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Estimation of Methane Emissions from Reservoirs Based on Country-Specific Trophic State Assessment in Korea

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Abstract: It has been reported that significant quantities of greenhouse gases are emitted from wetlands, from which emissions and their contributions to global warming have received much less attentions. Thus, a refinement to the previous published guidelines has recently been made to provide an updated and sound scientific basis for the purpose of supporting the preparation of national inventories. This study is aimed at demonstrating the applicability of the refinement for estimating methane emissions from reservoirs in the Republic of Korea. It is desirable to take the direct measurement of total methane fluxes across the reservoir surface, which may require a substantial amount of research efforts though. Alternatively, methane emissions from individual reservoirs may be estimated with relevant parameters accounting for the regional environmental characteristics. The assessment of trophic state has been employed to better represent the emissions behavior of reservoirs, based on which the methane emissions from local reservoirs in Korea are estimated. It is noted that the country has developed its own water quality index with the consideration of environmental characteristics. The seasonal variations in methane emissions are tested for their statistical significance and it is proposed that the emission estimates can be predicted from the trophic state assessment with the application of regression analysis. Following the guidelines prescribed by the refinement and procedures outlined in this study, the results from emissions estimation and prediction can be effectively used for the improvement of national inventories.

Keywords: methane emissions from reservoirs; trophic state assessment; IPCC guideline; emissions estimation; climate change

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1. Introduction

The world's water reservoirs are annually emitting carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases (GHGs) in significant quantities, depending on a variety of different characteristics such as age, land-use prior to flooding, climate, upstream catchment and management practices [1]. It is estimated that the GHG emissions from reservoirs are roughly equivalent to 1.07 gigatons of CO_2 [2], which surprisingly approach to 14% of the annual CO_2 emissions of 7.8 gigatons from fossil fuel combustion [3]. With the exception of CO_2, CH_4 is considered the most important greenhouse gas because its global warming potential is 34 times greater than that of CO_2, though its atmospheric concentration is approximately 200 times less. Especially, wetlands including reservoirs are the largest natural source of methane accounting for roughly one third of total natural and anthropogenic CH_4 emissions. It is argued that the global fossil fuel emissions would have to be reduced by as much as 20% more than previous estimates to achieve the Paris Agreement targets because of the natural GHG emissions from wetlands and permafrost, which is thus critical in the assessment of emission pathways to limit global warming [4]. However, CH_4 emissions from wetlands and their contribution to global warming potential were poorly assessed before mainly due to the paucity of available data [5–7]. Most attempts are centered on upscaling the GHG emission rates from individual waterbodies to the regional or global estimates and simply multiplying an average emission rate by the total waterbody surface area in the region of interest [8–11]. It is pointed out in [12] that this upscaling approach can be highly biased unless the emission rate measurements come from a representative sample of lakes or reservoirs in the region of interest.

Providing an updated and sound scientific basis to support the preparation and continuous improvement of national inventories, the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [3] (hereafter referred to as '2019 Refinement') has been adopted to embrace recent scientific advances and technological developments. Scientists recognized the importance of including reservoir emissions in the nation's GHG inventory to better understand their climate impacts, and thus a significant refinement has been made to the estimation of GHG emissions from wetlands, especially from flooded lands, which is described in Chapter 7.3 of Volume 4. An exhaustive collection of related research efforts is well reviewed and presented in [3] emphasizing the urgency of accounting methane emissions from wetlands from the perspective of reporting inventories. The refinement for estimating CO_2 and CH_4 emissions from reservoirs provides the average emission factors for six major climate zones; boreal, cool temperate, warm temperate/dry, warm temperate/moist, tropical dry/montane, and tropical moist/wet. The emission factors for each climate zone are derived from an extensive literature survey and they are multiplied by the total area of water surface to estimate the emissions from reservoirs. Even though the region may be classified as the aggregated climate zone of 'Cool Temperate', it may exhibit different climatic characteristics from season to season due to the noticeable seasonal variations in temperature and precipitation. In addition, the emissions estimation can be adjusted based upon the assessment of trophic state of reservoirs. Even though feasible to obtain the region-specific estimates of emissions from reservoirs by assessing the tropic status of individual reservoirs, there hardly exists such an attempt to adopt the 2019 Refinement for estimating the GHG emissions from wetlands with the consideration of regional climatic characteristics. The objective of this study is to estimate the amount of methane emissions from reservoirs as per the procedure outlined in the 2019 Refinement. Further, it is also proposed to predict the methane emissions based on the country-specific trophic state assessment by employing the statistical regression analysis. For the purpose of this study, selected are six reservoirs in the Republic of Korea, which is recognized as the 9th largest emitter of GHG emissions with more than 700 million tons of carbon emissions in 2019 [13]. It was reported that the methane emissions from wetlands are merely 0.283 million tons equivalent to about 1% of the total methane emissions, which may seem negligible. However, the refinement has not yet been adopted to obtain the emissions estimation in the report and it is extremely probable that the refinement yields a much greater amount of total emissions from wetlands. To the best of authors' knowledge, this study is the first attempt, at least for Korea, to apply the refinement for estimating the methane emissions from individual reservoirs. The defining aspect of this study is that the estimation of methane emissions has been carried out based on the region- or country-specific trophic state assessment method to better account for regional climatic characteristics and the trophic state assessment may also be used to predict the emissions from different reservoirs. The remainder of this manuscript is organized as follows: First, the methodology prescribed in the 2019 Refinement is briefly summarized and the index for country-specific trophic state assessment is introduced in the next section. Section 3 describes the results from the assessment of trophic state of individual reservoirs and their emissions estimation. It is also discussed that the results may be used to predict the methane emissions from reservoirs based on the trophic state assessment. The conclusions will follow in the last section.

