MODELING TRICKLING FILTER EFFICIENCY UNDER VARIABLE LOADING

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ABSTRACT

The variation which occurs in wastewater flow and strength can have a substantial impact upon the effectiveness of treatment processes. Design equations are often based upon data obtained in steady-state laboratory studies and thus may not reliably predict efficiency under variable loading conditions. In order to determine the usefulness of such equations data were collected on a daily basis during most of 1995 at the Reading, PA municipal wastewater treatment plant. The data obtained during the first six months of the year were used to calibrate a modified version of the Velz equation for trickling filters. The equation was then used to predict the effluent quality over the entire year and the predicted and measured values were compared. The model was found to provide a satisfactory simulation of the actual plant performance under conditions in which the flow varied from 35,000 to 119,000 m$^3$/d, the temperature varied from nearly zero to 29.4°C, the BOD$_5$ concentration varied from 170 to 810 mg/l and the BOD load varied from 8800 to 68,000 kg/d.

Palabras clave: trickling filter, wastewater treatment, mathematical modeling, waste variability

INTRODUCTION

Wastewater is not constant in character from place to place nor from time to time. Further, the techniques commonly used in its sampling and analysis are subject to substantial error. The combination of inherent variability and experimental error produce considerable uncertainty regarding the actual characteristics in any given situation. In the United States the "typical" BOD$_5$ of domestic sewage is often said to be about 220 mg/l (Metcalf & Eddy, Inc, 1991), but this value, at best, is a nation-wide average which reflects neither differences from community to community nor from time to time at a single location. In the study reported in this paper, for example, data collected at the municipal treatment plant of the city of Reading, PA were utilized. The wastewater in Reading contains a substantial industrial component, much of it from a paper mill. The resulting waste is considerably stronger than "typical" sewage. During calendar year 1995 the average daily composite BOD$_5$ was 435 mg/l with a maximum of 810 mg/l and a minimum of 170 mg/l. Other contaminant concentrations exhibited similar variation: the total suspended solids concentration, for example, varied from 90 to 2000 mg/l with an average daily value of 520 mg/l. This, like the average BOD$_5$, is more than twice the "typical" value. In addition to variation in concentration, there are also variations in flow resulting from a variety of factors including water use, inflow and infiltration. During 1995 the daily flow in Reading varied from 35,000 to 119,000 m$^3$/d with an average value of 52,500 m$^3$/d. The contaminant load received by the plant is the product of concentration and flow. In the case of BOD$_5$, during 1995 the load ranged from 8800 to 68,000 kg/d with an average value of 22,800 kg/d.

Since Reading is located in the northeastern United States, there are also substantial temperature fluctuations during the year. In 1995 the temperature of the wastewater varied from close to zero to 29.4°C. Such temperature fluctuations have a decided impact upon biological treatment processes.

The natural variations in flow and waste strength complicate the process of design of wastewater treatment facilities. It is normally not sufficient to design for average conditions. In the United States, for example, waste discharge permits normally specify an average monthly concentration, an average weekly concentration and an instantaneous concentration which must not be exceeded. Thus, one must consider anticipated variations in waste strength, flow and temperature in assessing the adequacy of proposed treatment facilities. Unfortunately, it is not always clear what the effect of flows and loads different from the design conditions will be. Design procedures are often based upon empirical equations developed from measurements of average influent and effluent quality or upon theoretical equations developed from steady-state laboratory studies. There
is little published data concerning whether these equations provide a reliable prediction other than on an average basis.

This paper deals with the operation of a trickling filter plant. Such plants are not as common in present practice in the United States as are variations of the activated sludge process. Nevertheless, trickling filter plants have certain advantages which are significant in developing countries. Under the most favorable conditions no energy may be required, the materials needed are generally locally available and little skill or training is necessary for successful operation. The major operational problems associated with trickling filters are encountered in cold weather operation when freezing and reduced biological activity can have very severe impacts upon treatment efficiency. Such cold weather operation is addressed in the United States, when necessary, by covering the filters. In most of Latin America, particularly in the larger cities, extended periods of low temperature are not likely.

