Environmental impact assessment of a sewage treatment plant under different operating conditions

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Abstract: Environmental impact assessments of sewage treatment plants should consider not only emissions of greenhouse gases (GHG) from electricity use, but also N2O emissions generated by nitrogen removal processes, and the release of nitrogen nutrients into the water environment. Additionally, ecotoxicity of unionized ammonia is high, however no existing environmental impact assessment methodology addressed it. This study developed a methodology to evaluate the ecotoxicity of NH3 in the context of life cycle assessment. Nitrogen flow was measured in functioning sewage plants, allowing the environmental impact of changes in operating conditions, such as nitrification-inhibited or nitrification-promoted operation, to be compared. Result showed that in consideration of integrated environmental impacts, taking into account nitrogen emissions from discharge water and GHG emissions, nitrification-promoted operation is more preferable than nitrification-inhibited operation.

Keywords: sewage plant; nitrification; nitrous oxide; unionized ammonia; life cycle assessment

Introduction

Environmental impact assessments of sewage treatment plants should consider not only emissions of greenhouse gases (GHG) from electricity use, but also N_2O emissions generated by nitrogen removal processes, and the release of nitrogen nutrients into the water environment. The nitrogen composition of treated water and level of GHG emissions vary widely across sewage treatment plants according to the nitrification process employed.

Biological nitrogen removal is carried out in two steps: conversion of NH_4^+ to NO_3^- by nitrification in the aerobic condition followed by the conversion of NO_3^- to N_2 gas by denitrification in the anoxic condition. Nitrous oxide (N_2O) is generated in these two steps and discharged into the atmosphere. Approximately 7,000,000 tons CO_2/year of greenhouse gases (GHGs), including CO_2 and N_2O, are generated from sewage treatment plants in Japan. In particular, N_2O has a greenhouse effect approximately 300 times stronger than that of CO_2 (IPCC, 2001). In sewage treatment, nitrogen composition of treated water and GHG emissions from treatment processes varies widely depending on the condition of nitrification in the process. The conversion ratio to N_2O to the nitrogen load has been reported for 0-95% in the laboratory-scale and 0-14.6% in a full-scale (Kampschreur et al, 2009). Therefore, environmental impact assessments of sewage plants should be focus on not only emissions of GHG from electricity but also emissions of N_2O from nitrogen removal processes, along with the release of nitrogen nutrients into the water environment.

On the other hands, the high toxicity of unionized ammonia (NH_3) to aquatic life (Camargo et al., 2006) is well researched and ecotoxicity of NH_3 for some species (Servizi et al., 1990, Markle et al., 2000, and Kohn et al., 1994) have been assessed. In particular, consideration of the ecotoxicity of ammoniac nitrogen is essential when determining the operating conditions for lower environmental loads. However, an

Table 1 Operating condition of sewage treatment plant

Treatment process		Conventional activated sludge prosess	
Operation		Nitrification-inhibited	Nitrification-promoted
Period		−2012/6	2012/6−
Flow rate	(m^3/d)	23500	24700
Aeration rate	(m^3/d)	77000	91000
MLSS	(mg/L)	1100	1300
HRT	(h)	8.0	8.0
SRT	(d)	6.2	7.1

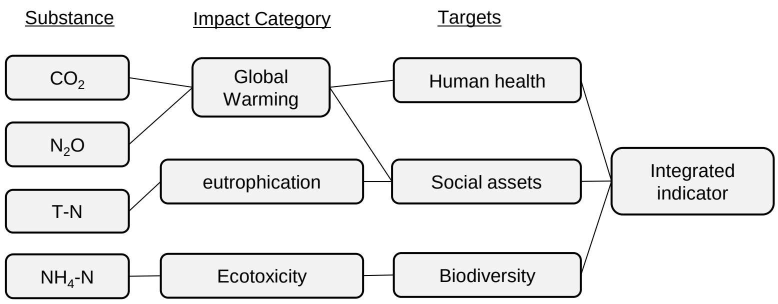


Figure 1 Targets of environmental impact estimation

evaluation methodology to comprehensively consider all associated environmental impacts of sewage treatment plants is not yet fully developed.