2. Methods

2.1. Methodology Based on IPCC Guidelines

The carbon emissions from wetlands are traced from three different source categories: managed peatlands, flooded land, and inland wetland mineral soils. No refinements have been made to the categories of managed peatlands and inland wetland mineral soils. Major developments with regard to the emissions from flooded lands are included in the refinement and described in a greater detail based on the collation of extensive literature survey. The usage of guidelines for the emissions estimation is contingent upon the types of flooded lands; land converted to flooded land, flooded land remaining flooded land, and other constructed water body. All the reservoirs under investigation here can be classified as the type of flooded land remaining flooded land since all of them are more than 20 years old. It is advocated that only methane emissions are estimated in this category to avoid the double counting of CO_2 emissions [3]. Annual total emissions estimation from flooded land remaining flooded land may be obtained by the following as given in [3]: First, the annual emissions from reservoir surface, denoted by $F_{CH_4 res}$, are estimated by

$$F_{CH_4 res} = \sum_{j=1}^{j} \sum_{i=1}^{nres_j} \alpha_i \left(EF_{CH_4 age>20,j} \cdot A_{totj,i} \right) \quad (1)$$

where i and $nres_j$ are the index for individual reservoirs and the number of reservoirs more than 20 years old in climate zone j, respectively. The total area of water surface in hectare is denoted by $A_{totj,i}$ and the CH_4 emission factor from reservoirs more than 20 years old located in climate zone j by $EF_{CH_4 age>20,j}$ measured in kg CH_4/year. The emission factors may be adjusted by α_i, if appropriate, depending upon the trophic state of individual reservoirs. In addition, $F_{CH_4 downstream}$ denotes the annual emissions from CH_4 originating from reservoirs but emitted downstream of corresponding reservoirs, which can be estimated by multiplying the emissions from water surface of individual reservoirs by the ratio R_d of total downstream methane emission to the total flux of methane from the reservoir surface as follows:

$$F_{CH_4 downstream} = \sum_{j=1}^{j} \sum_{i=1}^{nres_j} \alpha_i \left(EF_{CH_4 age>20,j} \cdot A_{totj,i} \right) \cdot R_{d,i} \quad (2)$$

The total annual emissions of CH_4 from all reservoirs under study, denoted by $F_{CH_4 tot}$, is simply the sum of emissions from water surface and downstream, that is,

