DETERMINATION AND ANALYSIS OF DAILY RELIABILITY LEVEL OF MUNICIPAL WASTEWATER TREATMENT PLANT

Détermination et analyse du niveau quotidien de fiabilité d'une station de traitement des eaux usées résiduaires

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RESUME

Cette étude présente une détermination et l'analyse du niveau quotidien de fiabilité d'une station de traitement des eaux usées résiduaires utilisant un procédé à boue activée dans l'Est de l'Algérie, on utilisant une méthodologie développée par Niku et al. (1979) pour la détermination du coefficient de fiabilité (CdF), pour les concentrations effluentes de la DBO_5, de la DCO, et des MES obtenus à partir des données de quatre ans d'opération (2009-2012). Nous avons calculé le Coefficient de fiabilité, et les normes algériennes de rejet pour déterminer le niveau quotidien de fiabilité pour les paramètres considérés.

Les résultats ont prouvés en global un bon niveau de performances puisque les concentrations de la DBO_5 et la DCO des eaux traités présentent une conformité avec les normes de rejet en Algérie, par contre le niveau de performance des MES est très médiocre dues aux problèmes par l'arrêt du troisième dessableur-déshuileur, et la grande variabilité des quantités et de la qualité des eaux usées.

MOTS-CLES: Eaux usées, station de traitement, analyse, fiabilité quotidienne, concentration des effluents, boues activées.

ABSTRACT

This paper presents a determination and analysis of daily reliability level of activated sludge wastewater treatment plant in Eastern of Algeria, using a method developed by Niku et al (1979) for determination of coefficient of reliability (COR), for effluent concentrations of BOD_5, COD, and TSS obtained from four years data operation (2009-2012). We calculated COR, and using Algerian standards concentrations we have determined a daily reliability level for the considered parameters.

The results showed that in global effluent BOD_5 and COD performances are in terms of compliance with the Algeria standards, effluent TSS performances are not enough good due to the problem in grit chamber, and the large variability of the influent quantity and quality.

KEYWORDS: Wastewater treatment plant, analysis, daily reliability, effluent concentration, activated sludge

1 INTRODUCTION

The reliability of a system can be defined as "the probability of achieving adequate performance for a specific period of time under certain conditions" (Chorafoas, 1960) or as "the ability to perform the specified period of time under specified operation requirements free from failure". For treatment plant performance, some more specific definition is proposed: "the percent of time that effluent concentration meets specified permit requirements" (Metcalf and Eddy, 2003; Kottegoda and Rosso, 2008).

The fundamentals of reliability engineering can be applied to quantification of the probability that undesirable events may occur. Consequently, reliability based analysis of wastewater treatment plants allows the engineer to exploit the statistical structure of influent and effluent data in order to predict the probability of undesirable events. The variable nature of both influent quantity and quality during the design life of the facility may result in deviations from predicted design efficiencies. However, targeted effluent levels (or thresholds) should be selected for daily operation purposes. Those thresholds could be backed with accepted probability of consistently achieving these values (Ellis et al., 1993).

Taking into account Metcalf and Eddy (2003) and Kottegoda and Rosso (2008), a WWTP will be completely reliable if, despite a failure to comply with the set discharge thresholds, there is no violation of the limits prescribed by environmental standards and regulations. Mathematically, a treatment plant is completely reliable if there is no failure in process performance (e.g., discharge requirement violation).

The interest of the study stems from the lack of research on the reliability of activated sludge treatment technologies since Niku et al. (1979) focused on the processes of activated sludge and Niku et al. (1982) in trickling filters. In the literature, no study performed a quantitative analysis of the reliability of WWTP using activated sludge treatment technologies.

This article present the mathematical background proposed by Niku et al. (1979) and implement it for assessing the reliability of Khenchela city (WWTP) (Eastern Algeria) and for stepping to a first assessment of critical components of the waste water treatment process.

2 THEORETICAL BACKGROUND

The reliability of a WWTP is based on knowledge of the process behaviour. Due to the time variability in both quantity and quality of influent, the treatment plant should be designed to discharge and effluent, which selected treated effluent quality parameters should remain below a set discharge threshold. Niku et al. (1979) developed a method based on a probabilistic analysis to determine this threshold. Their method relates the average concentration of a parameter with the threshold value to be met. This method has been used and recommended in two important textbooks (Crites and Tchobanoglous, 2000; Metcalf and Eddy, 2003) and used or consulted by several authors in the last 25 years (Quek et al., 1995; Etnier et al., 2005; Gupta and Shrivastava, 2006).

