

A methodology to evaluate water and wastewater treatment plant reliability

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Abstract Evaluating the reliability of treatment processes and treatment facilities should be an important part of the planning and design process for water resource, wastewater treatment, and particularly wastewater reuse projects. With the recent developments in technology, particularly the development of membrane processes and alternative disinfection processes for water and wastewater treatment, there is an increasing need for a common methodology to evaluate the reliability of alternative processes and treatment facilities that utilize different combinations of those processes. To assess the reliability of a treatment facility, several aspects of treatment must be considered including a methodical evaluation of both mechanical reliability and plant performance. A straightforward method for conducting these types of analyses is described herein along with a description of applications of this methodology. A discussion is provided highlighting the value of such a methodology for both the water quality engineer and the risk manager.

Keywords Reliability; treatment effectiveness; inherent variability; effluent characterization

Introduction

Evaluating the reliability of treatment processes and treatment facilities should be an important part of the planning and design process for water resource, wastewater treatment, and particularly wastewater reuse projects. Reliability evaluation for water and wastewater treatment has become more important, and more complex in recent years. This has occurred because there has been significant innovation in the range of available technologies. Also, planners, design engineers, and regulatory agencies are considering projects such as unrestricted irrigation with treated wastewater and planned indirect potable reuse of treated wastewater. Protection of the public health for that type of project depends to an unprecedented extent upon the consistent operation and effectiveness of the treatment processes and upon the overall reliability of the treatment facility. In previous decades, treatment was based only on a limited range of process technologies such as sand filtration and chlorine disinfection. Many of the common technologies had been proven during a century of widespread application. The strengths and weaknesses of these processes were thought to be well understood. Reliability was generally considered to be a function of how many key processes or components were provided with redundant back-up units. Public health was protected in most instances by assuming that the process will fail, and minimizing the potential for exposure under failure conditions.

With the recent developments in technology, there is increasing need for a common methodology to evaluate the reliability of alternative processes and treatment facilities that utilize different combinations of those processes. Such evaluations are useful in planning and regulatory review, to compare the level of protection that would be provided by projects that utilize new technology versus levels that would have been considered acceptable with previous conventional technology. Reliability evaluation is also a critical consideration when treated wastewater will be reused in a manner that involves high potential for human exposure. In such instances, the reliability of treatment is as important as effectiveness of treatment, and risk assessment for planning and regulatory purposes must include a

thorough and meaningful evaluation of the expected reliability of the facility in meeting necessary treatment levels. Such an evaluation may also provide the framework for development of long term monitoring requirements to verify reliable operation.

Reliability

Several methods have been used by others to evaluate and characterize the reliability of wastewater treatment. However, many of these methods are either limited in focus or are extremely theoretical. To carry out a comprehensive and useful reliability evaluation for wastewater treatment plants and wastewater reuse facilities, a methodology was developed that relies on a range of measurements and observations to characterize treatment facility reliability with respect to: 1) variability of treatment effectiveness under normal operation, 2) probability of mechanical failures, 3) impacts of observed or projected mechanical failures upon effluent quality. In addition, a methodology was incorporated which allows for the use of individual process performance data to make an estimation of overall treatment reliability for the entire facility, for constituents which may be removed to levels that are below levels of detection in the treatment plant effluent.

In their water treatment design text, the American Water Works Association (1998) mathematically defines the term “system reliability.” The two components of their equation are the probability of being *on-line* and the number of parallel components or treatment units. While system reliability defined in this way is an important aspect of water treatment, it is also important to understand that reliability can be defined in terms of the quality of the product coming out of the unit. Product quality can and will vary as a function of a variety of factors associated with the quality of the incoming stream or the manner in which the treatment units are operated. Measuring product quality variation is another means of assessing process reliability from the standpoint of understanding how robust the treatment step might be, i.e. how the process may respond to changes in source quality to consistently produce a product of a given quality. Alternatively, given a range of source water quality characteristics, measuring the response of the product quality to these changes will provide some assurance that the treatment unit will rarely be sufficiently compromised to be taken off-line.

Redundancy

In the context of the AWWA discussion on treatment reliability, redundancy means to provide excess treatment capacity providing the ability to treat an additional volume of water as a means of improving process reliability. The purpose of having a redundant unit is to ensure the process will be capable of meeting design output even if a component is removed from the treatment process train. It could be argued that some degree of redundancy is present in a new treatment plant design when the treatment train is not at design capacity. While the redundancy in this case is supplied by the excess capacity, a treatment facility that exceeds the needs of a community, will only have the degree of reliability supplied by such redundancy only until the demand approaches the design capacity. Generally, a multiple treatment barrier is comprised of a series of treatment units designed to achieve a given degree of treatment (log removal or product water concentration). Whether these treatment units and their components are operated in series or parallel influences how one estimates the reliability of the treatment process train and influences the definition of “treatment reliability.” Readers interested in a more detailed discussion are referred to Nash (1993) and Sakaji *et al.* (1995).

