Modeling the temporal behavior of influent flow rate in Wastewater Treatment Plants using second-order Fourier Series and statistical analysis

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Highlights:

- Introduced a pioneering approach for modeling the daily wastewater flow rate profile with acceptable hourly limits in WWTPs.
- Explored four methodologies for coefficient adjustment, emphasizing outlier removal and hourly median-based coefficient fitting using Discrete Fourier Transform.
- Analyzed historical data and demonstrated the model's effectiveness in identifying operational anomalies.

Keywords: Mathematical modeling; Fourier analysis; outlier detection.

INTRODUCTION

Mathematical models have been used to describe the behavior of many types of processes for years. Models for describing the dynamic behavior of influent parameters in Wastewater Treatment Plants (WWTPs) are valuable because they enable the generation of data for simulation of the plants when real data is unavailable or when the available data is insufficient (Dzubur and Serdarevic, 2020). Additionally, these models can serve as predictive tools with anticipation horizons of hours, providing forecasts on the behavior of variables, assisting in decision-making and process control (Stentoft et al., 2020).

Early models for influent wastewater parameters were developed in the 1990s. Carstensen et al. (1994) proposed and evaluated models based on harmonic functions to describe the behavior of ammonia and nitrate concentrations in the influent of the Aalborg West WWTP. Carstensen et al. (1998) addressed the challenge of predicting the hydraulic load of the influent in the same WWTP, considering the impact of rainfall. Subsequent studies employed these models for dynamic simulations and control strategies (Langergraber et al., 2008; Dzubur and Serdarevic, 2020). However, existing models lack descriptions of acceptable variable limits for different times of the day. This study introduces a mathematical model for daily influent flow rate profiles in WWTPs, specifying acceptable ranges for each hour, calibrated with historical data for precision and adaptability.

METHODOLOGY

This study used a dataset from a medium-sized WWTP in Curitiba, collected by Paula (2019) and Hernandez (2019) on five occasions over three consecutive days from July to November 2018. Influent flow rates were recorded hourly using a Nivetec SPA 390 ultrasonic meter sensor.

The initial analysis involved organizing the data according to the time of day and using descriptive statistics to identify key data characteristics and outliers, employing Tukey's method (Tukey, 1977) for outlier identification. The Discrete Fourier Transform (DFT) was calculated to analyze the influent flow rate's frequency content, aiming to detect typical 24-hour and 12-hour cycles.

A second-order Fourier series was used to model the daily pattern of influent flow rates. Model coefficients were determined using the first three components of the DFT and adjusted based on mean or median hourly values, considering the presence of outliers. Additionally, models for the upper and lower acceptable limits of influent flow rates were developed using the interquartile range method proposed by Tukey (1977).

Models were evaluated based on their fit to observed data and outlier detection ability, using the coefficient of determination (R^2) and accuracy metrics.

RESULTS AND CONCLUSIONS

The influent flow rate model was refined by focusing on data representing regular operational conditions, excluding periods affected by intense rainfalls that diluted organic loads and decreased biogas production. The Discrete Fourier Transform (DFT) revealed significant 24-hour and 12-hour cycles, confirming the expected daily patterns.

Four strategies for model coefficient adjustment (using mean, median, and their calculations excluding outliers) improved the coefficient of determination (R^2) from 98.6882% to 99.3072%. Removing outliers significantly enhanced performance, especially with the median.

To enable real-time monitoring and control, models for the upper and lower acceptable limits of influent flow rate were developed. These models define a range representing ideal operational conditions and were adjusted to fit hourly median data without outliers. The established models for upper and lower limits provide crucial parameters for ensuring the process stays within desired thresholds, enhancing treatment efficiency and stability.

The model's effectiveness in detecting outliers and anomalies was confirmed through a confusion matrix analysis, showing high accuracy in identifying both normal and outlier conditions. The model's accuracy in outlier detection was 97.1930%, demonstrating its utility in monitoring WWTP operations effectively.

To assess the model's effectiveness in identifying adverse operational conditions, an analysis using historical records of the studied WWTP was conducted. The proposed model was deployed to examine points collected over three consecutive days from July to November 2018. Historical data indicate that during October, there was a reduction in biogas production due to a dilution of the organic load, associated with high flow rates exceeding operational limits. Figure 1 illustrates the results, showcasing collected points alongside the model's curves and established limits.