Failure of treatment plant process occurs when required standards set to the discharged effluent are exceeded (Al Saleem, 2007). Niku et al. (1979) modelled the failure by the following simple equation:

$$F = C_e > C_S \tag{1}$$

where:

F: failure;

C_e: selected treated effluent quality parameter concentration;

C_S: selected treated effluent quality parameter concentration requirement set by standards.

From a technical point of view, the essential concept of reliability is "probability of success" or "probability of adequate performance", which is the percentage of time that selected treated effluent quality parameters concentration comply with the requirements (Niku et al., 1979):

$$R = 1 - P(F) \tag{2}$$

where:

R: Reliability;

P(F): probability of failure.

From equation (1), the value of R is equal to:

$$R = 1 - P(C_e > C_S) \tag{3}$$

The probability of failure is extremely sensitive to the probability distribution function of the selected treated effluent quality parameters concentration. Therefore, once this distribution law is known, an analytical expression can be used to process the fraction of time that a given concentration was exceeded in the past. Assuming that the process settings and controlling parameters are kept unchanged, that expression can be used to predict future behaviour of an WWTP (Dean and Forsythe , 1976a).

The threshold (m_x) set for a given treated effluent quality parameter average constituent may be derived from the equation:

$$m_X = COR \times C_S \tag{4}$$

where

m_x: average concentration of the constituent; regulation for a selected treated effluent quality parameter concentration;

COR: coefficient of reliability.

Niku et al. (1979) propose to process the coefficient of reliability (COR) using the following mathematical model:

$$COR = (Cv_X^2 + 1)^{1/2} \times e^{\left\{-Z_{1-\alpha}\left[\ln(Cv_X^2+1)\right]^{1/2}\right\}} \tag{5}$$

where

Cv_X: coefficient of variation (standard deviation divided by the mean) for selected treated effluent quality parameter concentration (identified by the suffix X);

$Z_{1-\alpha}$: Standardized normal variate (obtained from the standard normal variates tables) corresponding to the probability of no exceedance at a confidence threshold of (1-α);

α: significant level.

The theoretical material exposed here above was used to quantify the daily reliability of Khenchela WWTP (Eastern of Algeria). It was implemented using daily measured values of concentrations of selected parameters used for tracking the treated effluent quality.

3 APPLICATION TO THE ASSESSMENT OF THE RELIABILITY OF KHENCHELA CITY WWTP

3.1 Characterization of probability distribution law for selected treated effluent quality parameters

3.1.1 Preliminary statistics used for verification of data distribution

The reliability model of the theoretical approach of Niku et al. (1979) was designed to model data according to a lognormal distribution. Therefore, the first step to take is to determine the actual probability distribution laws of the selected treated effluent quality parameter for Khenchela city (WWTP). The quality of the treated effluents discharged by the WWTP has been studied using three parameters widely used for WWTP discharges: Five Day biochemical oxygen demand (BOD5), chemical oxygen demand (COD), and total suspended solids (TSS).

Table 1: Statistic parameters of effluent BOD_5, COD, and TSS concentrations. Khenchela WWTP (2009).

	BOD_5 (mg/l)	COD (mg/l)	TSS (mg/l)
Average	32.06	62.70	33.32
Standard deviation	17.15	37.66	31.04
Coeff. of variation	53.49%	60.06%	93.15%
Minimum	13.0	13.0	11.0
Maximum	99.0	164.0	363.0
Range	86.0	151.0	352.0
Stnd. skewness	7.956	2.719	37.823
Stnd. kurtosis	12.707	0.720	181.792

The coefficients of skewness and kurtosis presented in Table 1, were used for a preliminary check of data normality for treated effluents discharged by Khenchela city WWTP, as suggested by Pearson et al (1977), D' Agostino and Stephens (1986), D' Agostino et al. (1990), Helsel and Hirsch (1992). The asymmetry coefficient (stnd. Skewness) is a measure of deviation or distance from the symmetry of a distribution having a value close to zero when the distribution curve is symmetrical and tends to be positive when the distribution is skewed to the right. The coefficient of kurtosis measures the degree of curvature or flatness of a distribution. For a normal distribution, the kurtosis value is close to the value of three.