$$F_{CH_4 tot} = F_{CH_4 res} + F_{CH_4 downstream} \quad (3)$$

If sufficient data are lacking, the default values for parameters, such as R_d and α_i, may be used in a blanket manner even though acknowledged in [3] that it is *good practice* to develop the country-specific emission factors to reduce overall uncertainty. The procedure outlined in [3] is certainly useful to estimate the methane emissions from wetlands, but a certain degree of ambiguity is inevitable without a sufficient amount of data especially related to trophic states. This study uses the default value of 0.09 with the 95% confidence interval (0.05, 0.22) for R_d as recommended in [3] due to the lack of relevant data. On the other hand, the adjustment factor α_i is derived from the seasonal trophic state assessment of individual reservoirs as outlined in the below. It is most desirable to employ the Tier 3 approach by taking the direct measurement of CH_4 diffusion and ebullition fluxes across the reservoir surface or applying Greenhouse Gas Reservoir Tool (G-Res) model [14]. However, it may require a great deal of efforts and resources to capture both the spatial and temporal variability of emissions from a reservoir. As an alternative, the methane emissions from individual reservoirs may be estimated with the relevant parameters adjusted for trophic status and water withdrawal depths of reservoirs. For example, different values of the emission factor adjustment α_i are recommended in [3] depending upon trophic index (TI), surface concentration of chlorophyll-a (Chl-a), total phosphorus (TP), total nitrogen (TN), Secchi depth (SD), and trophic class. The emission factor adjustment of 10.0 is to be used for a eutrophic reservoir in lieu of its default value of 1.0. It is also noted that the emissions estimation needs to take environmental circumstances as well as properties of individual reservoirs into account. The methane emission factors are highly variable in different climate zones, and it is reasonable to apply different emission factors from season to season where the average temperature and precipitation are greatly fluctuating across the year. The Republic of Korea has four distinct seasons and a significant variation in seasonal weather may be observed. For example, one of the reservoirs investigated here is located near the city of Boryeong where the annual average temperature is 12.7 degrees Celsius and the difference in monthly average temperature between hottest and coldest months is 25.9 degrees Celsius. Further, the annual rainfall total is 1191.4 mm and the precipitation is mainly concentrated in summer with the average rainfall of 652.4 mm. Six reservoirs in the central region of Korea are investigated to demonstrate the applicability of the methodology described above for estimating the methane emissions with the consideration of seasonal climatic characteristics and the trophic state of individual reservoirs.

2.2. Country-Specific Trophic State Assessment

There are about 18,000 reservoirs and dams of various sizes in the Republic of Korea and most of them are more than 20 years old [15]. The country is relatively small in terms of the land area and ranked 109th in the world with the land area of 97,230 km^2. River Act of Korea designates five major river systems as National Rivers, along which a significant number of reservoirs and lakes are located. It is noted that the spatial variations in climatic characteristics are slightly noticeable, if any, compared to the seasonal variations mainly due to the small land area of Korea, and this study rather focuses on the temporal variations in methane emissions. Located in the central region of Korea, the third longest river system from the central region of Korea, called Geumgang, is selected for analysis in this study. From the perspective of data availability and readiness for the country-specific trophic state assessment, six reservoirs of different sizes, from the surface area of 59 to 7419 hectare, along the Geumgang river system are taken as shown in Table 1.

Table 1. Information of Six Reservoirs.

Name (Abbreviation)	Basin Area (ha)	Surface Area (ha)	Water Storage Capacity (10^3 m^3)	Main Use
Bunam (BN)	15,720	3560	21,100	Agriculture
Boryeong (BR)	16,360	217	116,900	Water Supply
Daeho (DH)	31,215	7419	112,000	Agriculture
Sapgyo (SG)	163,950	2017	84,082	Agriculture
Seokmun (SM)	1750	59	975	Agriculture
Tapjeong (TJ)	21,880	636	31,927	Agriculture

As mentioned earlier, the assessment of trophic states is crucial to better estimate the emissions from reservoirs by adjusting the emission factors. Carlson [16] proposed the use of a trophic state index (TSI) based on the measurement of SD, TP, and Chl-a from reservoirs, which is widely adopted for water quality assessment in the literature. On the other hand, it is argued in [17] that the trophic state assessment should be carried out in such a way to better represent environmental characteristics of the region of interest and the trophic state index suitable for Japanese river systems is proposed by modifying Carlson's index. Considering regional environmental characteristics of Korea, NIER [18] also developed the water quality assessment method and proposed the trophic state index named 'Korean Trophic State Index' (TSI_{KR}), which is basically based on the measurement of chemical oxygen demand (COD), TP, and Chl-a from individual reservoirs [19–23]. It is pointed out in [20,23] that the Korean index adopts the measurement of COD in place of SD used in the Carlson's and Japanese indices with the consideration of Korean river systems characterized by relatively short detention times and a higher intake of organic matters. The index TSI_{KR} separately evaluates the water quality of reservoirs in terms of COD, TP, and Chl-a as shown in Equations (4)–(6), respectively.