Related definitions

Water passes through a series of treatment steps before reaching its final destination. At

each treatment step the water is either prepared for further treatment or is improved with respect to water quality by the removal of one or more contaminants. When all of these treatment steps are examined collectively, they are said to be part of a “treatment process train.” To evaluate treatment reliability, the process train can be divided into smaller segments or steps, which shall be referred to as “treatment units.” Each unit can be further subdivided into “components” and “subcomponents”. These terms will be used throughout this manuscript.

Applications

In order to fully take advantage of treatment reliability as a tool for decision making, risk managers must understand reliability from the viewpoint of how the treatment units, components, and subcomponents are operated in the treatment process train (parallel or series, independent or dependent). When used properly, treatment reliability can be used to evaluate treatment process trains containing alternative or innovative treatment technologies. This would allow a risk manager to evaluate the equivalency between a conventional and non-conventional (containing an alternative technology) treatment process train. The proper use of this technique can help to build confidence in technology that does not have an extensive history of operation and use. The treatment reliability estimate may also be used to identify and evaluate key issues in scaling up small facilities or as a foundation for assessing threats to public health.

Methods

To assess the reliability of a treatment plant, one must consider several aspects of treatment. First, what is the probability that the plant is operating “properly”, and second, if the plant is operating properly, what is the probability that the effluent will meet or exceed a given set of criteria. Addressing these issues with respect to treatment plant reliability requires a methodical evaluation of both mechanical reliability and plant performance (inherent reliability). A straightforward method for conducting these types of analyses is described below.

Mechanical reliability

The fundamental goal of assessing the mechanical reliability of a treatment system is to determine key pieces of equipment in the plant whose failures may be related to effluent quality, and to determine the probability that the facility will be functioning according to design specifications. This component of a reliability analysis may be used to quantify the dependability of a plant in terms of operations, and to identify weak points in the treatment process. By identifying and improving the weak points in the treatment process, the reliability of the treatment system may be improved.

A review of the literature indicates that a number of approaches are available for analyzing the mechanical reliability of a treatment plant. Some of the more common approaches include Fault tree analysis, Event tree analysis, Failure modes and effects analysis, and Critical components analysis. All four of the approaches have been used by a variety of industries to assess the mechanical reliability of various types of facilities. In previous work, we successfully applied the Critical Component Analysis approach to evaluate the mechanical reliability of water treatment facilities ranging in size from a 0.3 Mgal/day pilot scale treatment system to a 30 Mgal/day treatment facility (Cooper *et al.*, 1992; Cooper *et al.* 1997; Eisenberg *et al.*, 1998). This method was originally developed by the U.S. Environmental Protection Agency to determine the in-service reliability, maintainability, and operational availability of selected critical wastewater treatment components (US EPA, 1982).

The objective of the critical component analysis is to determine which mechanical components in the treatment plant would have the most immediate impact on effluent quality should failure occur. The analysis is carried out by creating a list of all components in the facility, categorizing the components by treatment unit, component, and subcomponent, collecting data for all planned and unplanned maintenance events, aggregating the maintenance data appropriately, and computing performance statistics for treatment units and for individual components in the treatment system. The performance statistics describe the expected time between failures for treatment units, the overall mean time between failures for components, and the fraction of time that a unit or component was operating, either including or excluding preventative maintenance.

Table 1 presents a summary of the results of a critical component analysis conducted on a 1 Mgal/day advanced water treatment facility (Cooper *et al.*, 1997). The data used to generate the summary statistics presented in Table 1 were collected over approximately a 1-year period. Review of Table 1 indicates that there were a number of planned and unplanned maintenance events on each unit process. The expected time between failures within the unit processes varied from 9 to 212 days. It should be noted that the expected time between failure for a unit process is a function of the number and reliability of each of the components and subcomponents within that unit process. Finally, Table 1 shows that the Operating Availability, defined as the fraction of the study period that all components in the unit were operating for each of the treatment units was greater than 0.97.

