SHEWHART'S CONTROL CHARTS AND PROCESS CAPABILITY RATIO APPLIED TO A SEWAGE TREATMENT STATION

FÁBIO ORSSATTO[1], MARCIO A. VILAS BOAS[2], RICARDO NAGAMINE[3], MIGUEL A. URIBE-OPAZO[4]

ABSTRACT: The current study used statistical methods of quality control to evaluate the performance of a sewage treatment station. The concerned station is located in Cascavel city, Paraná State. The evaluated parameters were hydrogenionic potential, settleable solids, total suspended solids, chemical oxygen demand and biochemical oxygen demand in five days. Statistical analysis was performed through Shewhart control charts and process capability ratio. According to Shewhart charts, only the $BOD_{(5.20)}$ variable was under statistical control. Through capability ratios, we observed that except for pH the sewage treatment station is not capable to produce effluents under characteristics that fulfill specifications or standard launching required by environmental legislation.

KEY WORDS: STS, Sewage, Process Capability, Shewhart Control Chart

CARTAS DE CONTROLE DE MEDIDA INDIVIDUAL DE SHEWHART E ÍNDICES DE CAPACIDADE DO PROCESSO APLICADOS A UMA ESTAÇÃO DE TRATAMENTO DE ESGOTO DOMÉSTICO

RESUMO: O presente estudo utilizou métodos estatísticos de controle de qualidade para avaliar o desempenho de uma estação de tratamento de esgoto doméstico. A estação de tratamento em questão localiza-se no município de Cascavel, no Estado do Paraná. Os parâmetros avaliados foram: potencial hidrogeniônico, sólidos sedimentáveis, sólidos suspensos totais, demanda química de oxigênio e demanda bioquímica de oxigênio de cinco dias. A análise estatística deu-se através das cartas individuais de Shewhart e índices de capacidade do processo. Conforme as cartas de Shewhart, apenas a variável $DBO_{5,20}$ apresentou-se sob controle estatístico. Através dos índices de capacidade do processo, observou-se que, com exceção do pH, a estação de tratamento de esgoto doméstico não é capaz de produzir efluente com características que cumpram as especificações ou padrões de lançamentos exigidos pela legislação ambiental.

PALAVRAS-CHAVE: ETE, Esgoto doméstico, capacidade do processo, cartas de controle.

INTRODUCTION

Humanity has come across water scarcity issue as health threat and risk to planet earth life. The water scarcity or lack affects more than 40% of the worldwide population, for political, economic and climatic reasons (BRITTO & RANGEL, 2008). Water management importance is directly linked to environmental sustainability, being function of development of various components such as political, economic and social playing roles within a basin, and their sensitivity concerning water resources integrated management (SÁNCHES-ROMÁN et al., 2009). With this,

[1] Tecnólogo Ambiental, Prof.Mestre, Núcleo de Ciências Biológicas e Ambientais , UTFPR/Medianeira – PR, Fone: (45) 3240-8161, orssatto@utfpr.edu.br
[2] Engº Agrícola, Dr. em Irrigação e Drenagem, Pesquisador Produtividade do CNPq, Prof. Associado do PGEAGRI, UNIOESTE/Cascavel- PR, marcio.vilasboas@unioeste.br
[3] Engº Civil, Prof. Doutor, Departamento de Engenharia Ambiental, UTFPR/Londrina – UF, ricardocostanzi@utfpr.edu.br
[4] Estatístico, Dr. em Estatística, Pesquisador de Produtividade do CNPq, Prof. Associado do PGEAGRI, UNIOESTE/Cascavel-PR, miguel.opazo@unioeste.br
Recebido pelo Conselho Editorial em: 10-9-2010
Aprovado pelo Conselho Editorial em: 13-2-2014

sanitation services as sewage collection and treatment are becoming very important to assure people life quality.

