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PREDICTING THE RISK TO PERMIT COMPLIANCE OF NEW SEWAGE TREATMENT WORKS

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ABSTRACT

The privatised water industry in England and Wales has the requirement to construct a substantial number of new assets to meet new national and European legislation. In order to do so economically, the risk of performance of new assets has to be matched to the cost of construction. To undertake such risk management, a risk technique has been developed that allows the performance against permit compliance of new processes to be established. The technique is based on statistical analysis of data effectively creating a pure black box model to determine performance.

The technique has been further developed to take into account the dependency between influent quality and process performance. The dependency factor selected is the Spearman's Rank Coefficient which is a convenient way to define complex relationships. It can be used to define many dependent variables referring to the same independent variable and as such removes the need for complex mechanistic equations. This technique has been calibrated using two years, existing data and then validated for the next 6 months data of a wastewater treatment works in the North West of England. The results of the validation illustrate the ability of the technique to be used as a predictive tool.

The output from the model allows the direct comparison of different process options and permits executive management to make informed decisions about investment against risk to permit compliance. © 1998 Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Risk analysis; permit compliance; Spearman's Rank Coefficient; model calibration; Liverpool Works.

INTRODUCTION

The advent of new national and European legislation applying to the water industry in England and Wales has lead to the requirement for new treatment works to be constructed, or existing works upgraded. In order to achieve the most appropriate balance between the construction of new assets and the risk to permit compliance, a new risk evaluation procedure has been developed to predict the risk to permits of new assets that are yet to be built.

There are now many tools available that can mechanistically model works. However, these models tend to be data hungry. The technique described here is a black box model that predicts the performance of works through statistical analysis and compares the results against permits. The method is generic an can be used in different applications. It is described here in terms of predicting effluent quality for permit compliance.

THE METHODOLOGY

The developed risk technique uses the @RISK computer package from Palisade. This is a Monte Carlo dice thrower that allows multiple iterations to be undertaken. Consequently, the data required for the analysis needs to be expressed in a manner compatible with this tool. The data requirements are the inlet load, the performance of the existing works and the predicted performance of the secondary treatment process. Each aspect will be discussed in turn.

The inlet load

North West Water have an extensive archive of historic data. However, as works are upgraded, new sewers are often incorporated, and therefore the true flow and load is often not known. The existing data can however be used to establish the type of distribution of the inlet load which can then be factored to represent the load applied to the new works. Data from several works in the North West of England has found that the distribution of load to a works can best be described by a lognormal distribution. This confirmed previous data analysis undertaken by the USEPA (Niku *et al* 1981). In @RISK the distribution is described by its mean and standard deviation. An example of the distribution is given in Figure 1.

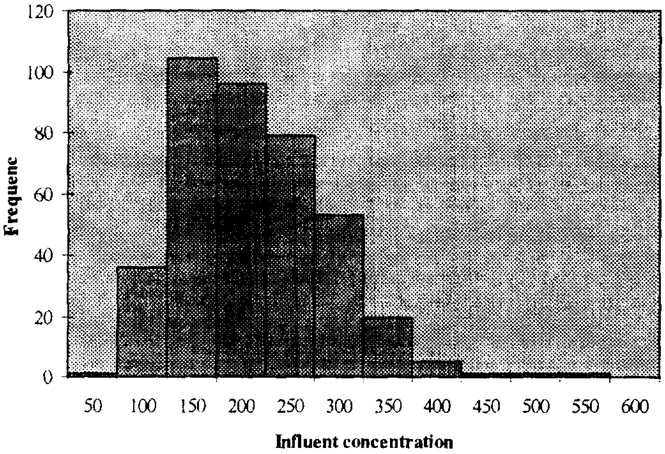

Figure 1. Distribution of inlet load at a wastewater treatment works.

The performance of primary settlement tanks

In order to predict the overall performance of a works, the performance of the individual process units needs to be considered. Where the process exists, archive data can be used. The performance of the primary tanks was initially described in terms of percentage removal. However expressing the performance in terms of percentage removed created a problem with the @RISK package. There are occasions when there is actually an increase in BOD across the PSTs. This may be due to internal liquor returns or storm events or operational breakdowns. To truly model the performance these events need to be included but they create negative percentage removals. A lognormal distribution starts at the point 0,0 and therefore does not produce negative numbers. To overcome this, the performance was expressed in terms of percentage remaining as illustrated in Figure 2.

