Application of bridle model in estimating greenhouse gases emissions from three wastewater treatment plants in Fukushima Prefecture, Japan

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Abstract. The estimation of Green House Gases (GHGs) plays an important role in reducing emissions to prevent global warming and climate change. The Intergovernmental Panel on Climate Change (IPCC) method is the most commonly used in estimating the emissions from a wastewater treatment plant (WWTP). However, it is difficult to establish technical strategies in emissions reduction as the method cannot identify which treatment unit contributes to the total emission. In this study, we estimated GHGs from WWTPs using the Bridal Model based on the operations and processes in each treatment plant unit. We applied the model to three WWTPs located in Fukushima, Koriyama, and Nihonmatsu City, Japan. The results were evaluated by comparisons with those estimated by the IPCC method. The bridle model results showed that the average daily GHG emissions in Fukushima, Koriyama, and Nihonmatsu in the 2015-2018 period were 86.4, 55.2 and 6.2 ton CO2 eq/day. Furthermore, emissions from the three WWTPs per m3 of treated wastewater were insignificantly different from those estimated by the IPCC method. Sludge treatment was the most sensitive treatment unit as it contributes to 31.8-70.3% of the total emission, followed by chemical and biological treatment units. The study suggests that utilizing biogases produced from the sludge treatment could reduce 21.4-49% of total emissions from a WWTP.

1. Introduction
A greenhouse gas (GHG) can be defined as any gaseous compound that absorbs and holding heat in the atmosphere [1]. GHGs emissions are added to the atmospheric gases, which increases the atmospheric concentration and leads to global warming [2]. Among GHG emissions (namely, CO2, CH4, N2O, HFCs, PFCs, SF6 and NF3), CO2 is the primary gas originating from human activity such as the combustion of fossil fuels, industrial processes, agriculture activities, land-use land-cover changes, and solid and wastewater management [3]. Rothausen and Conway [4] reported that energy in the water sector contributes to 3-6% of total energy consumption in the US, UK and India. Among components in the sector, wastewater management system (WMS), included in the water sector, is considered one of the major sources of GHG emissions [5]. These reports indicate the importance of quantifying WMS emissions and developing emissions reduction strategies as the growth of the population needs to be facilitated by the increases in WMS capacity.

The IPCC provides a methodology for quantifying GHG emissions from a WMS, including direct emissions from the biological process [6]. However, the IPCC method tends to underestimate both direct and indirect emissions [7]. It is also difficult to develop technical interventions using the IPCC method as the emission is calculated as a whole system instead of each component in a WMS. Various studies
have been conducted to estimate GHG emissions by WMSs based on the operational and processes data however, the number of studies considering the impact of nutrient removal is still limited [8]. Snip [9] proposed a method to quantify GHG emissions from a WMS based on the Bridal Model, which calculates GHG emission from each component/unit in a WMS.

In this study, we estimated GHGs from WMS in Fukushima, Koriyama, and Nihonmatsu, Japan, using Bridal Model. The monthly operations and processes data from each treatment plant unit during there years period were collected. Trends of emissions and main contributors to the emissions were identified and analyzed in this study.

![Image](image_url)

**Figure 1.** The treatment unit's typical configuration in WWTP Fukushima, Koriyama, and Nihonmatsu (Source: primary data).

2. **Materials and methods**

2.1. **Study area**

Three WMSs used in this study are located in Fukushima Prefecture, Japan. The three WMSs were the largest in the prefecture providing service to 174,800, 278,688 and 11,764 inhabitants of each Fukushima, Koriyama, and Nihonmatsu, respectively [10]. All selected WWTPs used activated sludge technology for removing organic contaminant, chlorination for disinfection, and sludge thickener coupled with sludge dehydrator for sludge treatment (Figure 1). The general profile of the three WWTPs is provided in Table 1, whereas the detailed profile is provided in Pratama et al [11].

**Table 1.** General profiles of WMSs in Fukushima, Koriyama, and Nihonmatsu [12]

| Parameter                        | Fukushima | Koriyama | Nihonmatsu |
|----------------------------------|-----------|----------|------------|
| Service area (Ha)                | 4,273     | 6,572    | 617.4      |
| Maximum capacity (m³/day)        | 69,600    | 142,800  | 12,256     |
| Length of collecting network (km)| 55.94     | 50.5     | 5.6        |
| Average loading:                 |           |          |            |
| BOD (mg/L)                       | 253       | 242      | 298        |
| TSS (mg/L)                       | 231       | 182      | 299        |

2.2. **The boundary of GHGs emissions**

According to Snip [9], the calculation of GHGs emissions using the Bridle model could be divided into four components, including:

2.2.1. **Biological treatment.** In the study areas, the biological treatment component includes the activated sludge process consisting of an aeration tank and a secondary clarifier.
2.2.2. **Sludge treatment.** The sludge treatment component includes sludge thickener and sludge dehydrator.