PLANT DESCRIPTION

The Reading, PA wastewater treatment plant was originally built in the early 19th century and has undergone a number of modifications and expansions since that time. At present the wastewater passes first through a series of preliminary treatment processes in which coarse suspended solids and grit are removed, respectively, on bar screens and in stirred sedimentation units. The flow then passes through primary clarifiers in which finer suspended solids are removed and then through a two-stage trickling filter process with intermediate and final clarification in which the bulk of the soluble and colloidal organic matter is removed. The final stages of the plant include a biological nitrification process, disinfection with gaseous chlorine and dechlorination prior to discharge to the Schuylkill River. Solids removed in the clarifiers are stabilized in heated anaerobic digesters prior to dewatering on belt filters. Liquid separated from the solids in the digesters and the belt filters is returned to the head of the plant.

The analysis presented in this paper is limited to the primary and secondary processes illustrated in the flow diagram of Fig. 1. The primary clarifiers are circular and have a total surface area of 3530 m$^2$, providing an average surface overflow rate of 27.7 m/d during the period of this study. The trickling filters are also circular and have a total area of 14,760 m$^2$; 8200 m$^2$ in the first stage and 6560 m$^2$ in the second stage. The filter depth is 1.98 m. The recirculation flow shown in the figure is pumped at a constant rate of 45,400 m$^3$/d, a rate equal to approximately 86 percent of the average daily flow during the study.

As noted above, the influent waste varied considerably in flow and concentration during the period of the study. The frequency distribution for BOD$_5$ concentration is presented in Fig. 2 and shows an approximately normal distribution with a mean of 435 mg/l. The frequency distributions for flow and load are presented in Fig. 3 and Fig. 4, with means of 52,500 m$^3$/d and 22,800 kg/d respectively. These figures exhibit somewhat more skew than does Fig. 1.
The plant discharge permit specifies an average monthly effluent BOD$_5$ of 20 mg/l in summer and 25 mg/l in winter and an average monthly TSS of 30 mg/l. These limits were met during the period of this study, as were the higher limits for average weekly and instantaneous maximum concentrations.

In order to evaluate the efficiency of the trickling filter process, it was necessary to separate the removal in the primary clarifiers from that in the secondary process. Since the wastewater in Reading was not "typical" in character there was no reason to expect that the primary clarifiers would provide the degree of removal expected in plants treating ordinary domestic wastewater. In order to evaluate the efficiency of the sedimentation process, 24-hour composite samples of the effluent from the primary clarifiers were collected on 28 occasions. On the days chosen the surface overflow rate varied from 38 to 44 m/d. At such overflow rates the BOD$_5$ removal predicted for ordinary domestic wastewater would be about 32 percent and the suspended solids removal would be about 57 percent (McGhee, 1991). The actual removals measured on those days averaged 48 percent for BOD$_5$ and over 70 percent for suspended solids. The unusually high BOD$_5$ removal in primary treatment is attributed to the nature of the waste - which contained a high concentration of suspended solids. In subsequent analyses it was assumed that the BOD$_5$ removal in primary treatment was 48 percent.

**Biological Process Analysis**

Trickling Filters use a relatively porous bacterial support medium such as rock or formed plastic shapes. Bacterial growth develops on the surface while oxygen is provided by diffusion through the void spaces. The wastewater is applied to the surface of the medium and percolates downward, flowing over the bacterial growth in a thin film.
The process can be represented as shown in Fig. 5. Nutrients and oxygen are transferred to the fixed water layer and waste products are transferred to the moving layer, primarily by diffusion. As the bacteria on the filter surface metabolize the waste and reproduce, they will gradually cause an increase in the depth of the slime layer. With thickening of the biological layer, the bacteria in inner layers find themselves in a nutrient-limited situation, since the organic matter and the oxygen are utilized near the surface. Eventually these interior cells die and lyse, breaking the contact between the slime layer and the support medium. When sufficient cells have lysed, the slime layer will slough off and be carried from the filter by the waste flow. The solids in the filter effluent are removed from the flow in a secondary clarifier.