Life cycle assessment (LCA) is a known technique for evaluating various environmental impacts and has been widely applied to sewage treatment systems (Corominaset et al., 2013). However, research examining the trade-off between environmental impact and changes in operating conditions is minimal. Although a number of life cycle impact assessment methodologies have recently been developed (Steen, 1999, Goedkoop et al., 2009, Itsubo et al., 2012), none have addressed the ecotoxicity of NH_3. Consequently, there is a need to broaden existing techniques in order to consider this important aspect of sewage treatment, and thereby support decision making with regard to service conditions and suitable equipment. This study developed a methodology to evaluate the ecotoxicity of NH_3 in the context of life cycle assessment. In addition, nitrogen flow was measured in functioning sewage plants, allowing the environmental impact of changes in operating conditions, such as nitrification-inhibited or nitrification-promoted operation, to be compared.

Material and Methods

Investigation of a working sewage treatment plant operated using the conventional activated sludge process was conducted in the Saitama Prefecture, Japan (actual flow rate: approximately $24*10^3$ m^3/d). The operating condition of sewage treatment plant is described in Table 1. The overflow water in the final sedimentation tank was collected as effluent and the nitrogen composition analyzed. N_2O in gases were collected before entering the deodorizing tower and measured using a N_2O meter. It

Table 2 Damage factors

	Targets	Damage coefficients	Unit
CO_2	Human Health	1.31E-07	DALY/kg-CO_2
N_2O	Human Health	3.91E-05	DALY/kg-N_2O
CO_2	Social Assets	3.23E-01	JPY/kg-CO_2
N_2O	Social Assets	1.45E+02	JPY/kg-N_2O
T-N	Social Assets	8.25E+01	JPY/kg-T-N
NH_4-N	Biodiversity	-	EINES/kg-NH_4-N

Table 3 Economic value conversion factors

Targets	Economic value conversion factors	Unit
Human Health	1.47E+07	JPY/DALY
Social Assets	1	JPY/JPY
Primary production	46.2	JPY/kg
Biodiversity	1.42E+13	JPY/EINES

was reported that there were two kinds of N_2O discharge from wastewater treatment process, gaseous discharge into the atmosphere and dissolved discharge into the water environment (Foley et al, 2010). Therefore, both gaseous N_2O and dissolved N_2O were measured, and totaled in this study. The emissions of CO_2 from the aeration process were estimated based on the electricity consumption of the sewage treatment plant.

The environmental impacts of eutrophication, ecotoxicity, and global warming were evaluated based on LIME2 (Itsubo et al., 2012), a life cycle environmental impact assessment methodology established for Japan. In this methodology, it is possible to evaluate these impacts by converting the environmental impact into an economic value.

This was accomplished by multiplying economic value conversion factors and damage factors, which indicate impacts on targets needing protection (human health, social property, and biodiversity) per unit emission of environmental load, with evaluation of environmental emission loads. The relationship between substances, environmental problems, and targets of concern to sewage systems, is shown in Figure 1. Factors related to CO_2, N_2O, and T-N have already been developed in LIME2 (Tables 2 and 3). However, that of un-ionized ammonia has not yet been estimated; therefore, in this study, an NH_3 damage factor was developed and included as a part of the LIME2 technique.

Equations (1) - (5) and figure 2, show the method used to estimate the environmental impact of NH_3. Environmental impact was calculated by multiplying the damage factor and the economic value conversion factor (Expression 1). The damage to biodiversity with NH_3 was assessed by the expected number of species extinctions (EINES) over a defined number of years. The number of extinct species was calculated using the increased density of the water environment determined by the model based on LIME2 methodology, and then estimated using the damage factor according to environmental conditions in the Saitama Prefecture or Japan. The model, which estimates the increase of species extinction, implements a function between NH_3 concentration and extinction probability according to species group and rank (by threat of extinction) as well as LIME2. The index concerning the toxicity data (in animals the LC50 is the density where half the number of individuals die by the toxicity test) is included in the parameter of this function.

