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Optimization of Operation Conditions for Improving the Nitrogen Removal Efficiency in Wastewater Treatment Plant

질소제거효율 향상을 위한 하수처리장 최적 운전조건 도출 연구

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ABSTRACT
네덜란드 브리젠빈 하폐수처리장 최종방류수의 NH_4-N 및 TN(Total Nitrogen)농도를 방류수 수질기준인 각각 4 mg/L와 10 mg/L에 맞추기 위한 최적의 운전조건을 도출하기 위해 다양한 제어시스템이 시뮬레이션 되었다. 본 연구에 사용된 모델은 IWA (International Water Association) 활성슬러지 모델 No.1 (ASM No.1)이었고, GPS-X가 시뮬레이터로 사용되었다. 모델링을 위한 매개변수 민감도 분석결과 ASM No.1의 총 19개 매개변수 중 8개 변수 (Y_H, ksh, koh, b_H, μ_a, k_{NA}, kh, ka)가 방류수 수질에 영향을 미치는 것으로 조사되었고 이들 매개변수에 대해 보정을 수행하여 사용하였다. SRT, 호기/무산소기간, 외부탄소원 주입시간 변화에 따른 방류수질 변화를 시뮬레이션하였는데, 호기/무산소 11h/1h인 조건에서 SRT가 20일에서 25일로 증가되면 NH_4-N가 5.0 mg/L에서 2.9 mg/L로 감소되었고 호기/무산소 2h/1h의 조건에서는 SRT증가에 따라 NH_4-N은 큰 감소를 보이지만, 바이패스되는 유입수량의 감소로 탈질율이 낮아 방류수 TN이 11.1~11.5 mg/L로 예측되는 결과가 도출되었다. 탈질율을 높이기 위한 아세트산 주입은 동일한 양의 아세트산을 무산소 전기간 (1h)동안 균일 주입하는 것 보다는 무산소 초기 15분내에 주입하는 것이 효율적인 것으로 나타났다.

Keywords: N-removal, Oxidation ditch, ASM no.1, GPS-X, Parameter estimation, Simulation

NOMENCLATURE

b_H = Heterotrophic decay rate (1/d)
k_a = Ammonification rate (m^3/g COD/d)
k_h = maximum specific hydrolysis rate (1/d)
k_{NA} = Ammonia half saturation coefficient for autotrophs growth (g N/m^3)
k_{oh} = Oxygen half saturation coefficient (g O_2/m^3)
Y_H = Heterotrophic yield coefficient (g COD/g COD)
k_{sh} = Readily biological substrate half saturation coefficient (g COD/m^3)
μ_a = Autotrophic maximum specific growth rate (1/d)
μ_H = Heterotrophic maximum specific growth rate (1/d)

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I. INTRODUCTION

The communal wastewater treatment plant (WWTP) of Vriezenveen, the Netherlands consists of two trickling filters followed by an oxidation ditch. The oxidation ditch is operated by intermittent aeration to achieve N-removal based on alternating nitrification and denitrification. There is insufficient organic carbon (BOD) available for denitrification as most of the BOD is removed in the trickling filters.

One of the solution for carbon supply is that a certain amount of influent to the primary settler is bypassed directly to the oxidation ditch during the anoxic period.

Two control methods are applied for the aerobic/anoxic cycle time, i.e. set point control based on nitrate concentration (summer season) and fixed time control (winter season) for offering longer nitrification time in winter. However the WWTP of Vriezenveen has still a low nitrification rate in winter season and the denitrification rate is low too. As a result, the N-removal of the plant is too low during the winter. Therefore an external carbon source (acetic acid) is added during the winter season, but the required N-removal (NH_4-N<4 mg N/L, TN<10 mg N/L) is not obtained.

The aim of this study was to find out an appropriate operation method which one resulted in the lowest nitrogen concentration in the effluent. Model calibration and validation have been carried out for the WWTP of Vriezenveen and then the effect of each operation method was examined in higher SRT(Sludge Retention Time), different aerobic/anoxic cycle times, dosing time.