Effluent launching impact in water bodies by sewage station is cause of great concern for most the countries. Whole series of environmental laws, criteria, politics and reviews seek to influence both in the discharge place selection and demanded treatment level to make sure that environmental impacts by effluent disposal to be acceptable (OLIVEIRA & SPERLING, 2005a).

Sanitary and environmental engineering together with biotechnology have quickly evolved in developing wastewater treatment methods. This is mainly due to increasing requirements of environmental control public agencies, as response to the public health concern, increasing adverse conditions caused by wastewater discharges and greater environmental awareness (CATTONY et al., 2007).

In Brazil, although pilot scale or individual STSs studies and evaluations, the knowledge on performance of current national sewage treatment technologies is relatively sparse(OLIVEIRA & SPERLING, 2005a).

Generally, there is not only one variable responsible for effluent quality and variability. It depends on affluent load variations, environmental conditions in reactors, source of sewage to be treated, toxic substance presence, variability to biological treatment processes, plus mechanical and human imperfections in system. All these factors may lead to process problems and instability, which will cause adverse effect in effluent quality (OLIVEIRA & SPERLING, 2005b), for this, efficient techniques and means to identify process imperfections must be used.

Quality control statistical methods are techniques that verify whether domestic sewage treatment is being effective or not. Although these techniques are widely used in industrial processes, the statistical techniques can be equally applied in non-industrial processes (MONTGOMERY, 2004). In this perspective, as example statistical quality control use in non-industrial activities, JUSTI et al. (2010) had successfully applied the process capability ratio in sprinkling irrigation aiming to evaluate water distribution uniformity. COBERTT & PAN (2002) mention that these techniques have been applied in lots of environmental performance researches.

The present research aimed to use the statistical methods of quality control to evaluate the performance of a sewage treatment station, identifying process errors and arguing their possible causes.

MATERIAL AND METHODS

The sewage treatment station (STS) is located in Cascavel city, in Paraná State, Brazil. The geographic coordinates are 24º 56' 07”' South and 53º 30' 12” West. The station is called ETE Oeste (Sewage Treatment Station - STS West). A grating bar system with manual cleaning, gravity desander with tangential flowing and sand withdrawal through airlift, flow meter Parshall pipeline, and biological treatment through two parallel up-flow anaerobic sludge blanket reactors (UASBs) constitutes the treatment station. Complementary physical-chemical treatment using a coagulation process, flocculation and laminar sedimentation using ferric chloride as coagulant, Parshall pipeline and effluent disinfection with chlorination. This station serves approximately 45,000 inhabitants with an average outflow of 80 L^{-1}. The reactors has 26-meter upper diameter, 14-meter bottom diameter and 6-meter useful height. The place also presents drying beds to remove humidity and reduce sludge volume from UASBs.

Bezerra stream is the water body of the station. The stream is Anta river tributary, which is situated in Paraná River III basin (ORSSATTO, 2008). It is a perennial river, considered by Environmental Institute of Paraná (IAP) as class II in agreement with classification of National Council of Environment (CONAMA), regulation #357/05 and presents lotic characteristics (BRAZIL, 2005).

Station monitored point was right after disinfection (treated sewage) and database comprise the period from January 2006 to January 2009 monthly recorded.

The evaluated parameters were hydrogenionic potential (pH), settleable solids (SS), total suspended solids (TSS), chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in five days.

The pH is a launching control parameter stated by CONAMA regulation #430/11 being the limits between 5 to 9 pH units.

Settleable solids present as maximum launching limit, demanded regulation #430/11, at 1 mL L^{-1} in one-hour test with Imhoff cone rack (BRAZIL, 2011).

Total suspended solids is also a launching parameter controlled by same regulation; however, ETE Oeste environmental permit claims for a maximum concentration of 60 mg L^{-1}.

Even though CONAMA regulation #430/11 does not refer to COD parameter in water body classifications and liquid effluent standard, a few state environment laws establish maximum limits for launching standards (AQUINO et al., 2006). Environmental Institute of Paraná State (IAP) stipulates a maximum concentration for COD at 150 mg of O_2 L^{-1}.