Based on the mechanical reliability analysis summarized above, it would be reasonable to conclude that all treatment units were operational more than 97% of the time and that neither component maintenance nor failure caused a significant interruption in the operation of the plant. This type of analysis provides a foundation from which one may assess the inherent reliability of a treatment system. If for example, it may be demonstrated that a treatment facility is operational nearly 100% of the time on a long-term basis, plant performance data may be used to evaluate the probability that the effluent will meet a specified set of criteria. Otherwise, it may be prudent to investigate if and/or how component failures impact treatment plant effluent quality.

One issue that has yet to be addressed is redundancy within in a treatment facility. Redundancy refers to extra components or sub-components that are available for use in case of planned or unplanned maintenance. In some cases redundant components are designed into treatment systems and are incorporated into the daily use. With respect to the data presented previously redundant components increase the operating availability of a given treatment unit. Interested readers are referred to Cooper, *et al.* (1997) and Eisenberg *et al.* (1998).

Table 1 Plant performance statistics for mechanical reliability

Treatment unit	Number of maint. Events ¹	Number of unplanned events ²	ETBF (days) ³	Operating availability ⁴
Headworks	16	13	26	0.9953
Primary	36	28	41	0.9985
Secondary	82	40	9	0.9757
Tertiary	30	27	13	0.9994
UV	1	1	212	0.9991
Reverse Osmosis	55	35	10	0.9990

¹Number of times repairs were made including scheduled maintenance on components within the given unit.

²Number of times repairs were made due to component failure within the unit.

³Expected time between failure somewhere in unit process, based on chi-square distribution.

⁴Fraction of the study period that all components in the unit were operating.

Inherent reliability

Evaluating the inherent reliability of a treatment facility involves quantifying effluent variability. This type of evaluation involves summarizing observed effluent quality using the basic statistics associated with frequency analysis, i.e. mean values, standard deviations, etc. The inherent reliability of a treatment system may be uniquely characterized by estimating the cumulative probability distributions associated with individual contaminants at key treatment units throughout the facility. These probability distributions explicitly characterize the variability of treatment performance and allow one to estimate the probability that treatment goals would be exceeded. To carry out such an analysis, effluent data must be fit to a distribution using one of several techniques (Ott, 1995). Fortunately, in many cases constituents in effluent from a treatment facility may be well characterized using a lognormal distribution (US EPA 1991).

A reasonable first step in carrying out an analysis of inherent reliability is to inspect the observed data for temporal trends. The intensity of this type of analysis may vary from simple to highly complex depending on the specific situation. In many cases however, time series plots of key constituents at key locations in the treatment facility may provide sufficient insight to determine if temporal trends need to be investigated further. As an example, a time series plot for TOC in secondary effluent from the City of San Diego's Aqua III treatment facility is provided in Figure 1 (Cooper *et al.*, 1997).

Characterizing treatment plant effluent variability may be conducted conveniently by constructing cumulative probability plots for constituents of interest at key locations throughout the facility. As an example, Figure 2 presents TOC data observed in raw wastewater, secondary effluent, tertiary effluent, and reverse osmosis effluent from the City of San Diego's Aqua III AWT treatment facility from October 1994 through September 1995. Plots such as Figure 2 are generated by ranking observed data from lowest to highest, computing the proportion of samples less than a given sample using Blom's transformation or equivalent (SPSS 1993), and plotting that proportion versus the observed concentration.

Inspection of Figure 2 provides insight into the reliability of the treatment system with respect to removal of TOC. TOC levels in the raw wastewater ranged from approximately 30 to 500 mg/L. The secondary and tertiary effluents were both highly consistent with observed values ranging from 7 to 20 mg/L and 2 to 7 mg/L, respectively. Inspection of the reverse osmosis effluent results reveals that over 70% of the data were reported below detectable limits (0.5 mg/L), and that 99% of the reported data were below 1 mg/L.

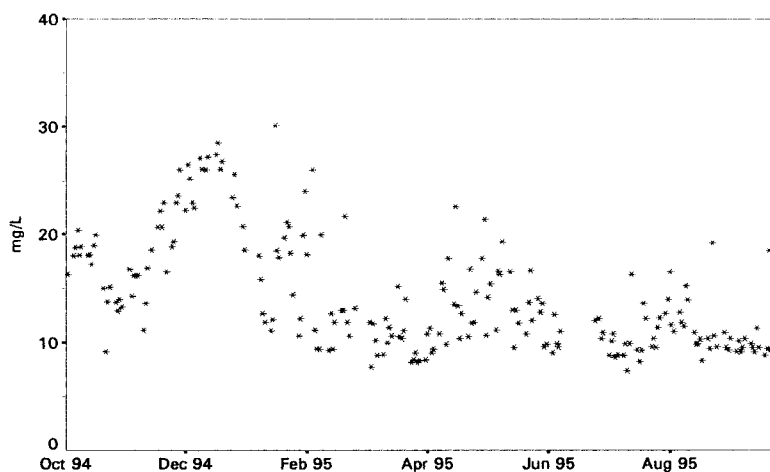


Figure 1 Time Series Plot for TOC in Secondary Effluent (10/94-9/95)