The ECOTOX database (USEPA, 2006) was used for this study, with geometry averaged LC50 values for each species group investigated. As there was insufficient data on other species groups, our impact estimate was only targeted on fish and crustaceans, in contrast to LIME2, which targets six species groups. This study used the toxicity parameter (LC50) for fish of 14.5 mg/L and 14.4 mg/L for crustaceans. Other parameters (rate of natural increase and environmental capacity, etc.) used set values in LIME2. The output of these functions in current density is an increment of the extermination probability by the increase in unit density. Increase in EINES by the unit density rise of NH_3 was calculated by multiplying the inclination of function and number of species by species groups and rank in threat of extinction (Equation 3).

Unionized ammonia, the strongly toxic form of NH_4-N, is in an equilibrium condition in the case of ammonium ions (NH_4^+) in solution, and it is known to be dependent on pH and water temperature. The ratio of NH_3 increases as the water temperature or pH rises. Therefore, even if the magnitudes of NH_4-N emissions from different sewage treatment facilities are fairly identical, the magnitudes of increase in NH_3 densities differ, according to the effluent drained from the aquatic environment. We used the equation by Emerson et al. (1975) to estimate the existence ratio of NH_3 (Equation 4, Figure 3).

For estimation purposes, this study used 10% of the trimmed mean of pH and water temperature from the results of a nationwide water quality survey of public areas in Saitama Prefecture. Moreover, aquatic NH_3 concentrations were also calculated in a similar fashion, using NH_4-N data and the existence ratio of NH_3, since non-ionized ammonia was usually not directly observed.

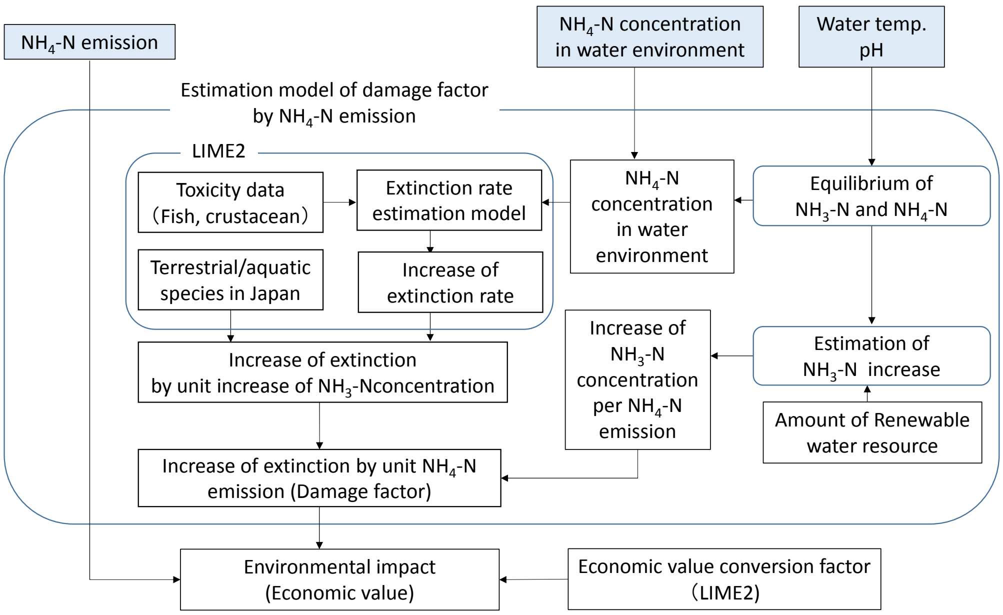


Figure 2 Estimation flows of the environmental impact of NH_3

$$EI = E_{NH4-N} * DF_{NH4-N} * WF \qquad \textbf{(1)}$$

$$DF_{NH4-N} = DF_{NH3-N} \frac{[NH_3 - N]}{[NH_4 - N]} * \frac{\Delta[NH_4 - N]}{\Delta NH_4 - N} \qquad \textbf{(2)}$$