3.1.2 Distribution laws for concentrations of selected parameters used for tracking the treated effluent quality

Variability of concentrations for selected parameters used for tracking the treated effluent quality can be shown and analyzed by determining the histogram and probability density function of each concentration. Figure 1, 2, and 3 present an example of one year (2009) historical data histograms and the Probability Distribution Function (PDF) of the effluent BOD_5, COD, TSS concentrations of Khenchela WWTP.

As shown in Figures 1, 2, and 3 the data are generally not symmetrical and are skewed to the right, which is consistent with table 1 results (Standard skewness).

Normal, lognormal, and gamma distribution laws for concentration of BOD_5, COD, and TSS were tested. The tests used to check the goodness-of-fit of these effluents concentrations data were, Kolmogorov-Smirnov (D), Cramer-Von Mises (W^2), Anderson Darling (A^2), and Watson (U^2). For normal and lognormal distributions, Kolmogorov-Smirnov test has considerable higher power than Chi-squared test (D'Agostino and Stephens, 1986; Wondruff and Moore, 1988). The "software" used to perform the tests was STATGRAPHICS Centurion XVI.I.

The probability plots of the effluent BOD_5 concentration, effluent COD concentration, and effluent TSS concentration for Khenchela WWTP are shown on Figure 5, 6 and 7. The "software" used to perform the plots was MINITAB 16.

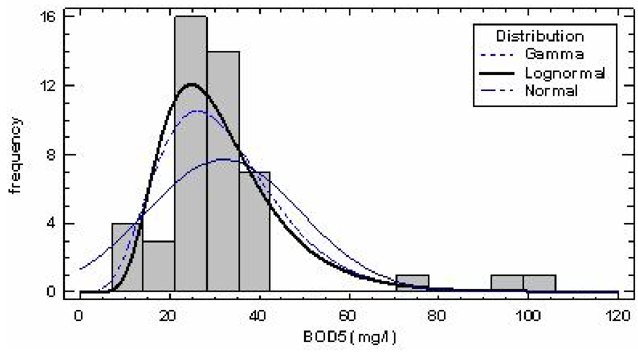

Figure 1: Histogram and PDF of effluent BOD_5 concentration. Khenchela WWTP (2009).

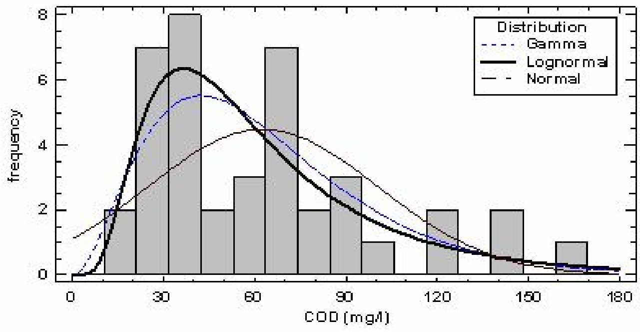

Figure 2: Histogram and PDF of effluent COD concentration. Khenchela WWTP (2009).

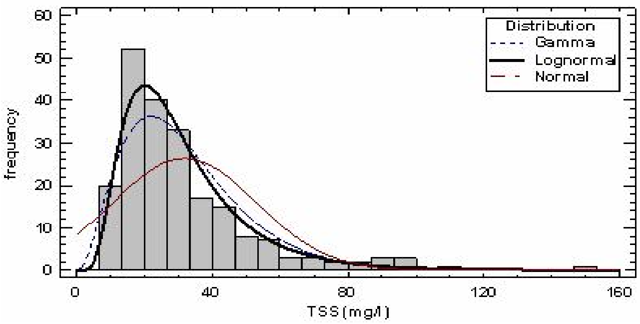

Figure 3: Histogram and PDF of effluent TSS concentration. Khenchela WWTP (2009).

