be explained by the fact that the intake was from a large dam, a lentic environment that favors the natural sedimentation of suspended solids.

For finished water, the mean and median values of parameters remained below the targets, however, considerable and punctual violations occurred for turbidity and chlorine. The parameters with the greatest variation were colour and turbidity. Possibly, the peaks of turbidity and colour are reflections of observed variations of raw water quality influent to the WTP.

Adhesion tests

The results of the adhesion tests are shown in Table 3. The Kolmogorov–Smirnov test does not show adherence of any parameter to any one of the distributions tested. The exceptions were the parameters pH and fluoride that were fitted to the log-normal and gamma distributions. Even with these results, the analysis was followed in order to identify which distribution could better represent the behaviour of the data. Comparisons were made visually through histograms. In a general evaluation, the distribution closer to the behaviour of parameters was log-normal, required for reliability analysis.

Application of reliability analysis

The results of reliability analysis are presented in Figure 3. There is peculiar behaviour when there is a high CV, such as when turbidity (96%) and apparent colour (119%), are associated with levels of reliability lower than 50%.

Table 2 | Descriptive statistics of monitored parameters

<table>
<thead>
<tr>
<th>Statistic</th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (m³ s⁻¹)</td>
<td>127</td>
<td>3,948</td>
<td>3,892</td>
<td>3,422</td>
<td>4,571</td>
<td>333</td>
<td>8</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>1,682</td>
<td>9.18</td>
<td>7.67</td>
<td>2.20</td>
<td>35.95</td>
<td>5.6</td>
<td>61</td>
</tr>
<tr>
<td>Apparent colour (HU)</td>
<td>1,682</td>
<td>19.77</td>
<td>18.17</td>
<td>4.82</td>
<td>50.67</td>
<td>9.0</td>
<td>46</td>
</tr>
<tr>
<td>pH</td>
<td>1,682</td>
<td>6.78</td>
<td>6.78</td>
<td>6.12</td>
<td>7.46</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>Finished water</td>
<td>Turbidity (NTU)</td>
<td>1,734</td>
<td>0.70</td>
<td>0.48</td>
<td>0.19</td>
<td>5.85</td>
<td>0.7</td>
</tr>
<tr>
<td>Apparent colour (µC)</td>
<td>1,734</td>
<td>1.38</td>
<td>1.00</td>
<td>1.00</td>
<td>14.33</td>
<td>1.6</td>
<td>119</td>
</tr>
<tr>
<td>pH</td>
<td>1,734</td>
<td>7.19</td>
<td>7.19</td>
<td>6.65</td>
<td>7.80</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>Aluminum (mg L⁻¹)</td>
<td>1,572</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.11</td>
<td>0.0</td>
<td>64</td>
</tr>
<tr>
<td>Chlorine (mg L⁻¹)</td>
<td>1,734</td>
<td>1.62</td>
<td>1.62</td>
<td>1.26</td>
<td>2.44</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>Fluoride (mg L⁻¹)</td>
<td>1,734</td>
<td>0.79</td>
<td>0.79</td>
<td>0.60</td>
<td>1.00</td>
<td>0.1</td>
<td>8</td>
</tr>
</tbody>
</table>

CV: coefficient of variation.
such cases, the resulting mean value of apparent colour is greater than the unit, leading to required means greater than the targets. Except for turbidity, all observed means remained distant and below the required means, indicating a high percentage of compliance (level of reliability).

In Figure 4 estimated and observed percentages of compliance are presented. The magnitude of the differences for turbidity, limit of 1.0 NTU (16%) and 0.5 NTU (6%), and fluoride (5%) cannot be ignored, leading to the belief that non-adherence to log-normal distribution was crucial for the observed deviations. For the other parameters (apparent colour, pH, aluminum and chlorine), although no differences were observed between the estimated and observed percentages, it cannot be said if non-adherence to log-normal distribution interfered significantly or not, since they are close to full compliance.

Therefore, based on these results, it appears that the lack of adherence to the log-normal distribution led to inaccurate
results in reliability analysis where the observed percentage of compliance was below 90%. Such behaviour puts into question the validity of the calculated required mean values. If estimated percentages do not resemble those observed, it is believed that observed mean values will hardly result in the percentages of compliance pre-established (desired).

Regarding the parameters pH and chlorine, with upper and lower limits, no definite conclusions could be made about the adequacy of reliability analysis. At least for high percentages of compliance, it was found that estimated and observed values were similar for pH (100%), chlorine (99%) and, respectively, 100 and 95% for fluoride. It is recommended that comparison of observed and estimated percentages of compliance be made from other databases with lower values of compliance providing a wider range of study.

CONCLUSIONS

Except for turbidity, all observed means remained distant and below the estimated required means under established percentages of compliance. This can be taken as an indicator of high reliability and high compliance with standard water quality. The good results are related to the fact that the intake was from a large dam, a lentic environment that favors the natural sedimentation of suspended solids, contributing to reduce turbidity and apparent colour, and lowering chlorine demand at the disinfection stage, facilitating dosage control.

Comparison between expected percentage of compliance (based on observed mean values) and observed percentages, for the parameters turbidity and fluoride, resulted in differences that must not be ignored. Probably, non-adherence to log-normal distribution was crucial for
the observed deviations. For the other parameters (apparent colour, pH, aluminium and chlorine), no differences were observed between the estimated and observed percentages. However, as they are close to full compliance, it cannot be said if non-adherence to log-normal distribution interferes in the case of low percentages of compliance. If estimated percentages do not resemble those observed, it is believed that observed mean values will hardly result in the percentages of compliance pre-established (desired).

Regarding the parameters pH and chlorine, with upper and lower limits, no definite conclusions could be made about the adequacy of reliability analysis. At least for high percentages of compliance, it was found that estimated and observed values were similar for pH, chlorine and fluoride. It is recommended that comparison of observed and estimated percentages of compliance be made from other databases with lower values of compliance providing a wider range of study.

Overall, it was found that reliability analysis is a very interesting and useful tool for performance evaluation of WTP. The results arising from it are practical and easily associated with monitoring variables (mean concentrations) and indicators (percentage of care) used in the daily routine for operating WTP. The limits of application still need more comprehensive studies, but it has much to contribute to the progress of knowledge in this area of study.

ACKNOWLEDGEMENTS

The authors thank CNPq, Capes and Fapemig for financial support and the Federal University of Minas Gerais (UFMG) for the infrastructure provided.

REFERENCES


enhanced surface water treatment rule (lt1eswtr) implementation turbidity provisions (epa 816-r-04-007). washington, dc.


who 2004 world health organization. guidelines for drinking-water quality. 3rd edn. who, geneva.

who 2011 world health organization. guidelines for drinking-water quality. 4th edn. who, geneva.

zhang, k., achari, g., sadiq, r., langford, c. h. & dore, m. h. i. 2012 an integrated performance assessment framework for water treatment plants. water research 46 (6), 1673–1683.

first received 2 december 2013; accepted in revised form 24 february 2014. available online 8 march 2014