$$DF_{NH3-N} = \sum_i \sum_j \left(\frac{\delta f_{ij}(x, LC50_{ij})}{\delta x} * N_{ij} \right) \qquad \textbf{(3)}$$

$$[NH_3 - N]/[NH_4 - N] = \frac{1}{1 + 10^{-0.09018 - 2729.92/T} / [H^+]} \qquad \textbf{(4)}$$

$$\frac{\Delta[NH_4 - N]}{\Delta NH_4 - N} = 1/w \qquad \textbf{(5)}$$

Here, EI :Environmental impact [Yen], E_{NH4-N} : NH4-N emission [kg-N], DF_{NH4-N} : Damage factor of NH4-N emission [EINES/ kg-N], WF : weighting facto (economic value conversion factor) [円/EINES], DF_{NH3} : damage factor of NH3 [EINES/ (mg/L)], $[NH_3 - N]/[NH_4 - N]$: ratio of NH3 in NH4-N of environmental water[-]、

$\frac{\Delta[NH_4 - N]}{\Delta NH_4 - N}$: increase of NH4-N concentration by unit NH4-N emission[(mg/L)/kg]、

$\frac{\delta f_{ij}(x)}{\delta x}$: increase of NH4-N extinction probability by unit increase of NH4-N concentration [EINES/(mg/L)], N_{ij} : Number of species in specie group *i* and rank in threat of extinction *j* in Japan, x : NH3 concentration in environmental water [mg/L)]、$LC50$: index of ecotoxicity, *i* : species group（Fish and crustacean）、*j* : rank in threat of extinction (four ranks), *T* : water temperature[℃]、wr :total renewable water resource in Japan [m^3].

The emitted NH_4-N was diluted by natural water and contributed to a rise in NH_3. The rise in the aquatic NH_4-N density in the unit emissions of sewage plants was estimated as expressed in Equation 5. It was assumed that the NH_4-N was diluted uniformly in a wide geographic range. A dilution water volume of 410 km^3 was assumed to be equivalent to the total volume of renewable water resources in Japan, MLIT, 2008), although the extent of the impact of NH_3 was actually geographically limited.