$$TSI_{KR\_COD} = 5.8 + 64.4\log(\text{COD } mg/L) \quad (4)$$

$$TSI_{KR\_TP} = 114.6 + 43.3\log(\text{TP } mg/L) \quad (5)$$

$$TSI_{KR\_Chl\text{-}a} = 12.2 + 38.6\log\left(\text{Chl-a } mg/m^3\right) \quad (6)$$

where TSI_{KR_COD}, TSI_{KR_TP}, and $TSI_{KR\_Chl\text{-}a}$ denote the trophic state indices assessed from the measurements of COD, TP, and Chl-a, respectively. Then, the overall TSI_{KR} is derived by taking the weighted average of three sub-indices in the above. The weights of 0.5, 0.25, and 0.25 are assigned to TSI_{KR_COD}, TSI_{KR_TP}, and $TSI_{KR\_Chl\text{-}a}$, respectively, as follows:

$$TSI_{KR} = 0.5(TSI_{KR\_COD}) + 0.25(TSI_{KO\_TP}) + 0.25(TSI_{KR\_Chl\text{-}a}) \quad (7)$$

It should be noted that the trophic state assessment is twice more influenced by TSI_{KR_COD} than the others considering the characteristics of regional reservoirs which are highly affected by allochthonous and autochthonous organic matters [20]. The trophic state of individual reservoirs is to be determined by the value of TSI_{KR} as shown in Table 2. The index has been adopted as the official index for trophic state assessment designated by the Ministry of Environment of Korea in Ministry Notice 2013-134 since 2013. The reasoning behind the development of TSI_{KR} is beyond the scope of this study, and interested readers are referred to [17] for more detailed discussions on TSI_{KR}.

Table 2. Classification of Trophic Class Based on the Value of TSI_{KR}.

Range of TSI_{KR}	Trophic Class	Range (Recommended Value) for Adjustment Factor α_i
0~30	Oligotrophic	0.7 (0.7)
30~50	Mesotrophic	0.7~5.3 (3.0)
50~70	Eutrophic	5.3~14.5 (10.0)
70~100+	Hypertrophic	14.5~39.4 (25.0)

3. Results and Discussion

3.1. Seasonal Trophic State Assessment of Reservoirs

Based on the water quality data on COD, TP, and Chl-a, the trophic state of each reservoir can then be assessed season by season to capture the seasonal variations. The seasonal assessment of trophic state for individual reservoirs has been performed by [18]. Collecting data on the water quality for almost 15 years, the seasonal averages of measurement data are used to determine the trophic state season by season. In addition, the emission factors need to be adjusted for the trophic state to estimate the methane emissions from individual reservoirs. For each trophic class, the range and recommended value for adjustment factor are provided as shown in Table 2 [3]. For example, the range of adjustment factor for mesotrophic state is from 0.7 to 5.3 and it is recommended to use 3.0 when sufficient data are not available. On the other hand, the range of TSI_{KR} value is from 30 to 50 for mesotrophic reservoirs, and it seems reasonable to use the interpolated adjustment factor. Provided that $TSI_{KR} = 45$, the interpolated adjustment factor can then be calculated as

$$\alpha_i = 0.7 + \frac{(45 - 30)}{(50 - 30)} \times (5.3 - 0.7) = 4.15. \quad (8)$$

Table 3 presents the result of trophic state assessment along with the TSI_{KR} values, their standard errors, and corresponding adjustment factors. As observed from the standard errors of TSI_{KR} values, the trophic state indices do not fluctuate much throughout the data collection period. On the other hand, a relatively large seasonal variations of indices may be observed especially for such reservoirs as DH, SM, and TJ as shown in Figure 1. It is obvious that the trophic state index should be closely related to the adjustment factor, which is depicted in Figure 2. The Pearson's correlation coefficient between them corresponds to 0.98 indicating that there exists a strong positive correlation and the seasonal variations in trophic states are well reflected in the interpolated adjustment factors.

Table 3. Seasonal Assessment of Trophic State and Corresponding Adjustment Factor.