In this study, the system was simulated using Activated Sludge Model No. 1 (ASM1). ASM No.1 proposed by the International Water Association (IWA) task group on Mathematical Modeling for Design and Operation of Biological Wastewater Treatment are the most commonly applied mathematical models for the modelling of the biological compartments of wastewater treatment plants. The ASMs have been successfully applied to full-scale treatment plants and shown to be a good compromise between the complexity of the activated sludge processes and reduction of the plant behavior under dynamic conditions.

GPS-X (Hydromantis, 1999), developed by using a mechanistic approach which combines the robust IWA ASMs, is a modular, multi-purpose modeling environment for the simulation of municipal and industrial wastewater treatment plants. In this study GPS-X was used as a simulator.

II. MATERIALS AND METHODS

1. Description of Vriezenveen wastewater treatment plant

The WWTP of Vriezenveen consists of two main biological processes; biological conversion in a trickling filter and the activated sludge process in an oxidation ditch. Wastewater first passes a primary clarifier and then a trickling filter where most of carbonaceous matter (BOD) is removed. The next step is nitrogen removal by nitrification and denitrification in the oxidation ditch. The oxidation ditch (volume 1,700 m^3) is equipped with an on-line DO and NO_3-N analyzer and is operated at an SRT of 20 days treating an average flowrate of 4,300 m^3/d. The flow velocity in the ditch is 0.2-0.3m/s. The oxygen concentration maintained at 1.5 mg/L of DO. The aerobic/anoxic cycle time was controlled by time setting during the winter and during the summer, set point control was achieved based on nitrate concentration (4-8 mg/L NO_3-N). External carbon source (acetic acid, 85 %) as denitrification supporter during the anoxic period is only added in the winter period. The average temperature is 10 ℃ (in winter) and 17 ℃ (in summer).

2. Model calibration

Model calibration was carried out with the following steps: sensitivity test, parameter estimation and validation. A GPS-X simulator was used for calibration and simulation. The activated sludge model No. 1(Henze, et al, 1986) was used for the oxidation ditch and the simple 1d model (Horner et al, 1986) was used for the 2nd clarifier. Wastewater characterization was performed according to the STOWA-method (Roeleveld and Loosdrecht, 2002). The data of 2002-2003 was used for calibration of the model.

The model (Fig. 1) consisted of two influent streams (trickling filter effluent and influent of the primary settler as a bypass flow), an oxidation ditch by a loop of six equal CSTR(Continuous Stirred-Tank Reactor)'s and a secondary clarifier. The trickling filter effluent was modelled as a continuous stream and the bypass flow as a discontinuous stream (only during the anoxic period).

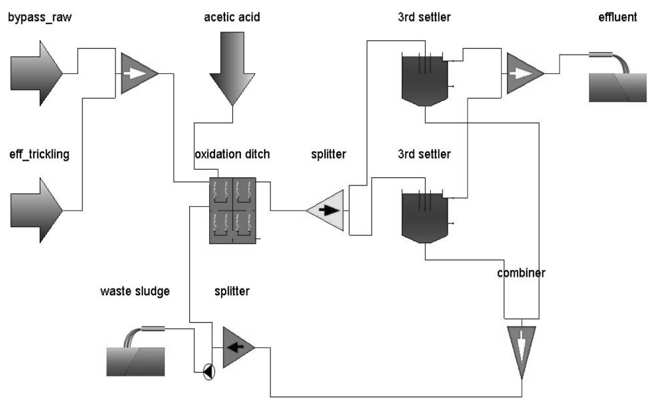

Fig. 1 Layout of Vriezenveen WWTP focused on the oxidation ditch

A. Sensitivity Test

The sensitivity test was conducted based on the performance assessment, developed for benchmarking of activated sludge systems by the COST 624 working group (Pons et al, 1999) and the IWA Task group on respirometry (Copp, 2000). Performance assessment for benchmarking consists of four sub-levels: effluent quality (EQ), pumping energy (PE), aeration energy (AE) and total sludge production (TSP). Except EQ, all levels are related to cost-factors for operation. In this work only the EQ-index was used in order to detect the main effects of the parameters on the effluent quality. All the parameters were in turn varied around their default value, while the others remained fixed.