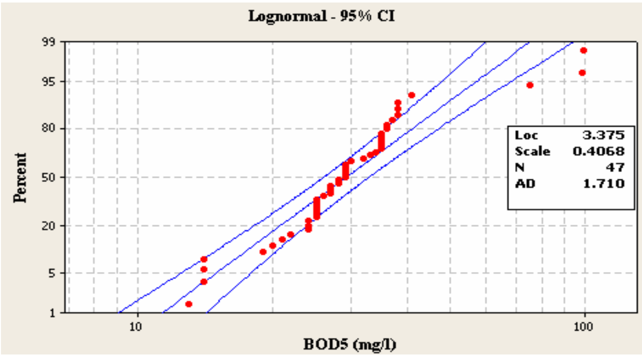

Figure 4: Lognormal probability plot with curve offset at 5% significance level of K-S test of effluent BOD_5 concentration. Khenchela WWTP (2009

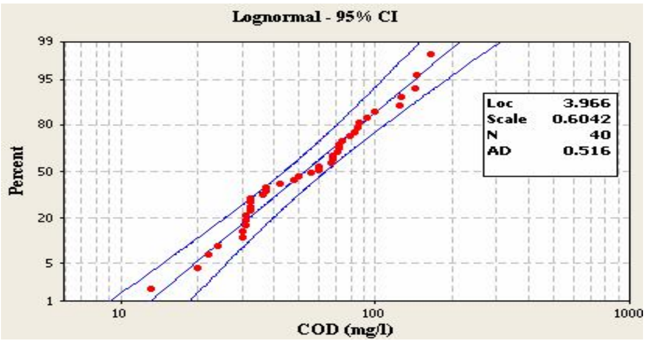

Figure 5: Lognormal probability plot with curve offset at 5% significance level of K-S test for effluent COD concentration. Khenchela WWTP (2009).

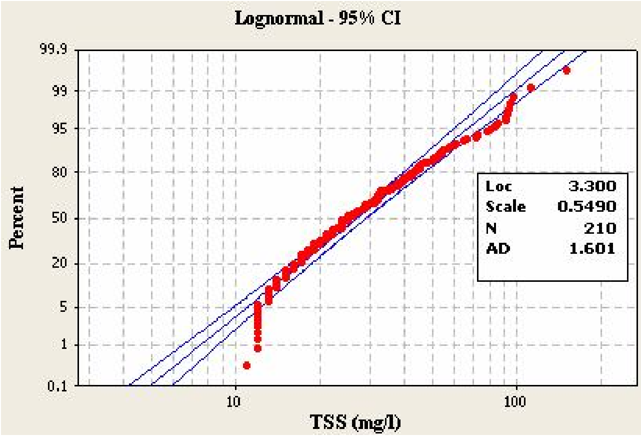

Figure 6: Lognormal probability plot with curve offset at 5% significance level of K-S test for effluent TSS concentration. Khenchela WWTP (2009).

The results show that the lognormal distribution is the most representative of the behaviour of considered effluent parameters (BOD_5, COD, and TSS). To confirm the choice of this distribution, the data was transformed to its logarithmic value and a normality test was performed. The normality of the data was checked using Shapiro-Wilk test (W). The log-transformed data was observed to be normally distributed.

The result obtained are consistent with the observation made by Dean and Forsythe (1976), Niku and Schroeder (1981), and Olivera and Sperling (2008). A series of studies published about the distribution of the concentration data from WWTP (most of them considering BOD and TSS) report that the lognormal distribution gives a good overall fit to effluent concentrations values (Dean and Forsythe, 1976 a,b; Niku et al., 1979, 1981, 1982; Niku and Schroeder, 1981; Berthouex and Hunter, 1981, 1983; Ott, 1995; Burmaster and Hall, 1997; Charles et al., 2005;, ,Oliviera and Sperling, 2008). The lognormal distribution of effluent concentrations was also consistent with other research (Cohen et al, 1975; Culp et al, 1980; Ossenbruggen et al, 1987; Kahn and Marvin, 1989; USEPA, 1991). Sherwani and Moreau (1975) cited by Loftis et al. (1983) found it useful to propose the lognormal distributions for effluent concentrations to model the water quality. Ward et al. (1981) suggest that the normal and lognormal distributions are the most widely applicable for water quality.

Being cognizant of this fact, the lognormal distribution was used in this research for effluent BOD_5, COD, and TSS concentrations.

3.2 3Proposed operating guidelines values for selected treated effluent quality parameters

3.2.1 Application of Coefficient of Reliability (COR) calculation to Khenchela WWTP

Values assumed by the coefficient of variation (Cv) for the selected treated effluent quality parameters were processed for year 2009 to 2012. The corresponding values of the coefficient of reliability were processed for a unique confidence threshold equal to 95% ($\alpha = 5\%$, significance level, equation 5). Selection of values for α (significance level, equation 5) (and subsequently $1-\alpha$ values) leads to the corresponding cumulative probability of the standard normal distribution (Z-distribution).