Regarding to $BOD_{5.2}$, CONAMA #430/11 establishes maximum concentration for launching either at 120 mg O_2 L^{-1} or 60% removal in relation to non-treated domestic sewage; however, station environmental permit is more restrictive demanding the maximum concentration at 60 mg O_2 L^{-1}.

The pH was quantified through potentiometric method. All other parameters followed *Standard Methods* recommendations (APHA, 2005).

Descriptive statistics was applied to all evaluated parameters through average records, median, standard deviation, variation coefficient, minimum, maximum, and statistical control techniques in case of charts or graphics of Shewhart individual measure and process capability ratio.

Data must be normally distributed under average rate and with fixed constant for the process statistical control techniques. Null hypothesis used for normality tests, consists of normal data distribution 5% significance level (HELSEL & HIRSCH, 2002). The applied normality tests were Anderson-Darling, Ryan-Joiner (similar to Shapiro-Wilk) and Kolmogorov-Smirnov, that when normality is accused by one those, data normal distribution is considered. When measured data did not followed normal distribution, we applied *Box-Cox* transformation technique.

In order to use the control charts, data must be independent from one another, being crucial the auto-correlation assessment of information group. Auto-correlation compromise performance of traditional control graphics by misleading special and common causes of the process. The most important assumption is data independence. Breaking this assumption would become invalid those statistical tests, unless it is appropriately compensated (ZHOU et al., 2008). Auto-correlation checkup occurred through sample auto-correlation function (MONTGOMERY, 2004).

Graphics of individual measure control consist of lower and upper control limits and a midline (ALBERS & KALLENBERG, 2004). Assuming that process average ($\bar{x}$) is known and data have normal distribution, average is used as midline, and three times moving range average ($\overline{AM}$) in control limits (MONTGOMERY, 2004) as shown in equations 1, 2 and 3:

$$UCL = \bar{x} + 3\frac{\overline{AM}}{d_2} \quad (1)$$

$$ML = \bar{x} \quad (2)$$

$$LCL = \bar{x} - 3\frac{\overline{AM}}{d_2} \tag{3}$$

where,

UCL – upper control limit;
LCL - lower control limit;
ML - the midline, and
d_2 - a graphic building factor of control for variables found in MONTGOMERY (2004) appendix VI.

Conceptually, process capability ratio (C_p) compares process permissible propagation and process real propagation (PALMER & TSUI, 1999). This also compares project specification range [specification upper limit (SUL) - specification lower limit (SLL)] with process range (LNTU - LNTL = 6σ) (CORREA, 2007). Hence, process capability (potential) is defined by ratio between project specification interval variation and 6 standard deviations (σ) as seen in equation 4:

$$Cp = \frac{SUL - SLL}{LNTU - LNTL} = \frac{SUL - SLL}{\mu + 3\sigma - (\mu - 3\sigma)} = \frac{SUL - SLL}{6\sigma} \tag{4}$$

In practical applications, process standard deviation σ is usually unknown and must be estimated. This index was exclusively applied to the pH, once presents upper and lower specification limits.

One-sided processes, that is, having an only specification limit, either upper or lower, one-sided capability ratios are applied. CHEN et al. (2007) assume that one-sided ratios can be used to not only stability monitoring, but also to quality, following specification ratios and evaluating the stability. In the present research, upper one-sided capability ratio was applied (C_{ps}) because used parameters, except for pH, presents only maximum limits (upper) of launching onto water body.

It is represented by equation 5, following recommendations of SONOOCH et al, (2007).

$$C_{ps} = \frac{SUL - \mu}{3\sigma} \qquad 5)$$

As well as in C_p, it is also needed to estimate standard deviation (σ) and average (μ).

The used specification limits were followed by standard launching stipulated by CONAMA regulation #430/11 and station environmental permit.