Although trickling filters have been used for a great many years, their operation is still not readily described mathematically. The process rate is affected by mass transfer of oxygen to the liquid from the air and from the liquid to the bacterial slime; by transfer of biodegradable material from the liquid to the slime; and by the rate of utilization of the organic material by the bacteria (Mistry and Himmelblau, 1975). A variety of mathematical models of the trickling filter process have been suggested. Some of these are empirical (Rankin, 1955) while others are based upon a postulated reaction (Velz, 1948; Eckenfelder, 1963), a simplified analogy (Jank and Drynan, 1973) or more complicated hypotheses (Ames, et al., 1962; Logan, et al., 1987). Most of the theoretical models are impractical for design purposes since they include variables which are very difficult to evaluate and which may not be subject to engineering control.

A modified version of the Velz equation (McGhee, 1991) is frequently used in trickling filter design and was chosen as the basis for analysis in this study. The modified Velz equations which were used include the effects of temperature, recirculation, organic loading, hydraulic loading and filter depth, but do not include the specific surface area (the area of support medium per unit volume of filter). This variable is difficult to evaluate and its effect can be incorporated in the rate constant \( k_1 \) for a specific plant. The equations used may be written as follows:

For a single filter or the first filter of a two-stage process

\[
C_e = \frac{C_i + r C_e}{1 + r} e^{k(1.035^T-20)/(D/(Q/A))}
\]  

(1)

For the second stage of a two-stage process

\[
C_e' = \frac{C_e + r C_e'}{1 + r} e^{k(1.035^T-20)/(D_e C_e/1/(Q/A))}
\]  

(2)

In these equations

- \( C_i \) = influent BOD (mg/l)
- \( C_e \) = first stage effluent BOD (mg/l)
- \( C_e' \) = second stage effluent BOD (mg/l)
- \( r \) = ratio of recirculation flow to waste flow
- \( D \) = filter depth (m)
- \( k \) = experimental constant
\( T \) = temperature (°C)
\( n \) = experimental constant
\( A \) = filter surface area (m²)
\( Q \) = waste flow (m³/min)

The values of \( k \) and \( n \) in these expressions vary somewhat with the characteristics of the waste and the specific design features of the plant. For "typical" domestic sewage, \( k \) is usually taken as equal to 0.02 and \( n \) as equal to 0.5 when using the system of units specified above (Benefield and Randall, 1980).

In the case of the Reading plant, the wastewater was not "typical", hence it was necessary to adjust the experimental constants to match the conditions in the plant. This calibration was performed in two stages. First, the average daily temperature, flow and influent and effluent BOD were determined for the first six months of 1995. These values were then substituted in the equations and the values of the experimental constants were adjusted until the average condition was matched by the equations. The values which best matched the average condition were \( k = 0.055 \) and \( n = 0.50 \). With these values established on an average basis it was then possible to address the question of whether or not the equations could offer a reliable prediction on a day-to-day basis as the flow, BOD and temperature varied. Using the established values for \( k \) and \( n \), the measured flow and the measured influent composite BOD were entered on a daily basis. The measured influent BOD was then reduced by 48 percent to reflect the effect of the primary clarifiers. The resulting value represented \( C_i \) in Eq. 1. The recirculation rate, \( r \), was calculated by dividing the recirculated flow rate (45,400 m³/d) by the measured daily flow. The spreadsheet then calculated \( C_e \) using the filter area and depth and the daily flow and temperature. \( C_e \) was then calculated in a similar fashion, using the original data, the results of the first calculation, and Eq. 2. These calculated values were then compared to the values measured at the plant and were found to match reasonably well.

The intention of the study was to continue collecting data during the remainder of the year in order to observe the response of the model to continued variations in load and temperature and compare the calculated and measured effluent BOD values for the process. The data were collected and the calculations were performed as planned, however, during the months of July, August and September the flow bypassed the clarifiers following the secondary filters, going directly to the nitrification process. The effluent prior to the nitrification process still contained the solids sloughed from the filters, while that following the nitrification process reflected the additional biological treatment provided in that system. Neither set of data was considered representative of the filter operation. In October the flow was restored to the original pattern for the remainder of the year.
The model was used to calculate the theoretical effluent BOD$_5$ for the entire year using the procedure described above. The calculated values were then plotted and compared to the measured effluent BOD$_5$ (Fig. 6). As discussed above, data which were representative of the effluent of the trickling filter process were not available for July, August and September. The measured values are indicated by the symbol $+$, while the calculated values are represented by the solid line.