Reservoir	Season	TSI_{KR}		Trophic Class	Interpolated Adjustment Factor
		Mean (Std. Error)			
BN	Spring	68.57	(2.63)	Eutrophic	13.84
	Summer	71.30	(2.91)	Hypertrophic	15.58
	Autumn	70.00	(1.90)	Eutrophic	14.50
	Winter	68.69	(2.14)	Eutrophic	13.90
BR	Spring	26.81	(1.30)	Oligotrophic	0.63
	Summer	31.92	(1.62)	Mesotrophic	1.14
	Autumn	30.68	(0.94)	Mesotrophic	0.86
	Winter	27.07	(0.71)	Oligotrophic	0.63
DH	Spring	50.81	(1.08)	Eutrophic	5.67
	Summer	59.80	(1.13)	Eutrophic	9.81
	Autumn	64.86	(2.80)	Eutrophic	12.14
	Winter	52.49	(1.40)	Eutrophic	6.45
SG	Spring	71.34	(2.01)	Hypertrophic	15.61
	Summer	72.31	(1.88)	Hypertrophic	16.42
	Autumn	70.93	(1.99)	Hypertrophic	15.27
	Winter	70.17	(1.72)	Hypertrophic	14.64
SM	Spring	62.34	(2.46)	Eutrophic	10.98
	Summer	73.74	(6.11)	Hypertrophic	17.60
	Autumn	67.86	(1.88)	Eutrophic	13.52
	Winter	55.60	(0.73)	Eutrophic	7.88
TJ	Spring	39.19	(2.63)	Mesotrophic	2.81
	Summer	50.59	(1.30)	Eutrophic	5.57
	Autumn	51.01	(1.91)	Eutrophic	5.76
	Winter	41.28	(2.06)	Mesotrophic	3.29

3.2. Estimation and Prediction of Methane Emissions from Reservoirs

Derived from the G-Res model, the unadjusted emission factors $EF_{CH_4 age>20,j}$ are provided for each climate zone in [3]. Most of the regions in the Republic of Korea are classified as 'Cool Temperate' zone except for southern and eastern coastal areas, and it is recommended to use the average emissions factor of 54.0 with the 95% confidence interval (48.3, 59.5). The refinement recommends using the default value of 0.09, unless otherwise specified, for the ratio of downstream emissions to the total flux of methane from reservoir surface [3]. Using Equations (1)–(3), the methane emissions from individual reservoirs under investigation can then be estimated with the parameters outlined above. For example, the methane emissions estimation from the reservoir BN over the spring season can be obtained with the following parameters: $EF_{CH_4 age>20,j} = 54.0$ for the climate zone of 'Cool Temperate', $A_{totj,i}$ = 3560 for the surface area, α_i = 13.84 for the adjustment factor, and R_d = 0.09 for the ratio of total downstream methane emission to the total flux of methane from the reservoir surface. The surface emissions of methane are 665,150 kg CH_4 and the downstream emissions are simply 59,863 kg CH_4 by adopting the default value 0.09 for R_d due to the lack of data availability, which sums up to 725,013 kg CH_4. Table 4 presents the seasonal methane emissions from individual reservoirs along with the annual per hectare emissions.

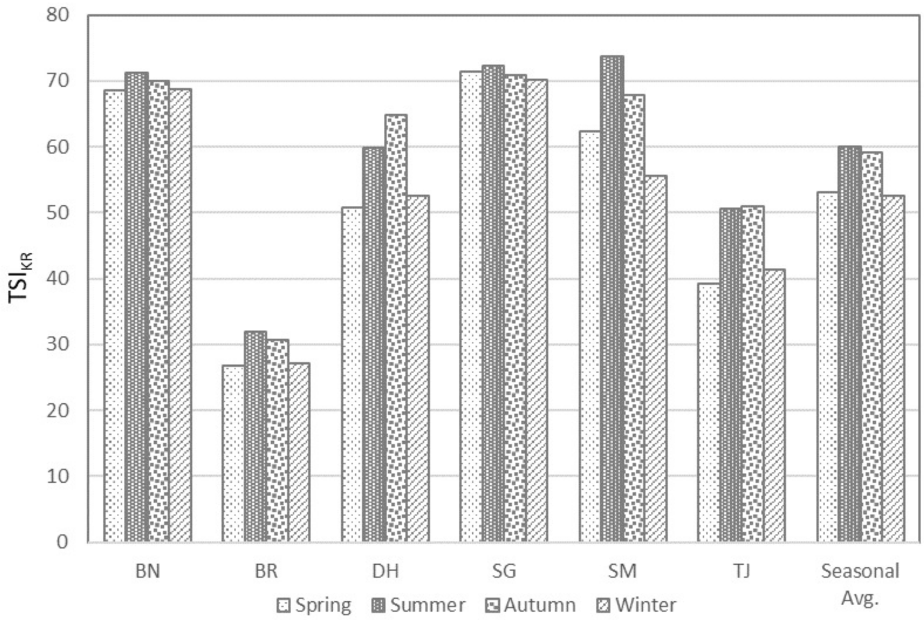


Figure 1. Seasonal Trophic State Assessment of Individual Reservoirs.