If index value is greater or equal to 1.33, the process will be capable or adjusted for those specifications. If value is between 1 and the 1.33, the process may be acceptable; and if it is lower than 1, the process will be incapable (MONTGOMERY, 2004).

In practical terms, if the index is greater or equal to 1.33, the sewage treatment station is capable to attend demanded launching standards of environmental agency. If it is between 1 and 1.33, it might attend launching standards; however, a process improvement must be performed. Finally, if the station is lower to 1, it is not capable to attend the launching standards.

Software Minitab 15 was used for data analysis, both for application of statistical quality techniques and for descriptive statistics.

RESULTS AND DISCUSSION

The statistical summary of the assessed variables can be seen in Table 1. The variable pH presented an average value next to neutral and varied between 6.4 and 8.3. Variation coefficient was below 10% (percent), so there is low variability in data.

Concerning to pH, all samples were within CONAMA #430/ 11 regulation limits.

SILVA et al. (2007) using ferric chloride for household effluent post-treatment from a station with up-flow anaerobic reactor as biological treatment, found an average pH equals to 6.9, which is close to our findings.

TABLE 1. Statistical summary of evaluated physical-chemical parameters.

Variable	Average	Median	Standard deviation	V.C. (%)[1]	Minimum	Maximum	p-value[2]	AC[3]
pH	7.10	7.10	0.40	5.70	6.40	8.30	0.093	No
SS (mL L^{-1})	0.33	0.20	0.35	105.92	0.10	80.1	<0.005	No
TSS (mg L^{-1})	49.73	40.00	31.03	62.40	8.00	144.00	0.059	No
COD (mg O_2 L^{-1})	130.28	120.00	48.61	37.31	60.00	263.00	0.102	No
$BOD_{5.20}$ (mg O_2 L^{-1})	53.53	47.50	23.69	44.26	26.40	131.50	<0.005	No

[1]Variation coefficient percentage. [2]p-value of normality test. [3]Time auto-correlation and data dependence.

For settleable solids, values were between 0.1 to 1.8 mL L^{-1} and present high variability since the variation coefficient was above 20%. Just one sample was above maximum allowed limit for effluent launching established by CONAMA regulation #430/11.

Yet for total suspended solids, values varied from 8 to 144 mg L^{-1}. A high variation coefficient occurs and consequently high variability in data is observed. Comparing data with maximum allowed launching standards, eight samples exceeded the limits that are established by environmental permit of the station.

High data variability can be explained by solid dragging by decanter during physical and chemical treatment at flow peak time. This high variability might also be justified by poor system operation, once coagulant dose is not correctly made, the iso-electric point (colloid charge stabilization) is not reached, so colloids are not destabilized (KATO & PIVELI, 2005) then system may form flakes with insufficient weight to decant.

For the COD, values ranged from 60 to 263 mg L^{-1}. Variation coefficient remained above 30% what presents high data variability. Taking into account the maximum COD limit for launching, we observed that 10 out of the 33 analyzed samples have exceeded environmental license limit of the station.

SANTOS (2006), who worked with ferric chloride addition into effluent post-treatment with sludge blanket reactor, found COD values varying from 97 to 160 mg L^{-1}.

For $BOD_{5.20}$ we checked values from 26.4 to 131.5 mg L^{-1}. A high variability is noted since when observing variation coefficient we met values upper than 20%. Comparing data with maximum allowed launching standards, eight samples exceeded the limits that are established by environmental permit of the station.

Observing the p-value of normality test, the hypothesis of data being normal is not rejected considering 5% significance, that is, data present a normal distribution for pH, total suspended solids and chemical oxygen demand. In what concerns to settle able solids and biochemical oxygen demand, data set does not present a normal distribution.

Figure 1 shows that the Shewhart individual measure graphic for pH is out of statistical control. Sixth sample surpassed upper control limit, which pH value at this sample was 8.3. Ferric chloride ($FeCl_3$) dosage error would be a possible cause of this behavior physical-chemical treatment as final effluent burnishing of the station. The $FeCl_3$ is an inorganic salt that suffers hydrolysis easily and for this reason, it has acid character. In this way, when added to the effluent for chemical precipitation, pH tend to decrease, what did not happen in sample 6. However, this value did not exceed the upper specification limit that is 9.