2.2.3. **Chemicals treatment.** The chemical treatment component includes a chlorination tank that uses hypochlorite for the disinfection process.

2.2.4. **Energy consumption.** The energy consumption component includes indirect components from wastewater collection pumping, wastewater treatment pumping system, sludge treatment pumping system, and administrative building electrical consumption.

2.3. **The bridle model**
The model and the involved equation are only described briefly. The detailed calculation step of estimating GHGs emissions from a WMS is provided in Snip [9].

2.3.1. **Biological treatment.** The emissions are direct originating from the aerobic conversion of the organic contaminant into gaseous CO\(_2\) (Equation 1) and nitrogen removal resulting in CO\(_2\) (Equation 2) and N\(_2\)O (Equation 3) emissions.

\[
\begin{align*}
CO_{2,BOD} &= \left[ \frac{BOD_m}{f} - 1.42X \right] 1.1 \\
CO_{2,NH^+} &= NH_m 4.49 \\
N_2O &= Q \times TN_{wAS} \times 2.62
\end{align*}
\]

Where \(CO_{2,BOD}\) is CO\(_2\) emissions from the oxidation process of BOD (kg CO\(_2\)/day), \(BOD_m\) is the amount of BOD removed in the biological treatment (kg BOD/day), \(X\) is biomass production per day (kg VSS/day), \(f\) is the ration of BOD\(_5\) to BOD\(_m\), \(CO_{2,NH^+}\) is CO\(_2\) emissions from the oxidation process of ammonia (kg CO\(_2\)/day), \(NH_m\) is the amount of NH\(^+\) removed in the biological treatment (kg NH\(^+\)/day), \(N_2O\) is N\(_2\)O emissions (kg N\(_2\)O/day), \(Q\) is wastewater inflow rate (m\(^3\)/day) and \(TN_{wAS}\) is the concentration of total nitrogen in the influent of the biological treatment (kg/m\(^3\)).

2.3.2. **Sludge treatment.** The sludge treatment component directly emits CH\(_4\) due to the anaerobic process on organic matter in the sludge. The calculation is based on the removal of organic matter during sludge treatment (Equation 4).

\[
Biogas = VS_{sludge} \times VS_{rem}
\]

Where \(Biogas\) is the amount of gas produced during sludge treatment (kg/day), \(VS_{sludge}\) is the mass of organic matter in the sludge (kg/day) and \(VS_{rem}\) is the fraction of organic matter removed during the sludge treatment. Thereafter, based on the volume percentage of methane in the biogas, the emission of CH\(_4\) could be calculated.

2.3.3. **Chemical Treatment.** The emissions are indirectly originating from the production of the chlorine (Equation 5).

\[
CO_{2,Cl} = Cl_{used} \times EF_{ci}
\]

Where \(CO_{2,Cl}\) is CO\(_2\) emissions from the production of Cl (kg CO\(_2\)/day), \(Cl_{used}\) is the amount of chlorine used per day (kg Cl/day) and \(EF_{ci}\) is the emission factor of Cl production (kg CO\(_2\)/kg Cl).
2.3.4. Energy consumption. The emissions are indirectly based on the amount of electrical consumption of the WMS (Equation 6).

\[ CO_{2,EL} = P \times EF_{EL} \]  

(6)

Where \( CO_{2,EL} \) is \( CO_2 \) emissions from the electricity consumption (kg \( CO_2 \)/day), \( P \) is the power used per day (Kwh) and \( EF_{EL} \) is the emission factor of electricity production (kg \( CO_2 \)/Kwh).

2.4. Input data

The bridging model's input data in this study was operational and process data of wastewater treatment collected from the annual maintenance report of each WWTPs [12][13][14]. From each month during 2016-2018, influent flow, hydraulic retention time, sludge retention time, MLVSS, total nitrogen in influent and effluent, BOD in influent and effluent, TSS in influent and effluent, organic matter in influent and effluent of sludge treatment, chlorine usage and electricity consumption data were used to calculate the emissions. The unit of calculated GHGs emissions is in kg \( CO_2 \)/month and kg \( CO_2 \)/m³ of treated wastewater.

3. Results and discussion

3.1. Temporal trend of GHGs emissions

The estimated GHG emissions consisting of \( CO_2 \), \( CH_4 \) and \( N_2O \) were converted to a global warming potential to kg \( CO_2eq \). The total emissions were then divided by the volume of treated wastewater resulting in the total GHG emissions per m³ of treated wastewater as described in Figure 2. The WMS emissions in Nihonmatsu were the highest, with an average of 1.35 (±0.335) kg \( CO_2eq \)/m³. The WMS emissions in Fukushima were the second highest with an average of 1.29 (±0.29) kg \( CO_2eq \)/m³ whereas WMS in Koriyama emitted the lowest GHG with an average of 0.918 (±0.29) kg \( CO_2eq \)/m³. For the WMS in Fukushima City and Nihonmatsu, the emissions' positive trends were observed as indicated by the trend line. In contrast, the emissions from WMS in Koriyama has a negative trend.