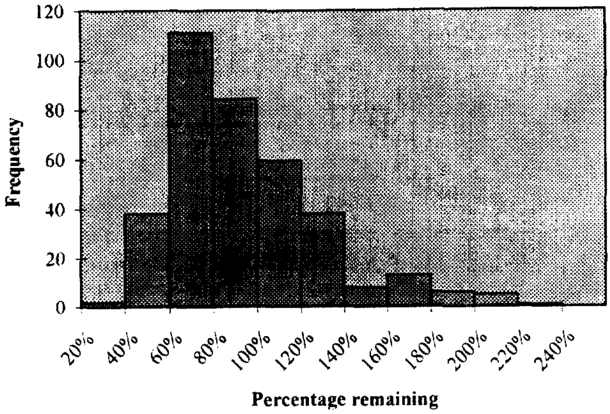

Figure 2. Distribution of the performance of PSTs

Figure 2 shows increases in BOD expressed as greater than 100% rather than negative values. Again, the distribution best matched a lognormal curve as defined by its mean and standard deviation.

The performance of the secondary treatment process

The proposed secondary treatment process was yet to be installed and therefore no historic data was available to establish a similar distribution for percentage remaining after treatment. However, there was substantial operational data from other works that spanned the design criteria to be used for the new works. Therefore a distribution of performance could be established from this data. This again was expressed in terms of percentage remaining. The distribution is illustrated in Figure 3 for one particular design situation. The distribution can be changed for any design scenario.

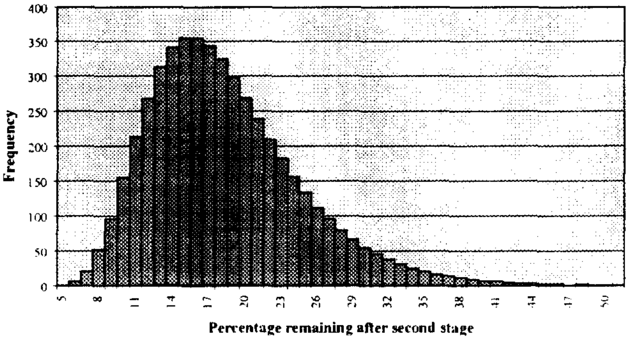

Figure 3. Distribution of the performance of secondary treatment process.

Running the model

The @RISK model randomly selects an inlet load from the inlet distribution and applies a randomly selected performance from the primary tanks performance curve. A further randomly selected performance is then applied from the secondary treatment performance curve to achieve an effluent value. This is run several thousand times to create an effluent distribution. An example of such an effluent distribution is given in Figure 4.

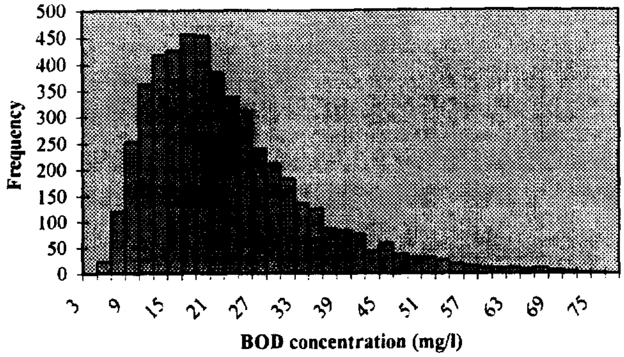

Figure 4. Effluent distribution generated from @RISK.

The effluent distribution can then be compared against the required consent. If the compliance is not as desired, the design criteria can be amended to improve the performance of the new secondary treatment process, and the model can be re-run. In this manner different processes can be compared on a like for like basis by amending designs to achieve the same output in the model.

IMPROVEMENTS TO THE ORIGINAL TECHNIQUE

The method developed relies upon the premise that the performance of the individual process units are independent of each other and the influent characteristics, and are stochastic.

This situation is different from the reality of a wastewater treatment plant. The characteristics of the influent are determining factors in the performance of an individual unit process within the plant. The relationship between influent quality and plant performance is often a complex and non linear function encompassing many variables and degrees of freedom. Deriving this relationship has been the subject of much modelling work and is outside the scope of work undertaken in the study described.

The simplification of the relationship described above can be achieved by defining a dependency between two variables, e.g. influent flow rate and primary tank performance. The dependency of the two variables can be described by assigning a Spearman's Rank Coefficient, which is given by:

$$R_s=1-\frac{6\Sigma(R(x_i)-R(y_i))^2}{n(n^2-1)}$$

Where

$R(x_i)$ is rank of data x
$R(y_i)$ is rank of data y
n is number of data points

Spearman's Rank Coefficient is a statistical determination of the connection between two sets of numbers. It enables a connection to be determined regardless of the number of individual factors that may affect the relationship. It allows correlations to be developed where relationships are non-linear and the factors involved are described by different shapes of distributions. Therefore, it provides a more appropriate, though less powerful, correlation for complex relationships when compared to more conventional regression analysis. The value obtained for R_s is checked for significance in published tables.