The reverse osmosis effluent data for TOC presented in Figure 2 demonstrate the use of probit analysis to estimate the distribution of treatment plant performance when a large percentage of data are reported below detectable limits. It should be noted that use of this procedure requires a minimum of detected data and that those data are considered to be highly reliable. The benefit of using this type of procedure is that summary statistics such as (geometric) mean values and (geometric) standard deviations may be estimated from the plots, even though a large proportion of the data may not have been quantifiable.

Consequence frequency assessment: an alternative method of assessing plant performance

Often times, the goal of an investigation is to estimate the removal of a particular constituent through a treatment system. It should be realized that water treated at a given facility will vary in quality regardless of the treatment processes used because of variations in the influent stream as well as variability in the performance of the individual unit processes (NRC, 1998). One type of analysis which has been used to estimate the performance distribution of each barrier in a multiple barrier system is known as the consequence frequency assessment methodology (Olivieri *et al.*, 1999; Soller *et al.*, 1997). This type of methodology was also endorsed by the National Research Council in a 1998 publication reporting on the viability of augmenting drinking water supplies with reclaimed water (NRC, 1998). A detailed description of using consequence frequency assessment to evaluate the performance of an advanced wastewater treatment facility is summarized under separate cover (NRC, 1998). Briefly, the procedure may be described as follows.

The concentration of a given pollutant at each stage of treatment may be described mathematically as a conditional probability density function. Formally, the probability distribution of the plant effluent may be expressed as a multiple integral (one integral for each unit process) (Stuart and Ord, 1987). Unfortunately however, the resulting integral may be difficult or impossible to evaluate. A practical alternative commonly used in the field of risk assessment is to employ a Monte Carlo simulation procedure (Finkel, 1990; Haas *et al.*, 1993; Burmaster and Anderson, 1994). Implementation of a Monte Carlo model for this type of application requires fitting distributions to the removal of a particular constituent across each treatment unit, sampling each distribution repeatedly, and computing the final concentration for each set of random samples. Using this procedure, one may represent

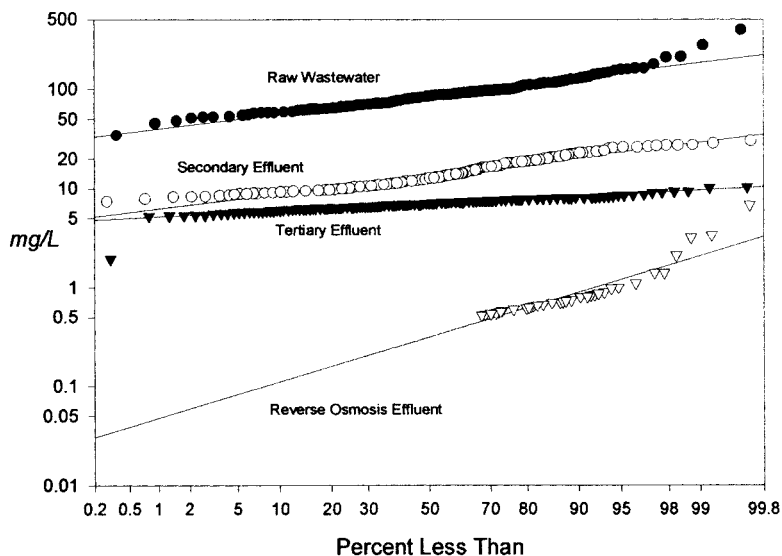


Figure 2 Lognormal probability plot for TOC October 1994–September 1995

plant performance in a probabilistic manner which explicitly acknowledges both the uncertainty and the variability of the underlying data.

In previous work, we applied the consequence frequency assessment methodology summarized above to estimate the removal of MS-2 bacteriophage through an advanced wastewater treatment facility (Soller *et al.*, 1999). To estimate process train performance, probability distributions of removal through each of the unit processes were identified using a Maximum Likelihood Estimate (MLE) approach (Ott, 1995). The identified probability distributions were then used in a Monte Carlo simulation model to estimate the distribution of coliphage removals and associated variability across the integrated treatment system (Soller *et al.*, 1999). A summary of the results from that investigation is presented in Figure 3.