This study introduced a comprehensive modeling approach to depict the daily influent flow rate behavior using a second-order Fourier series. Enhanced by outlier detection, the model has proven effective in fitting observed data points and in operational monitoring. This approach aids in maintaining optimal biogas production and serves as a predictive tool for managing WWTP operations, ensuring treatment efficacy and environmental compliance.

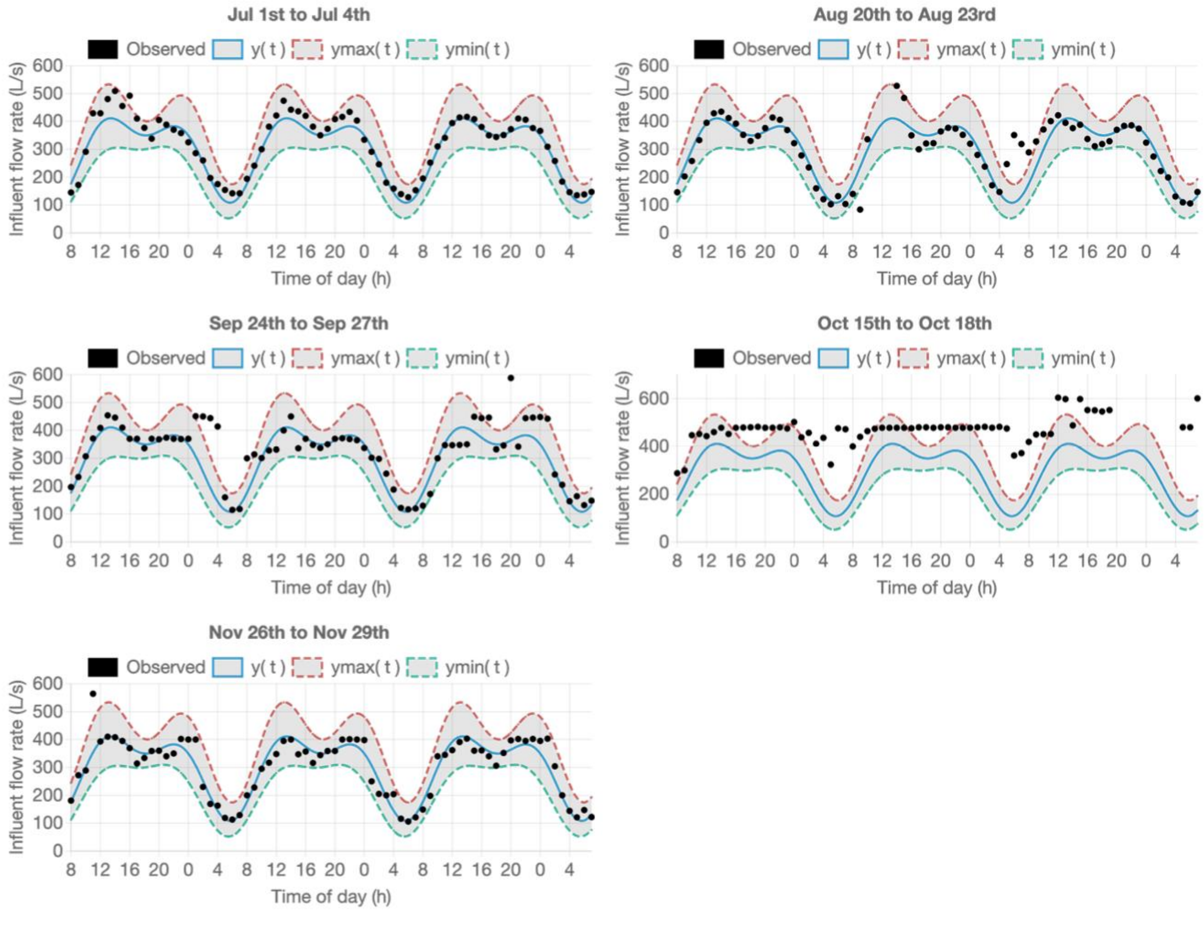

Figure 1. Comparison between historical sequence data and curve models

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