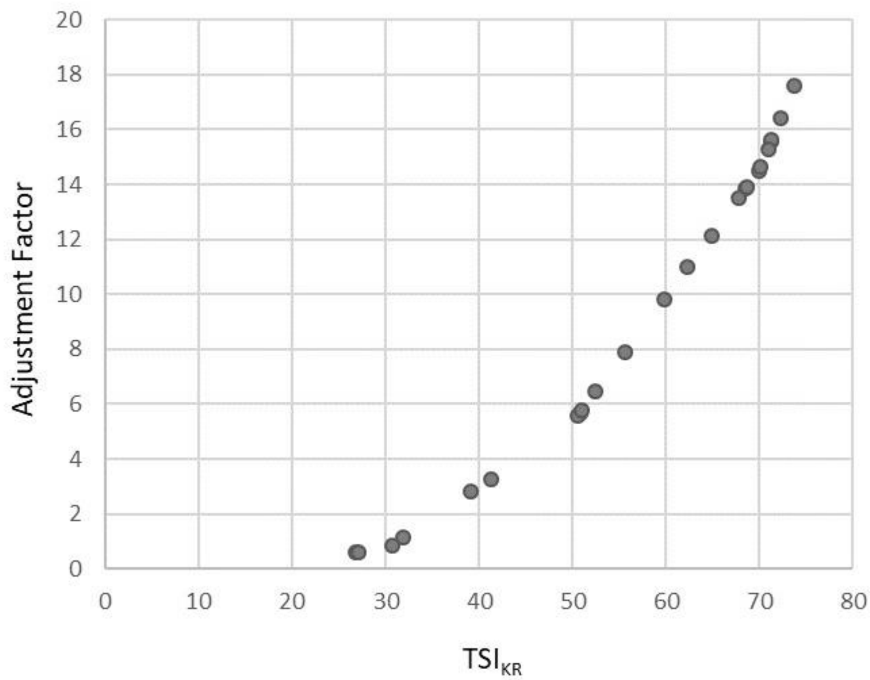


Figure 2. Relationship between Trophic State Index and Adjustment Factor.

Table 4. Estimates of Annual Methane Emissions from Reservoirs (10^3 kg CH_4).

Reservoir	Spring	Summer	Autumn	Winter	Total	Per Hectare
BN	725.0	816.2	759.6	728.2	3028.9	0.851
BR	2.0	3.6	2.7	2.0	10.4	0.048
DH	619.0	1071.0	1325.3	704.2	3719.4	0.501
SG	463.3	487.3	453.2	434.5	1838.4	0.911
SM	9.5	15.3	11.7	6.8	43.3	0.735
TJ	26.3	52.1	53.9	30.8	163.1	0.256

Note that the amount of per hectare methane emissions from the reservoir BR is significantly less than others, which may be contributed to the fact that the reservoir BR is mainly used for drinking water supply and the management of water quality is fairly rigorous. A relatively moderate variation is observed among the other reservoirs mainly used for agriculture. The reservoir SG exhibit the largest per hectare annual emissions of 911 kg CH_4. Rim and Shin [24] pointed out that the water quality of SG is deteriorated because of increased phytoplankton biomass with rich nutrient flowing from the upper stream of watershed. It is also confirmed that the reservoir SG exhibits consistently higher adjustment factors across the year. Since the emissions are affected proportionately to the surface area, the seasonal estimates of per hectare methane emissions from individual reservoirs are compared to reduce the scale differences, which is depicted in Figure 3. Noticeable differences in seasonal estimates can be observed for the reservoirs BR, DH, SM, and TJ whereas the methane emissions from BN and SG do not much differ season by season.

