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A Monte Carlo-based integrated model to optimize the cost and pollution reduction in wastewater treatment processes in a typical comprehensive industrial park in China

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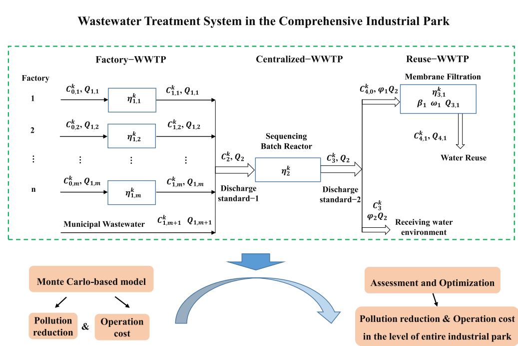
HIGHLIGHTS

- Models were set for pollutant reduction & operation cost at entire industrial park.
- Monte Carlo model was used to simulate the treatment and solve the models.
- Optimized and current pollutant reduction and operation cost were analyzed.
- Established model could improve wastewater pollution control in industrial park.
- Industrial parks should recycle water to expand economic, environmental benefits.

GRAPHICAL ABSTRACT

Wastewater treatment system in the comprehensive industrial park.



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ABSTRACT

Wastewater generated from an industrial park is usually characterized by large volumes, variation in composition, and high pollutant concentrations, and is generally toxic and difficult to biodegrade. Wastewater treatment at an industrial park includes several stages, namely, pretreatment inside factories (F-WWTPs), centralized wastewater treatment (C-WWTP), and reclaimed wastewater treatment (R-WWTP), during which the treatment efficiencies are mutually restricted. Therefore, water pollution control in industrial parks is extremely challenging. In this study, models, including those for pollutant reduction and operating costs, were established considering the F-WWTPs, C-WWTP, and R-WWTP stages at an industrial park. A Monte Carlo model was used to simulate the treatment and solve the above-mentioned models. Consequently, the characteristic values, including the extent of pollutant reduction, concentration of pollutants in the effluent, and operation costs, were predicted under optimal operating conditions of the wastewater treatment system. The established model was verified and applied to industrial park A in the Tianjin Economic-Technological Development Area in China. Based on the comparison of the above-mentioned optimization values with the sampled values as well as the theoretical analysis, the status of the wastewater treatment system in the industrial park was quantitatively

Abbreviations: BOD_5, biochemical oxygen demand after 5 days; CODcr, $K_2Cr_2O_7$-based chemical oxygen demand; NH_4-N, ammonia-N; SS, suspended solid; TP, total phosphate; Cu, copper; Cd, cadmium; Cr, chromium; Pb, lead; Hg, mercury; F-WWTP, pretreatment inside factories; C-WWTP, centralized wastewater treatment; R-WWTP, reclaimed wastewater treatment; TEDA, Tianjin Economic-Technological Development Area.

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evaluated to diagnose pertinent issues. Additionally, optimization and reformation strategies were proposed. Therefore, the established model can achieve optimization of pollution reduction and operation costs for the entire industrial park, thus contributing to industrial wastewater pollution control and water quality improvement.

1. Introduction

In China, surface waters with quality levels I, II, III, IV, V, and worse than V comprised 2.4%, 37.5%, 27.9%, 16.8%, 6.9%, and 8.6%, respectively of the total in 2016 (China Ministry of Environmental Protection, 2018). The main indicators of pollution in rivers are $K_2Cr_2O_7$-based chemical oxygen demand (CODcr), total phosphate (TP), and biochemical oxygen demand (BOD_5). In 2015, the CODcr and ammonia-N (NH_4-N) emissions attributable to wastewater were 22.2 and 2.3 million tons, respectively, of which industrial pollution accounted for 13.2% and 9.4% of the total, respectively, in China (China Ministry of Environmental Protection, 2017). Industrial wastewater generally contains complex hazardous substances, which are highly toxic and not easily biodegradable. The direct discharge of untreated industrial wastewater into surface water or groundwater can cause serious pollution and damage to human health and the environment (Englert et al., 2013; Wang and Yang, 2016).