The effluent quality index (EQ) (kg pollution /d) is defined as:

$$EQ = \frac{1}{T*1000}\int_{t=0}^{t=0+T}\begin{pmatrix} B_{SS}*SS_e(t) + B_{COD}*COD_e(t) + B_{NKj}*S_{NKj}(t) + \\ B_{NO}*S_{NO,e}(t) + B_{BOD5}*BOD_{5,e}(t) \end{pmatrix}*Q_e(t)dt \quad (1)$$

$$S_{NKj,e} = S_{NH,e} + S_{ND,e} + X_{ND,e} + i_{XB}(X_{BH,e} + X_{BA,e}) + i_{XP}(X_{P,e} + X_{i,e}) \quad (2)$$

$$SS_e = 0.75\,(X_{S,e} + X_{I,e} + X_{BH,e} + X_{BA,e} + X_{P,e}) \quad (3)$$

$$BOD_{5,e} = 0.25(S_{S,e} + X_{S,e} + (1-f_p)\cdot(X_{BH,e} + X_{BA,e})) \quad (4)$$

$$COD_e = S_{S,e} + S_{I,e} + X_{S,e} + X_{I,e} + X_{BH,e} + X_{BA,e} + X_{P,e} \quad (5)$$

The $B_{SS} \sim B_{BOD5}$ are weighting factors for the different types of pollution to convert them into pollution units (Table 1). The weighting factors have been deduced from Vanrolleghem et al. (1996).

Table 1 Weighting factors for the different types of pollution to convert them into pollution units

Factor	B_{SS}	B_{COD}	B_{NKj}	B_{NO}	B_{BOD5}
Value(g pollution /g)	2	1	20	20	1

B. Parameter Estimation and Validation

Based on the results of the sensitivity tests, 8 model parameters: (Y_H, ksh, koh, b_H, μ_a, kna, kh and ka) were selected for parameter estimation, for the other model parameters ASM No.1 default values (Henze, et al, 1986) were used. Input/output and operational data of 2003 summer (May to September) and 2003 winter (October to December) were used to estimate the parameters of each period. Measured variables were temperature (mean value of summer and winter: 17 and 10 ℃), MLSS/MLVSS (Mixed Liquor (Volatile) Suspended Solids) in the oxidation ditch, flowrate, BOD_5, CODtot, TKN, NH_4-N of influent/effluent, and effluent SS, NO_3-N. The estimation procedure was carried out with the optimiser module of GPS-X. The data of January 2002 - April 2003 (BOD, COD, TKN, TN, NH_4-N, NO_3-N, SS and MLSS) were used for validation.

3. SIMULATIONS

The simulations were focused on the effects of the SRT, aerobic/anoxic time and acetic acid dosing on the effluent nitrogen concentration. The SRT was varied between 20 and 30 days by controlling the flowrate of waste sludge. The defined aerobic/anoxic cycle times were 1h/1h and 2h/1h.

In practice, acetic acid (about 19 kg COD/cycle) is added to the oxidation ditch in 30 minutes time during the anoxic period. In this simulation, the same amount of acetic acid was added during the anoxic period (aerobic 2h /anoxic 1h) with dosing times of 15 min, 30 min and 60 min. In the cases of 15 and 30 min, the anoxic period was still 60 min. The temperature in the oxidation ditch was 10 ℃ in winter and 20 ℃ in summer.

III. RESULTS AND DISCUSSIONS

1. Vriezenveen WWTP

The treatment plant was first constructed to remove only organic matter (trickling filter process) and later extended for nitrogen removal. The TKN concentration of the wastewater was 61 mg N/L and BOD 253 mg/L (2002-2003 average) resulting in a BOD/TKN ratio of 4.1. However, the primary clarifier and the trickling filters removed most of the BOD. The overflow of the trickling filters only contains 35 mg/L of BOD and 25 mg TKN/L (BOD/N=1.4). For supplementing extra BOD,

Table 2 Results of parameter estimation

Parameter		Y_H	ksh	koh	b_H	μ_a	k_{NA}	kh	ka
Unit		g COD/g COD	g COD/m^3	g O_2/m^3	1/d	1/d	g N/m_3	1/d	m^3/g COD/d
Default value		0.67	20	0.2	0.62	0.8	1	3	0.08
Estimated value	summer	0.66	20.7	0.4	0.64	0.9	0.9	3	0.07
	winter	0.66	27.5	0.1	0.62	0.33	0.8	2.6	0.03

influent of the primary settler was bypassed directly to the oxidation ditch in the anoxic period and in winter also external carbon source was added (85 % acetic acid, 19 kg COD/cycle).