These values were determined by NORMSDIST function in Excel, but are easily found in statistical textbooks. Setting arbitrarily values for CvX yields COR values for a given confidence threshold ($1-\alpha$) (See table 2). Results for the coefficient of variation (Cv) are shown in Table 3.

Table 2: Some values of coefficient of reliability (COR) as a function of the coefficient of variation (Cv) and high reliability level (Oliviera and Von Sperling, 2008)

Reliability level	Cv 0	0,2	0,4	0,6	0,8	1,0	1,2	1,4	1,6	1,8	2,0
90%	1,00	0,79	0,66	0,57	0,52	0,49	0,47	0,45	0,45	0,44	0,44
95%	1,00	0,74	0,57	0,47	0,40	0,36	0,33	0,31	0,30	0,29	0,28
99%	1,00	0,64	0,44	0,32	0,25	0,20	0,17	0,15	0,14	0,13	0,12

Values displayed in Table 2 are plotted on Figure 7, which helps visualising the relationship between COR and Cv

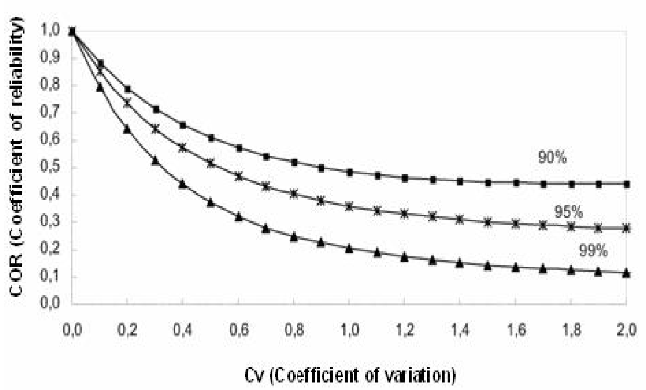

Figure 7: Coefficient of reliability (COR) as a function of the coefficient of variation (Cv) and reliability level (Oliviera and Von Sperling, 2008).

As can be seen from Figure 7, a given targeted value of the coefficient of reliability (COR) generates increasing values of the coefficient of variation (Cv) if the selected confidence threshold decreases. Vice versa, a given value of the coefficient of variation generates increasing values of the coefficient of variation if the confidence threshold decreases.

Table 3: Average values of Cv, and COR for BOD_5, COD and TSS concentrations for 95% confidence threshold at Khenchela WWTP (2009-2012)

	BOD_5 (mg/l)		*COD (mg/l)*		*TSS (mg/l)*	
	Cv_{BOD5}	COR	Cv_{COD}	COR	Cv_{TSS}	COR
2009	0.53	0.5	0.6	0.47	0.93	0.37
2010	0.65	0.45	0.58	0.45	0.75	0.42
2011	0.32	0.63	0.32	0.63	0.55	0.49
2012	0.29	0.65	0.58	0.48	0.69	0.43

NB: COR is expressed based on the properties of the original data (effluent concentrations) and not the logarithms of the data.

Table 3 shows that most of the coefficient of variation (Cv) values obtained for the effluent concentrations are lower than 1. For the same level of reliability (95%), a higher value of the Cv yields a lower COR and a lower average concentration of the effluent (m_x). In general, for all considered parameters (BOD_5, COD and TSS) the lowest COR values were obtained.

3.2.2 Application for setting operational guidelines

The theoretical background exposed in paragraph 2 leads to set operational limits (m_x) for concentrations of selected parameters used for tracking the treated effluent quality. Those operational limits are processed using equation (4) of the model exposed in paragraph 2.1 where the values assumed by the variable Cs are derived from the Algerian standards in force: $Cs_{BOD5} = 40$ mg/l; $Cs_{TSS} = 40$ mg/l; $Cs_{COD} = 130$ mg/l. Results of the numerical applications are presented in Table 4.