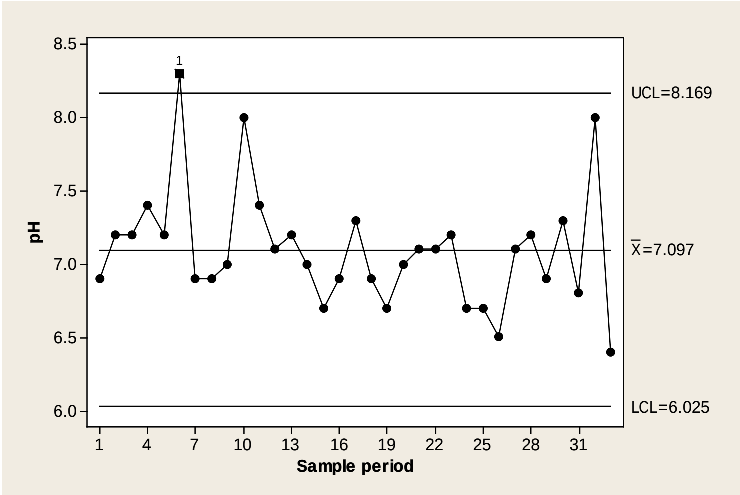

FIGURE 1. Shewhart individual measure graphic for treated sewage pH.

Shewhart individual measure graphic is presented in Figure 2 for settleable solids. This graphic was built with transformed data due to normality absence of them.

Shewhart graphic for SS points a process out of statistical control because between 22 and 29 points there is a displacement in process level. For non-transformed data, a concentration increase is observed at same SS interval.

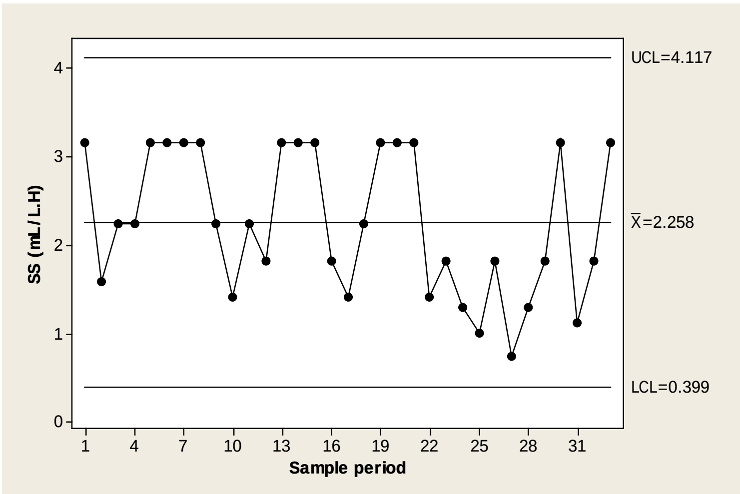

FIGURE 2. Shewhart individual measure graphic for settleable solids.

In Figure 3, it can be easily observed through Shewhart graphic that process is out of statistical control, as 24 point extrapolated upper control limit that is a discrepant point. When compared to SS of same sample, we verified equal result. Thus, this behavior can be supported due to lack of solid retention by decanter, which is followed by ferric chloride application tanks at outflow peak time, or due to coagulation process errors that did not form flakes with enough weight for sedimentation.