![Figure 2](image2.png)

**Figure 2.** Monthly average GHG emissions in Fukushima, Koriyama, and Nihonmatsu per m³ of treated wastewater.

The positive trend of emissions from the WMS in Fukushima could be due to the increasing amount of sludge and its organic fractions, resulting in increases in emissions originating from the sludge
treatment. Meanwhile, the positive trend of WMS emissions in Nihonmatsu may correspond to increases in sludge generation and BOD concentrations. For the WMS in Fukushima, GHG emissions increased from 1.11 kg CO$_2$eq/m$^3$ to 1.44 kg CO$_2$eq/m$^3$, while for WMS in Nihonmatsu, the emission increased from 0.93 kg CO$_2$eq/m$^3$ to 1.22 kg CO$_2$eq/m$^3$. For the WMS in Koriyama, the negative trend of emissions could be associated with decreasing sludge generation and nitrogen concentration in its wastewater. GHG emissions from the WMS in Koriyama City decreased from 1.24 kg CO$_2$eq/m$^3$ to 0.92 kg CO$_2$eq/m$^3$.

3.2. Emission from each WMS component

GHG emissions from the WMS's biological treatment in Fukushima and Koriyama City were 0.188 kg CO$_2$eq/m$^3$ and 0.191 kg CO$_2$eq/m$^3$, respectively (Figure 3). Meanwhile, the WMS in Nihonmatsu emits higher GHGs with an average of 0.306 kg CO$_2$eq/m$^3$. The difference can be caused by the quality of wastewater that enters WMS Nihonmatsu City with a higher BOD concentration. GHGs emissions from the sludge treatment at the WMS in Fukushima City and Nihonmatsu were 1,290 kg CO$_2$eq/m$^3$ and 1,354 kg CO$_2$eq/m$^3$, respectively, while emissions from the WMS in Koriyama were lower with an average of 0.912 kg CO$_2$eq/m$^3$. The low emissions from Koriyama could be associated with the lower organic fraction contained in the sludge than those in the sludge of WMS in Fukushima and Nihonmatsu. In addition, sludge granulation, which is used to treat sludge in Nihonmatsu, tends to emit a higher amount of GHGs.

GHGs emissions from chemical treatment at WMS in Fukushima and Koriyama City were low compared to those emitted from the WMS in Nihonmatsu (0.510 kg CO$_2$eq/m$^3$). This is because the WMS uses more hypochlorite per volume of wastewater than WMS usage Fukushima and Koriyama [12]. Greenhouse gas emissions resulting from non-aerated energy consumption at Nihonmatsu City WMS are lower than other WMSs. This can be caused by the smaller amount of electrical energy required by the processing equipment in Nihonmatsu City WMS. The smallest GHG emissions from energy consumption in Nihonmatsu City. This is because Nihonmatsu City relied solely on gravity and did not use pumps and the collection network.

Figure 3. Comparisons of GHG emissions from each WMS component in Fukushima, Koriyama and Nihonmatsu per m$^3$ treated wastewater.
3.3. Utilization of biogas

Based on the results, we found that sludge treatment was the highest contributor to GHG emissions. Thus, to reduce emissions from a WMS, the utilization of the generated biogas from sludge treatment is suggested. The sludge treatment produces CH₄ and CO₂ which are biogas that can generate electrical energy. To calculate the emissions that can be reduced by utilizing biogas from sludge treatment, the Bridle model equations suggested by Snip [9] were used. The results obtained are summarized in Figure 4.

![Figure 4](image_url)

*Figure 4. Comparison of GHG emissions before and after biogas utilization.*

It can be seen from Figure 4 that the WMS in Fukushima City can reduce its greenhouse gas emissions by utilizing biogas as an energy source of around 32.14% of total emissions. For the WMS in Koriyama, the use of biogas can reduce GHG emissions by around 25.70%. Likewise, for WMS in Nihonmatsu, biogas as an energy source can reduce GHG emissions by around 21.75%. Thus, the use of biogas for electricity in wastewater management should be considered a solution to reducing GHG emissions.

4. Conclusion

The study demonstrated the estimation of GHG emissions from activities wastewater management using the Bridle Model. Based on the results, the sludge treatment’s emissions were in the range of 31.88% - 70.34% of the total emissions, the most contributing component. Emissions from the energy consumption were in the range of 14.69% - 20.66% of the total emission, whereas 4.38% - 17.58% of the total emission was originated from biological treatment. Also, emissions from the chemical treatment contributed to 0.05% - 29.37% of the total emissions. The Bridle Model allowed the operator of a WMS developing technical intervention for reducing GHG emissions. In WMS in Fukushima, Koriyama, and Nihonmatsu, the utilization of biogas produced from the sludge treatment was proposed as it could potentially reduce GHG to 32%.

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