Inspection of Figure 3 reveals that the capacity of the treatment system to remove coliphage is significantly greater than what is necessary to remove virus at levels found in natural environment. (Coliphage is commonly found in wastewater in concentrations of 10^5 pfu/ml). This “excess” treatment capacity can be used as a measure of relative performance in evaluating an individual system or comparing two different systems.

Discussion

For any proposed water reuse scheme, and even for water resource or wastewater disposal plans, a risk assessment may be carried out based on expected properties of the treatment facility effluent. However, such assessments are valid only to the extent that they also include a reasonable assessment of the expected reliability of the treatment process. Such evaluation must incorporate expected variability of effluent quality, mechanical reliability,

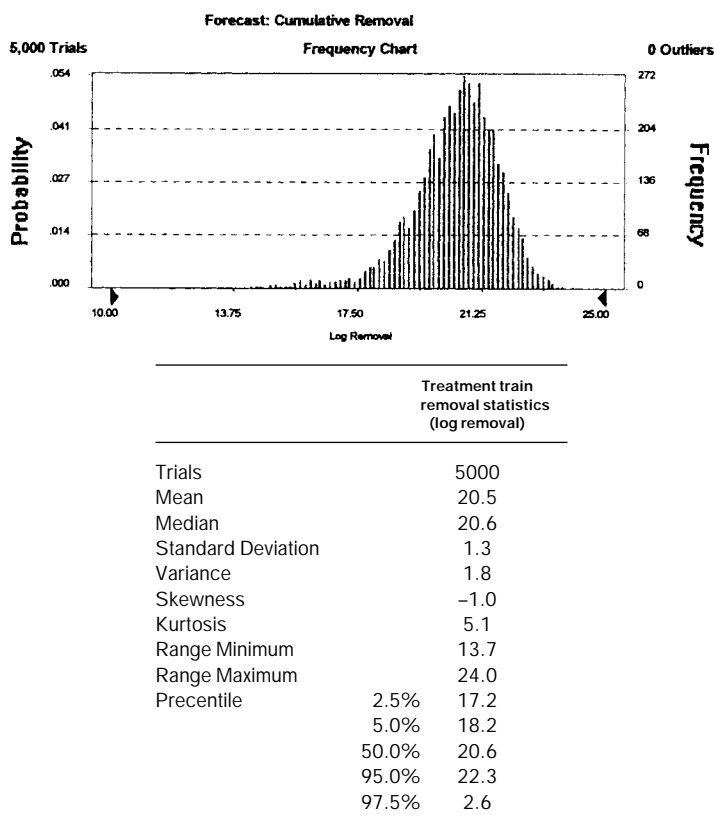


Figure 3 Summary of consequence frequency assessment results for MS-2 removal through an AWT

and the consequences of mechanical failure. Based on these considerations projects may be accepted or rejected, or they may be required to include additional measures to protect public health. Required measures may include more effective treatment units, more reliable processes or treatment trains, or additional measures to reduce potential for exposure.

Reliability evaluation is also an important tool for comparing processes or combinations of processes. The means for determining equivalent treatment unit or process performance for new technologies with limited pilot and small-scale performance data are limited. Estimating treatment reliability provides one means for evaluating and comparing treatment trains comprised of accepted conventional technology to proposed alternative trains containing innovative technology. The objective is to determine if the quality of the product from the two process trains would be the same. If one examines the range of quality produced by the two trains, they should either match perfectly or the process train containing the alternative technology should show less variability in product quality. As long as the variability in product quality for the process train containing the alternative technology does not exceed the variability of the "accepted" or conventional train, the process train containing the alternative may be considered equivalent. One potential complication might be with an innovative technology that requires fewer treatment units (i.e. steps) than a conventional system. In such a case, evaluating the variability in product quality from the process train must consider the impact of the number of treatment units and the adequacy of the product quality characterization from each step in the process train.

Conclusions

As water resource, wastewater treatment, and wastewater reuse become more visible aspects of modern life, quantitative reliability analyses of water and wastewater treatment facilities will be scrutinized more carefully. The methodologies described herein are intended to be interpreted as tools that water quality engineers and decision makers may use to assess the reliability of a treatment facility. The ability to estimate treatment reliability enhances the risk manager's arsenal and may be used in a variety of circumstances. For example, having this tool provides the water quality engineer with the ability to demonstrate whether incorporating an alternative technology into a process train would provide the same degree of public health protection as a conventional or accepted technology. Finally, it should be highlighted that evaluating treatment plant reliability should be both defensible and transparent to satisfy risk management needs. The intention of this manuscript was to identify and summarize a practical means to carry out that charge.

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