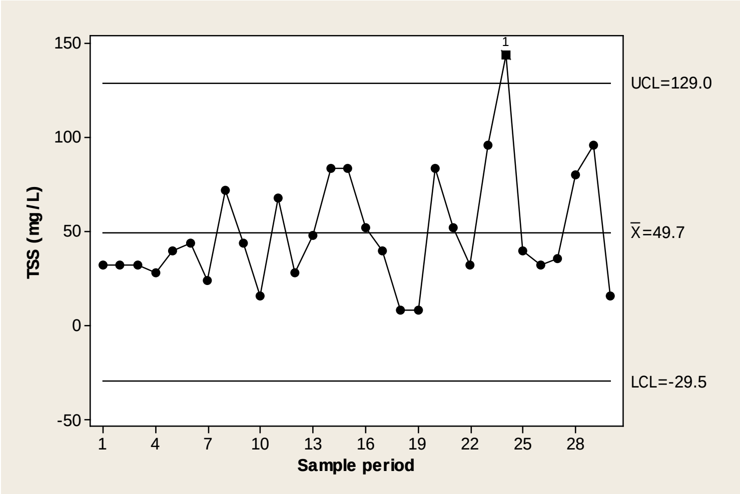

FIGURE 3. Shewhart individual measure graphic for total suspended solids of treated sewage.

With respect to COD variable, Figure 4 shows that it is out of statistical control as 16 point is above upper statistical control limit i.e. discrepant point in the data set. Comparing this to $BOD_{5.20}$ of same sample, we verified that both are high justified by errors in physical-chemical post-treatment.

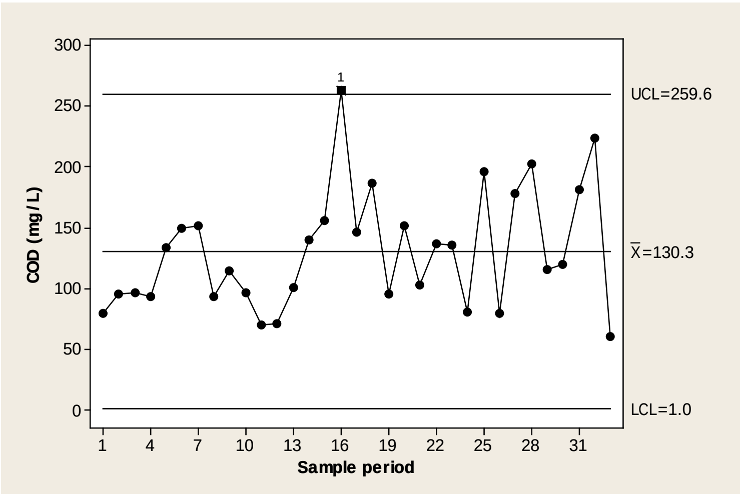

FIGURE 4. Shewhart individual measure graphic for treated sewage COD.

Figure 5 presents the Shewhart graphic for BOD $_{5.20}$ variable. The graphic building was performed by using transformed data due to their normality absence.

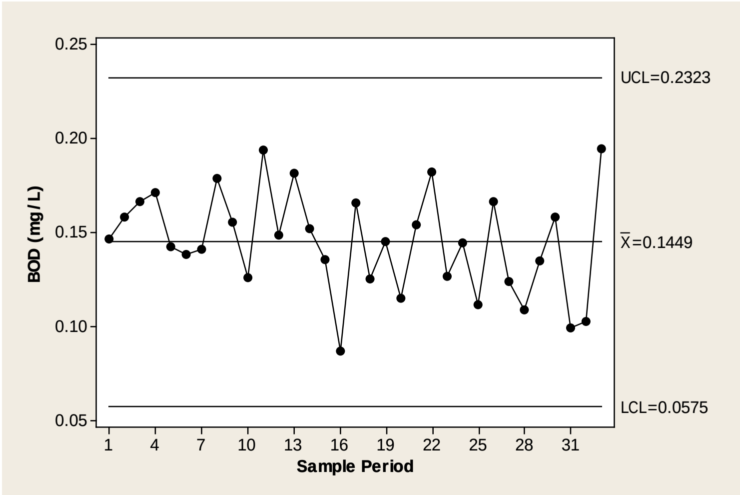

FIGURE 5. Shewhart individual measure graphic for treated sewage BOD.