The Spearman's Rank Coefficient for the existing primary tank installation was derived using applied BOD load and BOD removal performance. This was used to determine the dependency of the two variables and can be applied directly to the dependency function in the @RISK package. Having introduced dependency into the model, a simulation was performed to predict the performance of the primary tanks. Figure 5 illustrates the results achieved from the correlated simulation, the uncorrelated simulation and the actual operational data for two years of data from January 1995 to November 1996.

The important area of the curve is in the 95th percentile region. It is this area that is most relevant when predicting effluent quality against a 95th percentile permit. As can be seen, in the important 95th percentile area of the curve the data simulated using the dependency coefficient is a much closer representation of reality than the uncorrelated simulated data. This offers calibration of the model procedure.

The model was satisfactorily validated using the performance data of the primary tanks from December 1996 to May 1997.

A similar dependency can be assigned to the secondary treatment stage with an applicable dependency based on flowrate, organic or ammonia load, so that the performance of the whole works will be consistent with the influent load arriving at the works.

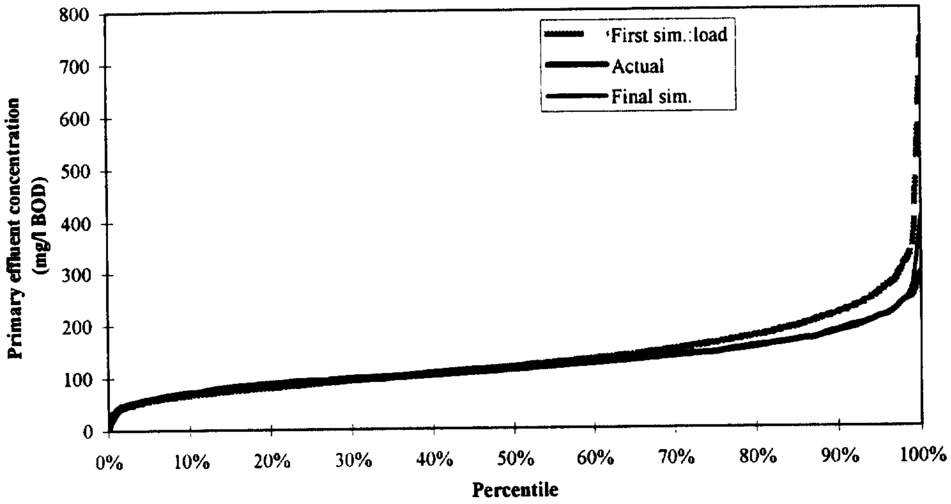

Figure 5. Calibration.

Case Study - Liverpool Works

In developing the process design for the upgrading of Liverpool Works facility in the UK, the risk technique was used to aid both design decisions and investment strategy for future permits.

In 1994, the European directive on Urban Wastewater Treatment became law in England and Wales. One of the primary requirements of the Directive was secondary treatment for all facilities treating a population equivalent of greater than 15,000. Secondary treatment was defined as either a BOD of 25 mg/l on a 95%ile composite sample or 70% BOD removal. In addition, no sample was to exceed a limit of twice the numeric limit, effectively creating an upper tier. This permit was interpreted as:

- If an effluent sample showed greater 70% removal against the influent, the sample passed;
- If an effluent sample showed less than 70% removal against the influent, but the effluent concentration was less than 25 mg/l, the sample passed;

- If an effluent sample showed less than 70% removal against the influent, AND the effluent concentration was greater than 25 mg/l, the sample exceeded a look-up table limit (i.e. one of so many permitted failures in any rolling 12 months);

- If an effluent sample showed less than 70% removal against the influent, AND the effluent concentration was greater than 50 mg/l, the sample failed the permit in terms of the upper tier limit (UTL).

The Liverpool sewage treatment facility currently has only primary treatment. It is the first works in the NWW region to have secondary treatment designed to meet the above criteria.

The permit is complicated by the additional requirement for Chemical Oxygen Demand (COD). The permit is based on 75 % COD removal across the works on a 95 %ile basis and is interpreted in a similar manner to the BOD permit. It has not been normal practise within NWW to design for COD removal since achieving the BOD permit normally allows compliance with any COD permits, but there was uncertainty about the validity of this assumption for a percentage removal based permit.

The plant was designed to achieve the 70 % BOD permit and comprised a single stage Biological Aerated Flooded Filter (BAFF). It was anticipated that should the single stage plant be incapable of achieving the COD permit then a second stage BAFF plant would be added.