2. Model calibration

A. Sensitivity test

Fig. 2 shows the results of the sensitivity tests. This figure presents the standard deviation of EQ index relative to the ASM No. 1 default values for 16 different model parameters. The EQ index is significantly sensitive to only eight parameters: Y_H, ksh, koh, b_H, μ_a, k_{NA}, kh, and ka and among these, ksh, μ_a, b_H and kh are revealed as the most sensitive to the EQ index. Even μ_h is known as a significant parameter for COD removal (Abusam et al, 2001), but due to weighting factors which were adopted in the EQ index equation to focus on nitrogen removal, it has less sensitivity to the EQ index.

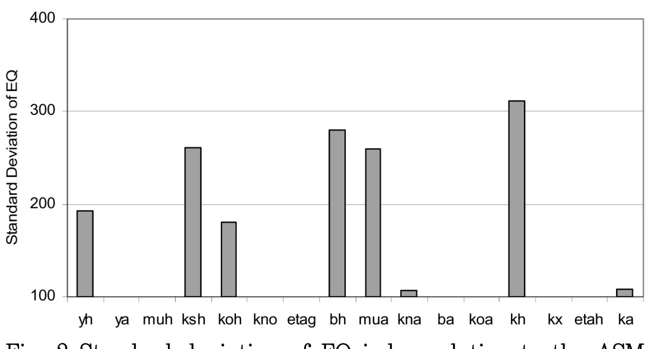

Fig. 2 Standard deviation of EQ index relative to the ASM No. 1 default value.

B. Parameter estimation

Table 2 presents the results of the parameter estimation and most of parameters have almost the same value as the default values of ASM No. 1 except μ_a and ka which are connected with nitrifier's growth and ammonification rate, respectively. Discrepancy of these value can explain why nitrification rate is lower and as a results the effluent NH_4-N concentration is higher in winter.

C. Validation

In Fig. 3, the simulation results over one and half year are plotted together with the real data set. The simulation results shows similar tendency of observed data, however during early 2003, the plant was operated with unusual aerobic/anoxic times and this explains the small discrepancy for TN during that period.

3. Simulation

A. Effects of the SRT and aerobic/anoxic time

Simulations at winter conditions (time controlled; addition of acetic acid) are presented in Table 3. At an SRT of 20 days and an aerobic/anoxic time of 1h/1h, the effluent NH_4-N and TN are 5.0 mg N/L and 10.3 mg N/L respectively, thus higher than the required 4.0 and 10 mg N/L. Increasing the aerobic time (2h/1h) results in a decrease of NH_4-N but NO_3-N increases, because less wastewater is bypassed in anoxic period. Increasing the SRT from 20 to 25 and to 30 days (aerobic/anoxic time 2h/1h) has almost no effect on the NH_4-N and NO_3-N concentrations.

Increasing the SRT to 25 days and then 30 days (1h aerobic/1h anoxic) results in a decrease in NH_4-N and smaller increase in NO_3-N compared with a SRT of 20 days. The concentration of nitrifiers is increased resulting in a higher nitrification rate and more nitrate production, but as a result of relatively insufficient substrate not all the extra nitrate is removed, resulting in an increase of the nitrate concentration; the sum of NH_4-N and NO_3-N decreases gradually. Increasing the SRT improves thus the NH_4-N and TN and they are below the limits of 4 and 10 mg N/L respectively.