Table 4: Average values of operational guidelines (m_X) for BOD_5, COD and TSS concentrations at Khenchela WWTP (2009-2012)

		2009	**2010**	**2011**	**2012**
	Cv	0.53	0.65	0.32	0.29
BOD_5 (mg/l)	COR	0.5	0.45	0.63	0.65
	m_x=CORxCs	20	18	25.2	26
	Cv	0.6	0.58	0.32	0.58
COD (mg/l)	COR	0.47	0.45	0.63	0.48
	m_x=CORxCs	61.1	58.5	81.9	62.4
	Cv	0.93	0.75	0.55	0.69
TSS (mg/l)	COR	0.37	0.42	0.49	0.43
	m_x=CORxCs	14.8	16.8	19.6	17.2

The method implemented for defining operational guidelines yields more demanding thresholds than the regulation in force. In other words, putting the focus on reliability should lead to design and to operate the plant in such a way that the average concentration of given selected parameter is set below the limits in force. The gap between the set value and the limit in force depends on the actual variation of the concentration (modelled and quantified by the coefficient of variation) and by the confidence threshold selected for processing the coefficient of variation. Therefore, for an identical legal threshold (e.g. 40 mg/l set for both BOD_5 and COD), the operational limit is not the same

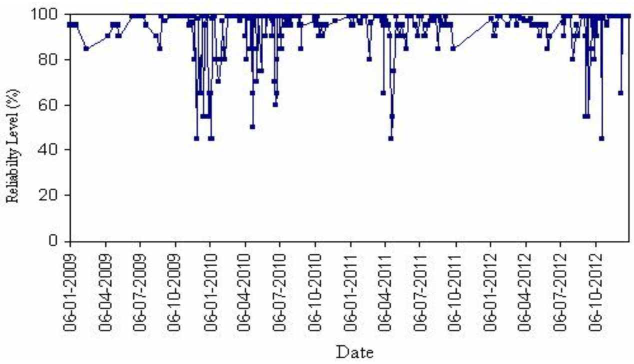

Figure 10: Reliability level of COD effluent. Khenchela WWTP (2009-2012)

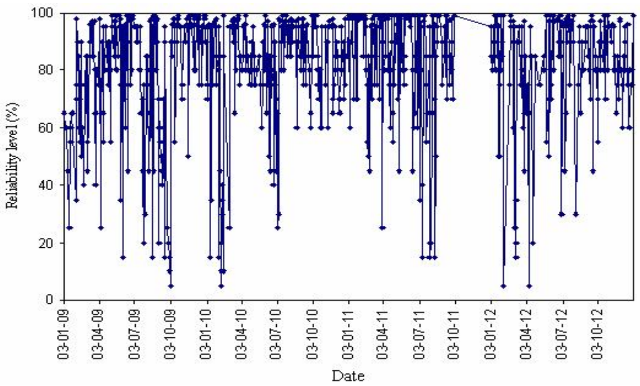

Figure 11: Reliability level of TSS effluent. Khenchela WWTP (2009-2012)

3.3 Assessment of compliance to discharge standards

3.3.1 Determination of reliability level of Khenchela WWTP

The reliability level is processed using equation 3 of the model exposed in paragraph 2. In that model, the variable Cs assumes the values calculated for the m_X concentration. The daily follow-up of the WWTP provides the data for calculating the probability $P(Ce>Cs=m_X)$, taking into account the fact that the distribution laws of the concentration of the selected treated effluent quality parameters are log-normal distributions.

Khenchela city WWTP has been operated for four years. Operators are now expressing interest in implementing the method of Niku et al. (1979) for making a daily assessment of the reliability of the WWTP. They express specific interest to the reliability of the treatment process (activated sludge), and how it impacts on the parameters characterizing the discharge quality (BOD_5, COD and TSS). Subsequently, a comprehensive analysis of operation data was first performed to collect all necessary data for fulfilling the operators' needs. Then we perform a comparison between daily effluent concentrations of WWTP and the range of average concentration according to the different reliability level to determine the appropriate reliability for the parameters considered. The calculations of daily reliability level of Khenchela WWTP for effluent BOD_5, COD and TSS are shown in Figures below.