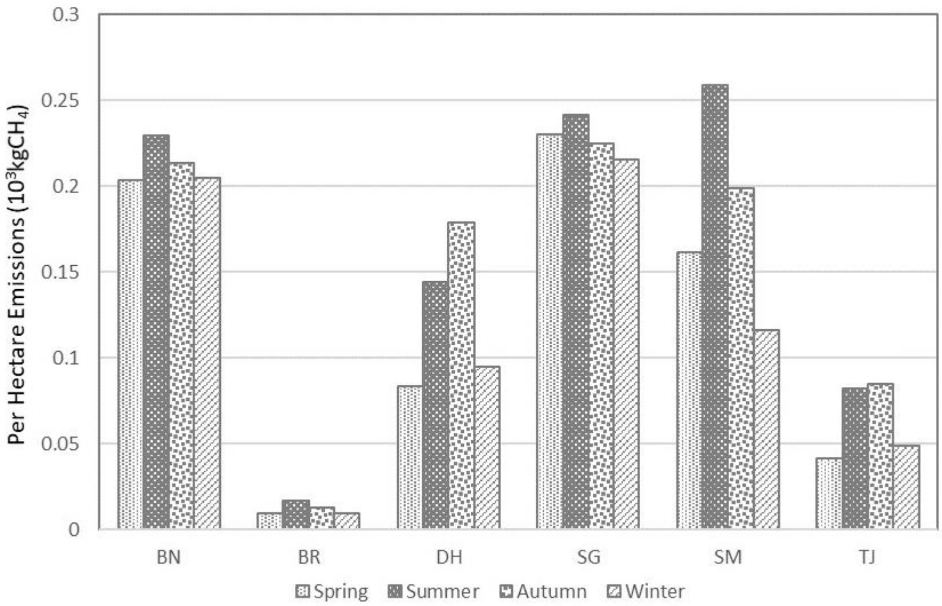
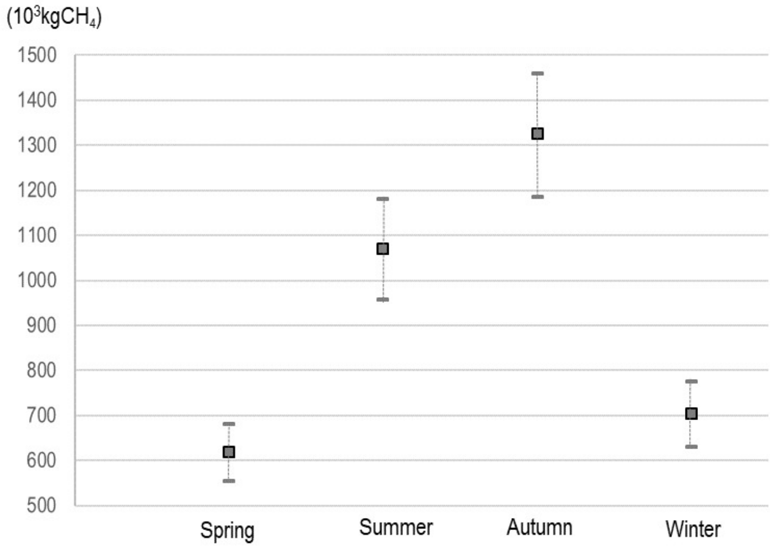
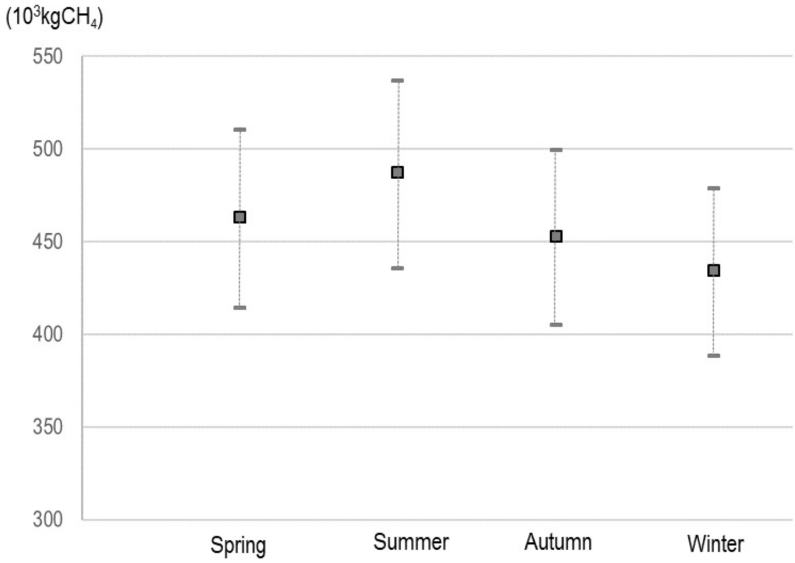


Figure 3. Comparison of Seasonal Estimates of Methane Emissions from Individual Reservoirs.