Industrial park construction has been heavily promoted by the Chinese government, with 626 national-level and 1141 provincial-level parks currently in the country (China Association of Development Zones, 2017). Reductions in CODcr, NH_4-N, total nitrogen, and TP in the wastewater treatment plants at the industrial parks in Haihe Water Basin, China, contributed to 26.2%, 23.9%, 20.3%, and 29.0%, respectively, of total pollutant reduction attributed to municipal and industrial wastewater treatment. Therefore, it is important to control the treatment and discharge of wastewater generated in industrial parks to further control water pollution in China. The composition of industrial wastewater is complex. The properties and concentrations of pollutants in the discharged effluents from different industries, especially toxic and non-biodegradable pollutants, vary greatly. Often, factories discharge wastewater without effective pretreatment into a centralized wastewater treatment (C-WWTP) at the industrial park. The actual wastewater quality and amount of influent entering the C-WWTP are typically inconsistent with its design, and thus, the effluent may not be able to meet the requisite discharge standard (Kamali and Khodaparast, 2015; Ly et al., 2018). Additionally, the per capita water resource in China is 2100 m^3, which is only one quarter of the world's per capita level (Lopez-Diaz et al., 2015; Wang et al., 2015). Therefore, it is particularly important to recycle and comprehensively utilize reclaimed water resources. Previous studies have found that the C-WWTP in industrial parks in China are often negatively affected by the wastewater shock loading, and the treated effluent still contained the high pollutant concentrations, thus requiring further treatment (Zhu et al., 2016). Wastewater pollution control in an industrial park involves many steps, such as pretreatment (inside factories; F-WWTPs), centralized wastewater treatment (C-WWTP), and reclaimed wastewater treatment (R-WWTP). These different elements of a wastewater treatment system in an industrial park are connected and restricted by each other. At present, most research focuses on assessing the operational status for individual treatments (Djukic et al., 2016; Hernández-Sancho et al., 2010; Molinos-Senante et al., 2015). The lack of both a comprehensive analysis for wastewater treatment for the entire park, as well as effective coordination among treatment steps, raises the cost of wastewater treatment in the industrial park, contributes to the instability of effluent quality, leads to the risk of not meeting the discharge standard, and harms the surrounding environment (Bertanza et al., 2018).

Several uncertainties in the wastewater treatment system in an industrial park result from the complexity of natural phenomena, anthropogenic activities, and the wastewater treatment process. Additionally, these uncertainties randomly fluctuate within a certain range for the amount, quality, and removal efficiencies of wastewater. The Monte Carlo method provides a means for capturing the uncertainty in parameter estimation when performing simulations (Pérez-López et al., 2018). It is based on the central limit theorem and the law of large numbers in probabilistic statistical theory (Yuan et al., 2017). The law of large numbers indicates that the frequency of a random event is approximately equal to the probability of event occurrence after repeated trials. For example, a mechanistic model was coupled to the Monte Carlo method to consider the influence of activated sludge input uncertainty in the decision-making process during a multi-criteria evaluation of control strategies in a WWTP (Flores-Alsina et al., 2008). A supervised committee fuzzy logic model was used to predict the effluent quality parameters of a wastewater treatment plant (Nadiri et al., 2018). The Monte Carlo probabilistic risk assessment was applied to investigate the environmental risks for the European aquatic environment associated with triclosan occurrence in treated wastewater (Thomaidi et al., 2017).

The objectives of this study were to 1) establish models of pollutant reduction and operating costs considering the F-WWTPs, C-WWTP, and R-WWTP for an entire industrial park; 2) simulate the treatments and consequently predict the characteristic values under optimal operating conditions of the wastewater treatment system using the Monte Carlo models; 3) verify and apply the models in a typical industrial park, to quantitatively evaluate the status of the wastewater system as a whole and diagnose problems associated with it. The established model helps improve industrial wastewater pollution control and water quality.

2. Materials and methods

2.1. Model construction

2.1.1. Comprehensive analysis of a wastewater treatment system in an industrial park

Investigations of wastewater pollution treatment in industrial parks located in Haihe Water Basin and Taihu Water Basin in China indicate two main ways to treat the wastewater generated by industrial parks (Long et al., 2018). The first involved treatment of wastewater by the F-WWTPs, C-WWTP, and R-WWTP in the industrial park. Part of this treated water is reused inside the industrial park and the remaining is discharged into the receiving waters. In the second method, the wastewater treated by the F-WWTPs, C-WWTP, and R-WWTP in the industrial park (called effluent) is discharged into the receiving waters. The former is a combination of "control of pollution source, centralized treatment, and wastewater reuse," which is important for building an ecological industrial park and strengthening the management and recycling of water resources in industrial parks. Based on the material and economic flows of the entire industrial park, the pollution reduction and operating cost models for wastewater pollution control in industrial parks were established.

2.1.2. Pollutant reduction model

The pollutant model can be used to predict the total extent of pollutant reduction for the entire industrial park as well as the effluent concentration after treatment by the F-WWTPs, C-WWTP, and R-WWTP in an industrial park under optimal operating conditions. According to the characteristics of the industrial park's wastewater quality and wastewater discharge standards of typical pollutants, CODcr, NH_4-N,