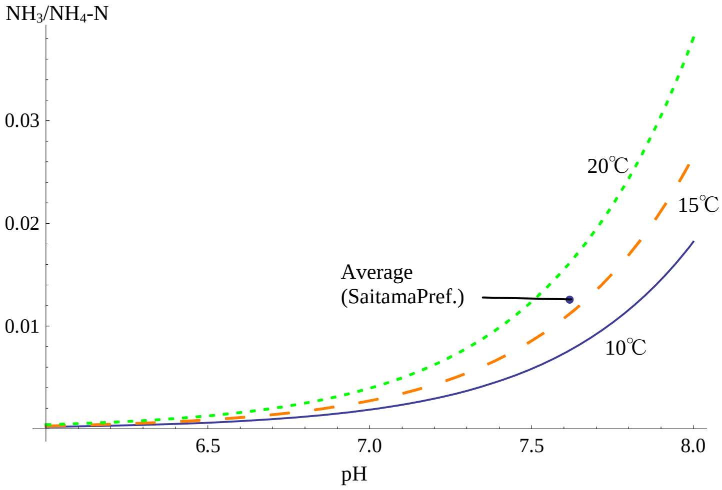


Figure 3 Relationship between water temperature, pH and ratio of NH_3 in NH_4-N

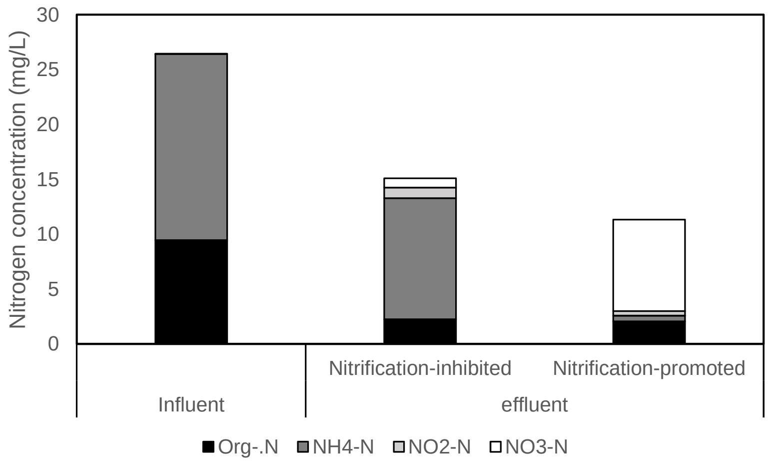
Since it was assumed that the rise in NH_4-N concentration per unit emission is small compared with the density in an aquatic environment (3.04*10-11 mg/L per 1kg of emission), an increase in the extinction probability with the rise in concentration was estimated by using the inclination of the density function, and the extermination probability.

We calculated the damage factor of NH_4-N using the unit increase of NH_3 per unit of NH_4-N, and increments in the number of extinct species as explained above. The environmental impact was then estimated by multiplying the damage factor, the economic value conversion factor, and the NH_4-N emission from the sewage plant.

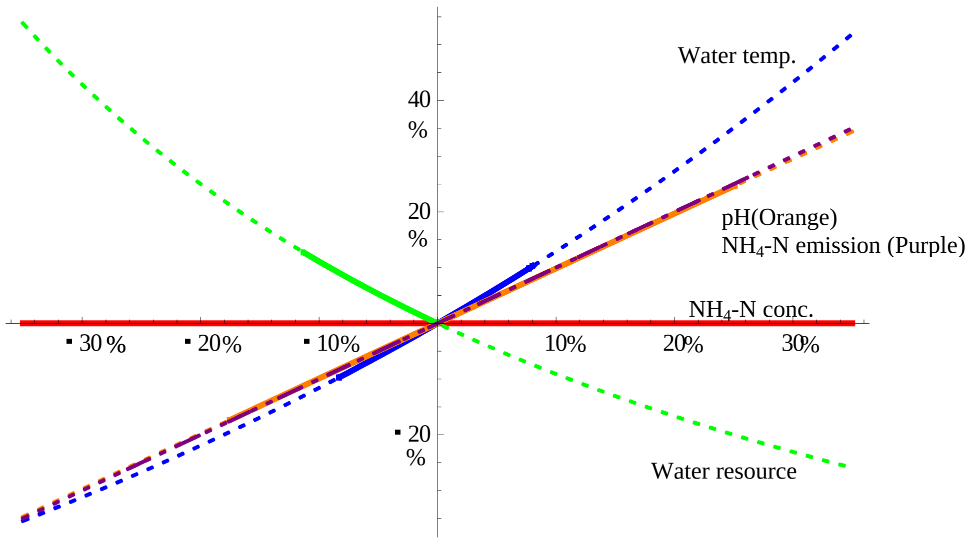
.Results and Discussion

Figure 4 shows the measurement results for nitrogen components in sewage treatment-plant influent and effluent under different operating conditions. Effluent in nitrification-promoted operation mainly contains NO_3-N, while that of nitrification-inhibited operation contains mostly NH_4-N, with an absence of NO_3-N. Nitrification-promoted operations resulted in lower N_2O emissions from the treatment process, but CO_2 emissions from electricity use in the aeration process were increased.
As shown in Table 2, the estimated damage factor of NH_3 was 3.39 x 10^{-11}. Using this value, the impact of NH_3 on the ecosystem was equivalent to 11,900 yen/day in the case of nitrification-promoted operations. A sensitivity analysis was adopted to

evaluate the variability of the effect of this factor. The results are illustrated in Figure 5. Increases in water temperature, pH, and NH_4-N concentrations increased the magnitude of the factor, although the water resource amount resulted in a decrease. The effect of pH was larger than that of water temperature, when considering a possible range of variables. Figure 6 shows the sensitivity analysis results when setting the LC_{50} value by species group. Separating the data by species groups suggested that the impact on fishes was much higher as compared to crustaceans, because of sensitivities to NH_3. This finding also indicates that the reliability of the LC_{50} value is important for the accuracy of the estimated damage factor, because a 20% increase of the LC_{50} value roughly results in a 20% decrease of the damage factor.