The variations in the calculated values reflect the daily changes in influent flow, BOD$_5$ and temperature. It must be noted that the influent BOD$_5$, as observed earlier, is subject to a variety of sampling and measurement errors - as is the measured effluent BOD$_5$. The variations in the calculated values are a result then, in part, of real variations in influent parameters and, in part, of experimental error. The variations in the measured effluent quality, similarly, are a result, in part, of real variations and, in part, experimental error. It is likely that the occasional very high values of measured effluent BOD$_5$, for example, result from experimental error. It is similarly possible that some of the very low measured values are also due to error. Since the calculated values depend upon the measured influent BOD$_5$, errors in those measurements would cause errors in the calculated values. Given these sources of potential error, it would be impossible for the calculated and measured values to coincide exactly. The question, rather, is whether the calculated values reflect the general trend of measured values and whether the calculated values offer an adequate prediction of the performance of the plant on a day-to-day basis.

If one were to fit a band to both the calculated and the measured values, the band for the measured values

![Figure 6 - Comparison of Theoretical and Measured Effluent BOD$_5$](image-url)
would include all the calculated values. Thus, the prediction is not unreasonable. It is possible that the effect
of temperature is somewhat understated in the model. The measured values in early summer were frequently
lower than predicted by the equation. The lack of data in July, August and September made it difficult to
examine this possibility in more detail. Some investigators (Bruce and Merkens, 1975) have suggested a
temperature coefficient of 1.08 rather than the value of 1.035 which was used here. Use of a higher value would
increase the sensitivity of the model to temperature.

CONCLUSIONS

The comparison of measured and calculated effluent BOD\textsubscript{5} values presented above offers a reasonable
assurance that tools such as the modified Velz equations can be used to predict the performance of a
treatment plant under conditions substantially different from those of the design. The equations shown were
calibrated for an average condition of \( C_{24} = 204 \text{ mg/l}, \ T_{25} = 7.33^\circ\text{C}, \) and \( Q_{26} = 35.9 \text{ m}^3/\text{min} \)
and then applied to a range of conditions in which \( C_{27} \) varied from 88 to 420 \text{ mg/l}, \( T_{28} \) varied from 0 to 29.4^\circ\text{C}, and
\( Q_{29} \) varied from 24.3 to 82.6 \text{ m}^3/\text{min}. The predictions of the model over this broad range compare favorably to
the measured values. It thus appears reasonable to assess the efficiency of a treatment plant under a broad
range of loading conditions using the modified Velz equations. One may therefore conclude that it is possible,
in the initial design, to consider the probability that the plant will exceed an stipulated value of effluent BOD\textsubscript{5}
based upon estimated or measured frequency distributions for BOD\textsubscript{5} and flow. This should be a valuable tool in
designing to meet standards which specify instantaneous maxima as well as average effluent concentrations.

REFERENCES

Sanitary Engineering Division, American Society of Civil Engineers, 88:SA3, 21.

Englewood Cliffs.

Bruce, A.M. and Merkens, J.C. (1973) "Further studies of Partial Treatment of Sewage by High-Rate Biological
Filtration" Journal Institute Water Pollution Control, (London) 72, 5.

of Civil Engineers, 128.

Jank, B.E. and Drynan, W.R. (1973) "Substrate Removal Mechanism of Trickling Filters" Journal of the
Environmental Engineering Division, American Society of Civil Engineers, 99:EE3, 187.

Model" Journal of the Water Pollution Control Federation, 59,1017.


New York.

Mistry, K.J. and Himmelblau, D.M. (1975) "Stochastic Analysis of Trickling Filter" Journal of the Environmental
Engineering Division, American Society of Civil Engineers, 101:EE3, 333.

Rankin, R.S. (1955) "Evaluation of the Performance of Biological Beds" Transactions American Society of Civil
Engineers, 120, 823.