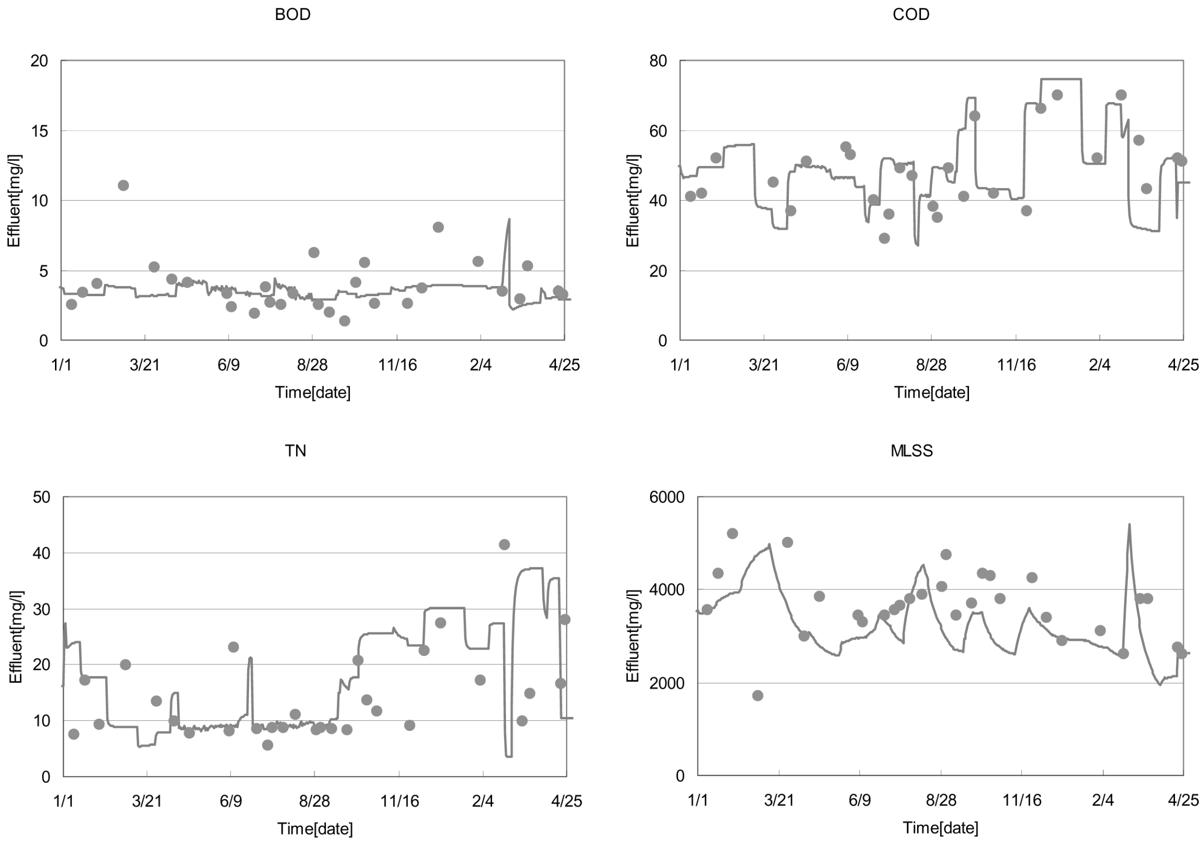

Fig. 3 Results of model validation: dot-observed, line-simulated

Table 3 The effect of changing SRT and aerobic/anoxic cycle time to effluent nitrogen concentrations

Time controlled	Aerobic/anoxic=1h/1h			Aerobic/anoxic=2h/1h		
SRT	20 days	25 days	30 days	20 days	25 days	30 days
Effluent BOD (mg/L)	3.8	3.6	3.7	3.6	3.5	3.4
Effluent NH_4-N (mg N/L)	5.0	2.9	2.5	1.5	1.3	1.2
Effluent NO_3-N (mg N/L)	3.7	4.5	4.6	8.4	8.3	8.2
Effluent TN (mg N/L)	10.3	9.2	8.9	11.5	11.2	11.1

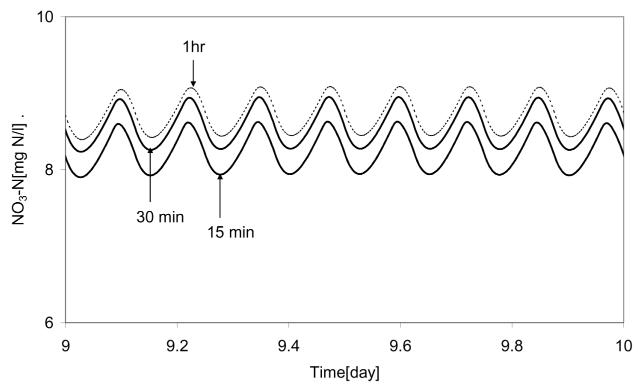

Fig. 4 The effect of acetic acid dosing time on NO_3-N in the effluent

B. Effect of dosing time

Acetic acid is in general added during the first 30 minutes of the anoxic period. The effect of the acetic acid dosing time was simulated (Fig. 4). The same amount of acetic acid (19 kg COD/cycle, aerobic 2h/anoxic 1h) was added to the oxidation ditch but in different dosing times: 15, 30 and 60 min. Decreasing the dosing time results in decrease of effluent NO_3-N to 0.5 mg N/L and 0.6 mg N/L, respectively.