. **Figure 4** Breakdown of nitrogen emitted



<Water temp> Range: 25% and 75% of the measurement value in Saitama Pref., 2011.
<pH> pH in this graph is alternated with [OH^-]. An increase of the indicator shows an increase in pH. Range: 25% and 75% of the measurement value in Saitama Pref., 2011.
<NH_4-N Concentration>Range: 25% and 75% of the measurement value in Saitama Pref., 2011.
<Water resource> Range: average year maximum, 25% of the minimum precipitation value from 1990 to 2010
< NH_4-N emission> Range: average $\pm$ σ (Standard deviation) of measurement

Figure 5 Sensitivity analysis of impact coefficient of NH_3, with possible range of variables (Solid line)

Weighted environmental impacts using LIME2 are shown in Figure 7. Nutrients from the nitrification-promoted operation contributed to negative ecosystem impacts. Specifically, eutrophication in aquatic ecosystems caused by nutrients is of concern with nitrification-promoted operations. In contrast, ecotoxicity is the most significant impact of nitrification-inhibited operations. Trade-offs between greenhouse gas emissions and water-related loads (eutrophication and ecotoxicity, respectively) were identified in this study. It was found that nitrification-promoted operations have an advantage over nitrification-inhibited operations when life cycle environmental impacts are considered.

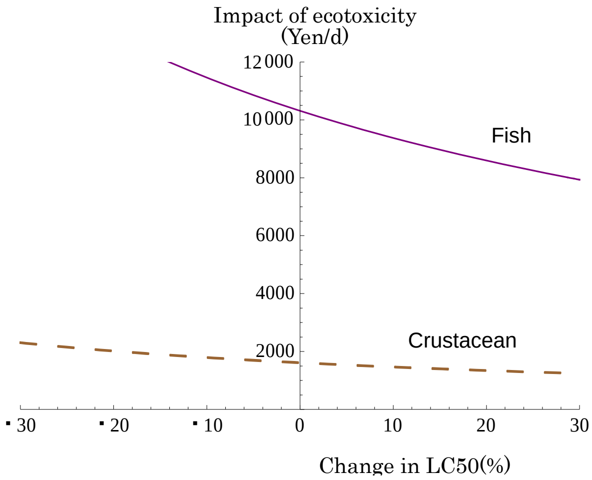


Figure 6 Variation in ecotoxicity impacts with changes in LC_{50}

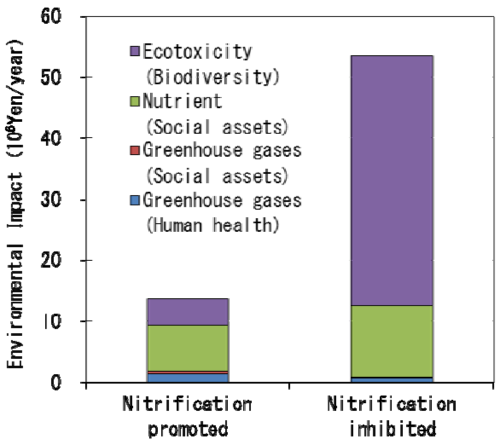


Figure 7 Comparison of environmental impact

Conclusions

In the this study, we develop methodology to evaluate the influence of the ecotoxicity of non-ionized ammonia in the context of life cycle assessment (LCA). The nitrogen flows were measured in real facilities, in the conditions of nitrification-inhibited and nitrification-promoted. The environmental impacts were compared under two types of experimental conditions. It was found that the main contribution to environmental impacts is eutrophication by nutrients (T-N) in nitrification-promoted operation, although is ecotoxicity by NH_4-N in nitrification-inhibited operation. In consideration of integrated environmental impacts, taking into account nitrogen emissions from discharge water and GHG emissions, nitrification-promoted operation is more preferable than nitrification-inhibited operation.

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