$BOD_{5.20}$ is under statistical control since it does not present discrepant points out of control limits plus systematic or non-random behavior.

Table 2 shows that process capability rate expressed that the station treatment is able to attend specifications referring to such parameter, that is, STS capability to generate an effluent with pH ranging from 5 to 9, as recommended CONAMA regulation.

TABLE 2. Process capability ratio.

Parameter	Cp	Cps
pH	1.87	-
Settleable solids	-	0.68
Total suspended solids	-	0.13
COD	-	0.15
$BOD_{5.20}$	-	0.18

For settleable solid variable, we observed that the station process was not able to frame into specification limit for all samples because 3% evaluated data was above the maximum concentration allowed for sewage launching into water bodies.

For total suspended solids, capacity index also accused that the process is not capable fit into the specification limit, therefore index values were below 1, that is, the station is not always able to launch into the water body an effluent with concentrations under 60 mg L^{-1}.

In terms of organic matter removal, the station did not present satisfactory performance, since in such a way for the COD as for the $BOD_{5.20}$, the capacity index was lower than 1, what has demonstrated the process incapability to produce in all the occasions an effluent with concentrations under 150 and 260 mg O_2 L^{-1} of COD and BOD, respectively.

CONCLUSIONS

Except for pH, all other variables presented high data variability in agreement with what is observed at variation coefficients.

Through Shewhart individual measure charts, only $BOD_{5.20}$ presented values under statistical control.

The generated Shewhart charts demonstrate to be a good alternative for the process statistical control for a sewage treatment station as they allowed process error visualizations, mainly for large changes.

By the means of process capability ratios, we observed that except for pH, the sewage treatment station is not capable to produce effluents under characteristics that fulfill specifications or standard of launching required by environmental legislation.

REFERENCES

ALBERS, W.; KALLENBERG, W. C. M. Estimation in Shewart control charts: effects and corrections. *Metrika,* New York, v. 59, n. 1, p. 207 – 234, 2004.

APHA. American Public Health Association. *Standard methods for the examination of water and wastewater.* 21th ed. Washington: American Water Works Association, 2005. 1368p.

AQUINO, S. F.; SILVA, S. Q.; CHERNICHARO, C. A. L. Considerações práticas sobre o teste de demanda química de oxigênio (DQO) aplicado a análise de efluentes anaeróbios. *Engenharia Sanitária e Ambiental,* Rio de Janeiro, v. 11, n. 4, p. 295 – 304, 2006.

BRASIL. Ministério do Meio Ambiente. Conselho Nacional do Meio Ambiente – Resolução nº 357, de 17 de março de 2005. *Diário Oficial da União*, Brasília, DF, 18 mar. 205. p. 58 – 63.

BRASIL. Ministério do Meio Ambiente. Conselho Nacional do Meio Ambiente – Resolução nº

430, de 13 de maio de 2011. Brasília, DF, 2011.

BRITTO, J. M.; RANGEL, M. C. Processos avançados de oxidação de compostos fenólicos em efluentes industriais. *Química Nova,* São Paulo, v. 31, n. 1, p. 114-122, 2008.

CATTONY, E. B. M.; RIBEIRO, R.; ZAIAT, M.; FORESTI, E.; VARESCHE, M. B. A. Remoção de etanol e benzeno em reator anaeróbio horizontal de leito fixo na presença de sulfato. *Engenharia Sanitária e Ambiental,* Rio de Janeiro, v. 12, n.2, p. 181 – 191, 2007.

CHEN, K. S.; HUANG, H. L.; HUANG, C. T. Control charts for one-side capability indices. *Quality & Quantity,* Amsterdam, v.41, n.3, p.413-427, 2007.

CORBETT, C. J.; PAN, J. N. Evaluating environmental performance using statistical process control techniques. *European Journal of Operation Research,* Cambridge, v. 139, n. 1, p. 68 – 83, 2002.