Fig. 5 shows the effect of the dosing time on the denitrification rate (DNR). The DNR increases immediately when acetic acid is added and decreases sharply at the end of the dosing period except in case of dosing time 1hr. By shortening the dosing time the DNR increased from 2.9 to 6.8 mg N/L.h. The observed DNR in the plant,

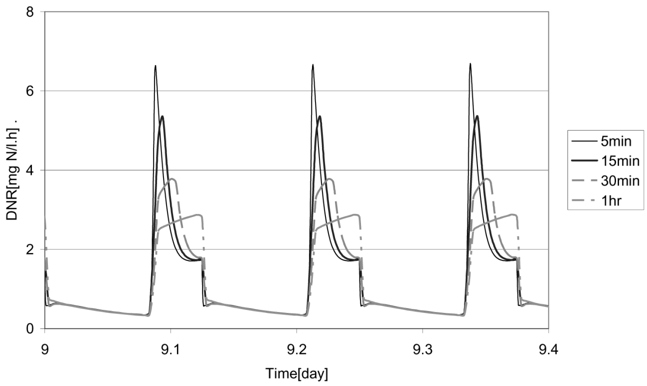

Fig. 5 The effect of acetic acid dosing time on DNR.

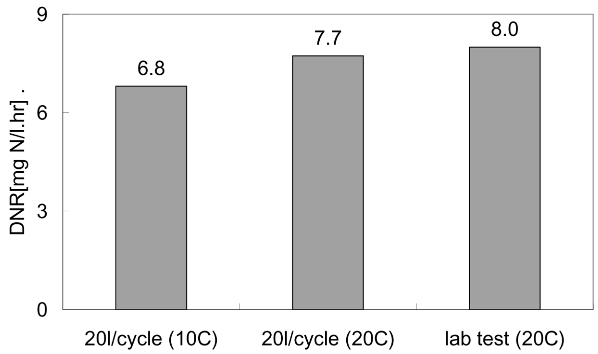

Fig. 6 Comparison of simulated DNR and DNR from a lab test

in case of no acetic acid dosage but bypass of influent of the primary settler is 1.8 mg N/L.h and it can explain that in this plant, lower dinitrification rate are derived from less organic carbon.

The DNR of the simulation was validated with a lab test at a temperature of 20 ℃ (Fig. 6). The acetic acid was added at the start of the test to measure the maximum DNR. The result of this test was almost the same as the DNR with 5 min dosing time at 20 ℃. The DNR in the simulation at 10 ℃ is of course lower. The result of the lab test confirms that the simulation results represent the plant situation quite well.

IV. CONCLUSIONS

The WWTP of Vriezenveen (intermittent aeration in an oxidation ditch) was modelled in three steps. 1) Based on the sensitivity test the model parameters Y_H, ksh, koh, b_H, μ_a, k_{NA}, kh and ka are mainly determining the effluent quality. 2) Parameter estimation with 2003-summer and winter data resulted for these parameters in values that were almost the same as the ASM No. 1 default values except μ_a and ka 3) The simulation results fitted with the 2002-2003 data.

Three control systems to improve N-removal were simulated, 1) Increasing the SRT 2) Increase of the aerobic time 3) Decreasing of the acetic acid dosing time and increasing dosage.

Increasing the SRT (aerobic/anoxic: 1h/1h) results in a lower NH_4-N and a small increase of NO_3-N because of insufficient available organic carbon. An aerobic/anoxic time of 2h/1h instead of 1h/1h results in lower NH_4-N but higher NO_3-N because of less bypass flow and longer aeration periods. Decreasing the dosing time of acetic acid without changing the total anoxic period results in decrease of NO_3-N and TN.

Increasing the SRT, aeration periods and dosage of acetic acid on the anoxic period results in NH_4-N and TN below 4 mg N/L and 10 mg N/L, respectively.

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