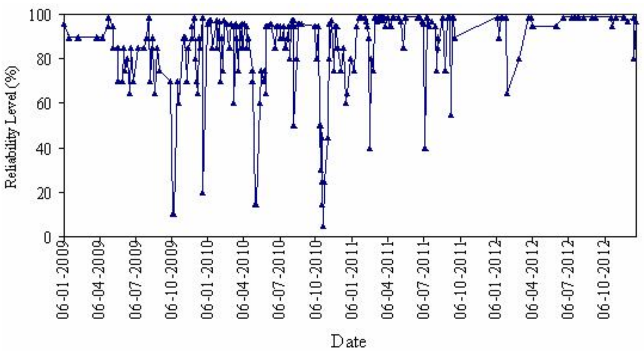

Figure 9: Reliability level of BOD5 effluent. Khenchela WWTP (2009-2012)

The variability level of reliability WWTP is observed, this variability is due to many factors that affect the performance of the plant wastewater treatment (reliability). Flow variability and their characteristics, the inherent variability of the behavior of processes wastewater treatment (intrinsic reliability), the variability is caused by mechanical failures, in addition to the lack of experience of the operators of treatment plants wastewater especially in developing countries.

3.3.2 Critical component analysis of Khenchela city WWTP

The excessive variability of TSS reliability level is mainly due to problems encountered in the grit chambers. The WWTP is equipped with three grit chambers, but only two are operational, which makes the residence time of soluble solids very short, and they do not have enough time to settle, which makes the TSS reliability level highly variable.

Critical component analysis approach was developed by the United State Environmental Protection Agency (USEPA) to determine in-service reliability, maintainability and availability of the critical wastewater treatment plant components. Components are considered critical if their failure causes an immediate impact on effluent quality (Shultz and Parr, 1982). Critical component analysis approach can be utilized by design engineers and plant operators to assist in the selection of new equipment and then improvement in treatment plant performance. Eisenberge et al. (2001) described a method to evaluate inherent reliability and mechanical reliability and showed the importance of the reliability evaluation for water and wastewater treatment (Baxter et al., 2003). The minimum requirement of reliability should be determined to establish the magnitude of the probability of failure that can be accepted. For this determination, Niku et al (1981) cite a statistical and economic decision theory, which states that the total costs of treatment plants, considering the construction, operation and the value of the cost of failure multiplied by the probability of their occurrence should be minimal.

4 CONCLUSIONS

The effluent concentrations variability has been described by the coefficient of variation. Effluent variables (BOD_5, COD and TSS) are not symmetrically distributed and generally their distribution is skewed to the right. The law of probability distribution for BOD_5, COD and TSS concentrations of an activated sludge process has been examined. The study showed that the lognormal distribution consistently gives a good overall fit to observe effluent parameters. It was also verified that the distributive model that best describes the behaviour of the data effluent.

A probabilistic model has been used for determining thresholds for effluent BOD_5, COD and TSS concentrations. From the knowledge of the behaviour of effluent concentrations, it was possible to calculate the values of coefficients of reliability (COR), using mean and average of effluent concentrations, for different level of reliability for the wastewater treatment plant.

This probabilistic approach provides a theoretical basis for setting operating thresholds for managing the WWTP. Additionally, the analysis of reliability stems from that probabilistic approach where reliability is expressed as the probability of success or adequate performance as a function of mean values and effluent variability. The application of statistical concepts to the setting of wastewater discharges standards have been the subject of several articles (Wheatland, 1972, Porter, 1975, Dean and Forsythe, 1976a, b; Niku and Schroeder, 1981; Niku et al., 1979, 1981, 1982, McBride and Ellis, 2001; McBride, 2003 Metcalf and Eddy, 2003), but in general, the legal requirements are not included in statistical considerations. If the performance of a wastewater treatment plant obeys to lognormal statistics (as shown by Dean and Forsythe, 1976a, b; Niku and Schroeder, 1981; Niku et al, 1979, 1981, 1982. Berthouex and Hunter, 1981, 1983, Metcalf and Eddy, 2003, Charles et al, 2005. Oliveira and Von Sperling, 2006, 2008), there is always a non-zero probability of exceeding an upper limit, even if this probability can be very low. Hence, using probabilistic methods in setting emission standards is a practical and realistic approach from an operational point of view. Knowing (or assuming) the values of the coefficient of variation of the key component of the effluent discharged by the plant, it should be possible to determine the thresholds below which the key indicators of the effluent quality must be maintained to meet a certain standard with a predetermined probability.

The contribution of the study lies in the generation of reliable information that can be used by operators of wastewater treatment plant to evaluate a daily reliability level, and understand the performance of biological treatment, considering the quality of the effluent for the development of discharge standards that are reasonable, effective and technically achievable.

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