CORRÊA, J. M. *Estudo do controle e análise da capacidade de processo de produção de água potável.* 2007. 120 f. Dissertação (Mestrado em Métodos numéricos em engenharia). Universidade Federal do Paraná, Curitiba, 2007.

HELSEL, D.R.; HIRSCH, R.M. *Statistical methods in water resources. Techniques of water-resources investigations of the United States geological survey, Book 4, Hydrologic Analysis and Interpretation.* Geological Survey, 2002. Chapt. 3, 524p.

JUSTI, A. L.; VILAS BOAS, M. A.; SAMPAIO, S. C. Índice de capacidade do processo na avaliação da irrigação por aspersão. *Enenharia Agrícola Jaboticabal*, v. 30, n. 2, p. 264-270, 2010.

KATO, M. T.; PIVELI, R. P. *Qualidade das águas e poluição: Aspectos físico-químicos,* São Paulo: ABES, 2005. 285 p.

MONTGOMERY, D.C. *Introdução ao controle estatístico da qualidade.* 4.ed. Rio de Janeiro: Editora LTC, 2004. 532p.

OLIVEIRA, S. M. A. C.; SPERLING, M. V. Avaliação de 166 ETEs em operação no país, compreendendo diversas tecnologias. Parte I – Análise de desempenho. *Engenharia Sanitária e Ambiental,* v. 10, n. 4, p. 347 – 357, 2005a.

OLIVEIRA, S. M. A. C.; SPERLING, M. V. Avaliação de 166 ETEs em operação no país, compreendendo diversas tecnologias. Parte II – Influência de fatores de projeto e operação . *Engenharia Sanitária e Ambiental,* Rio de Janeiro, v. 10, n. 4, p. 358 – 368, 2005b.

ORSSATTO, F. Avaliação do oxigênio dissolvido do córrego Bezerra a montante e jusante de uma estação de tratamento de esgoto sanitário, Cascavel, Paraná. *Revista Brasileira de Biociências*, Porto Alegre, v. 6, supl. 1, p. 27 – 28, 2008.

PALMER, K.; TSUI, K.L. A review and interpretations of process capability indices. *Annals of Operations Research,* Amsterdam, v. 87, p. 31 – 47, 1999.

SÁNCHEZ-ROMÁN, R. M.; FOLEGATTI, M. V.; ORELLANA-GONZÁLEZ, A. M. G. Situação dos recursos hídricos nas bacias hidrográficas dos rios Piracicaba, Capivari e Jundiaí utilizando modelo desenvolvido em dinâmica de sistema. *Engenharia Agrícola*, Jaboticabal, v. 29, n. 4, p. 578-590, 2009.

SANTOS, H. R. *Coagulação/precipitação de efluentes de reator anaeróbio de leito expandido e de sistema de lodo ativado precedido de reator UASB, com remoção de partículas por sedimentação ou flotação.* 2007. 331 f. Tese (Doutorado em Hidráulica e Saneamento), Escola Engenharia de São Carlos, Universidade de São Paulo, USP, 2006.

SILVA, M. E. R.; AQUINO, M. D.; SANTOS, A. B. Pós-tratamento de efluentes provenientes de reatores anaeróbios tratando esgotos sanitários por coagulantes naturais e não-naturais. *Revista Tecnologica, Fortaleza*, v. 28, n.2, p. 178 – 190, 2007.

SONOOCH, S.; KIATCHAROENPOL, T.; LAOSIRIHONGTHONG, T. An approach to comparing measurement system analysis with process capability study for prioritizing improvement. In: 9 CONFERENCE OF THE INTERNATIONAL DECISION SCIENCES INSTITUTE, 9., 2007, Bangkok. Anais…

ZHOU, W.; BECK, B. F.; PETTI, A. J.; WANG, J. Application of water quality control charts to spring monitoring in karst terranes. *Environmental geology* Berlim, v. 53, n. 6, p. 1311 – 1321, 2008.