APPLICATION OF THE TECHNIQUE

Liverpool currently has preliminary and primary treatment facilities and is to be extended to include a secondary treatment process to meet the permit described above. The facilities have been designed to accommodate a predicted future flow and load, incorporating population growth and the planned connection of further sewers to the network. Future mean and 95 percentile BOD and COD loads and average and dry weather flows were calculated theoretically. The flow to full treatment flow value was set by the permit requirement to treat 1.5 times the Dry Weather Flow (DWF). This multiple of 1.5 DWF is unconventional. The works still had to be designed to accommodate the average and 95 percentile load values which had been predicted, since the loads can arise in dry weather conditions and so are largely unaffected by the flow capping. It is the variation in concentration which is affected.

In order to derive a suitable flow and load distribution it was assumed that the distribution should be scaled from current to future figures, i.e. the shape of the distribution would remain the same but the absolute values would reflect the predicted future figures. Statistical distributions were therefore derived for flow, BOD concentration and COD concentration. The effect of this was that the concentration profile had to be scaled up to provide the overall load profile from the capped flow figures. Thus the combination of the flow and BOD and COD concentrations gave the required load profile.

The performance of the existing primary tanks has been monitored and hence a distribution for the BOD removal across the primaries could be derived. However, as there is no secondary treatment currently on site, other means were required to establish the performance distribution.

The BAFF single stage model was based on pilot work undertaken at Liverpool with a small scale BAFF plant. The results from this work were used to derive a distribution of BAFF performance based on BOD removal. A correlation between influent BOD concentration and BOD removal was found and this was built into the model using a Spearman's Rank. A similar distribution was derived for the COD performance.

The second stage BAFF model was derived from data from other NWW works employing tertiary BAFF technology. This performance distribution was added to the original model to provide a simulation of the proposed second stage BAFF.

Having defined the distributions for influent, flow and concentration and the performance of the relevant unit processes, the risk assessment was carried out using @ RISK software, for the two scenarios.

RESULTS

The resulting predicted return periods to permit failure are given in Table 1.

It is interesting to note that the prediction for failures against the BOD limit illustrates that there is no risk to the look-up table permit. This illustrates that the primary risk to permit failure is the Upper Tier Limit. The lower return period for the COD, even with the second stage BAFF installed, illustrates the greater difficulty of achieving the COD standard. This is partly due to stricter percentage removal limits specified and also partly due to a varying quantity of relcalcitrant COD due to industrial dischargers.

Table 1. Predicted Return Period to permit failure

Simulation	Single Stage BAFF Plant	Two Stage BAFF Plant
Return Period For BOD Look-Up Permit (years)	No failures predicted	No failures predicted
Return Period For BOD Upper Tier Failure (years)	16.5	312
Return Period For COD Look-Up Permit (years)	1.2	20.8
Return Period For COD Upper Tier Failure (years)	1.5	4.4

DISCUSSION

The method described allows a definition of plant performance through a description of the distribution of the range of performances attributable to the plant as designed. It facilitates a sensitivity analysis of the performance of the plant without the need to develop sophisticated mechanistic models.

The selection of suitable distributions for influent flows and loads and performance of the various unit processes for new works is of paramount importance. Where works are to be built on a green field site with new networks then it is often impossible to have sufficient influent data to allow a detailed analysis to be conducted. Selecting a suitable distribution to fit to an average flow figure will depend upon the nature of the network. Analysis of influent distributions from works with similar networks would provide the best information but in the absence of this data a lognormal distribution would be the most suitable distribution to use (Benjamin and Cornell 1970). Selection of the distributions for unit process performance can be derived from operational data from similar plants or pilot plant data.

Utilising the Spearman's Rank Coefficient to assign a dependency between the performance of a unit process and a characteristic of the influent to the unit is a convenient way to define a relationship. It can be used to define a non-linear relationship and relationships of varying significance without having to derive any equations or define constants. The method can be used to define many dependent variables referring to the same independent variable.

Although providing an improved data set the use of a dependency coefficient does depend on having suitable data available to allow calculation of the coefficient. Analysis of a large data set for several works would allow determination of a range of typical coefficients for a given unit process, allowing a suitable value to be selected for a new works.

However in the absence of such data the assignment of a distribution about a mean performance will allow an analysis to be carried out based on independence of the influent and performance distributions. The results of such an analysis will predict more failures than any analysis involving a dependency based correlation and so would provide a means of examining the predicted permit compliance with a margin of safety.

In the case study the technique illustrated that the return period for UTL failure for the BOD permit was 1 in 16 years for the single stage BAFF. The technique also confirmed that the COD permit would be exceeded every 14 months on the one stage BAFF. This return period was unacceptable to senior management, confirming the requirement of additional plant to meet the COD permit. During the period before the second stage BAFF is constructed there is a 1 in 16 year risk of exceeding the BOD permit. This was an acceptable risk for senior management in light of the cost savings associated with delayed construction of the second phase. The risk technique therefore allowed for a better informed decision concerning capital investment and allowed the risks to permit to be highlighted and understood.

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