Statistical analysis can be useful to determine whether there exist statistically significant differences in methane emissions season by season. For the sake of demonstration, the confidence intervals (CIs) of seasonal emissions estimation from DH and SG are derived and depicted in Figure 4. As shown in Figure 4a, the largest amount of methane is emitted in Autumn with mean 1,325,331 kg CH_4 and 95% CI of (1,185,435, 1,460,318). The annual total emissions from DH sum up to 3,719,442 kg CH_4 and its 95% CI is (3,326,834, 4,098,274). It should be noted that the pairwise comparison of CIs reveals the existence of statistically significant differences in seasonal emissions with the significance level of 5%. To the contrary, all the 95% CIs of seasonal estimates of methane emissions from SG overlap with each other, as shown in Figure 4b, implying that the amount of methane emission does not differ significantly from the statistical point of view with the significance level of 5%. While emissions from DH are fluctuating seasonally to a great extent, a relatively stable amount of methane emissions is observed across the year. It is concluded that the seasonal behavior of methane emissions is quite different from one reservoir to another and it is closely related to the seasonal trophic states of individual reservoirs.



(**a**)



(**b**)

Figure 4. Mean and 95% CI of Methane Emissions by Season. (**a**) Reservoir DH. (**b**) Reservoir SG.

The procedure prescribed in [3] emphasizes the influence of trophic states on emissions estimation from wetland, which is further investigated by way of regression analysis. The estimates of seasonal methane emissions are regressed against surface area and the results from trophic state assessment. It is assumed that the surface area of reservoirs is constant over the years, which seems unreasonable but can be accounted for whenever sufficient data are provided. The omnibus analysis of variance (ANOVA) table and corresponding model coefficients are provided in Tables 5 and 6, respectively, all of which indicate the statistical significance of regression model. The coefficient of determination R^2 is 0.872 implying that 87.2% of variations in the emission estimates can be explained by the model. One of the advantages of regression model is that it can be used for the purpose of prediction.

The marginal means plot with respect to TSI_{KR} is constructed for a reservoir with the average surface area as depicted in Figure 5. The straight line and gray area represent the predictions on emission estimates and their 95% CI, respectively. The estimated marginal means of emission estimates are summarized in Table 7. For example, the emission estimate for a reservoir with average surface area and the mean TSI_{KR} is predicted to be 367 with the 95% CI of (303,430) measured in 10^3 kg CH_4.

Table 5. Omnibus ANOVA Table.

Sources of Variation	Sum of Squares	Degree of Freedom	Mean Square	*F*-Value	*p*-Value
Surface Area	2.22×10^6	1	2.22×10^6	98.7	<0.001
TSI_{KR}	266,863	1	266,863	11.9	0.002
Residuals	472,579	21	22,504		

Table 6. Summary of Regression Model Coefficients.

Predictor	Estimate	Standard Error	95% CI		*t*-Value	*p*-Value
			Lower	Upper		
Intercept	−320.023	115.3802	−559.9692	−80.077	−2.77	0.011
Surface Area	0.123	0.0124	0.0976	0.149	9.94	<0.001
TSI_{KR}	7.127	2.0696	2.8230	11.431	3.44	0.002

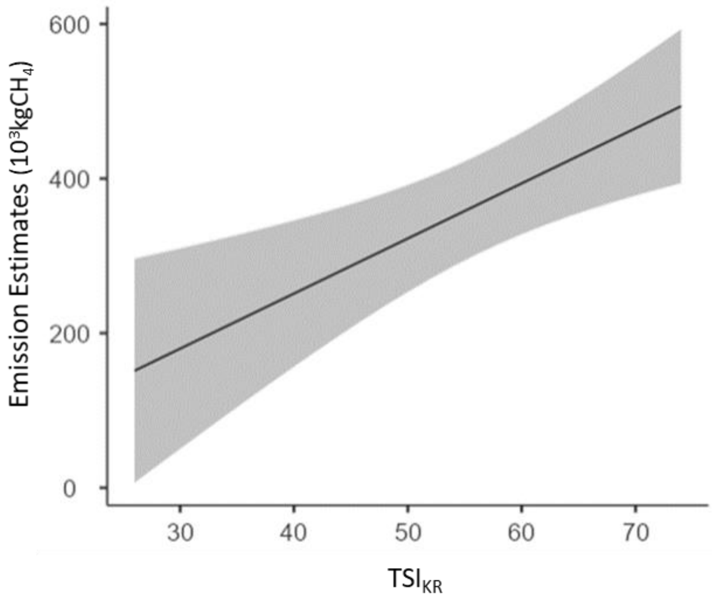


Figure 5. Estimated Marginal Means Plot.

Table 7. Estimated Marginal Means Table.

TSI_{KR}	Marginal Mean	Standard Error	95% CI	
			Lower	Upper
40.4 (1)	254	44.8	161	347
56.2 (2)	367	30.6	303	430
72.1 (3)	480	44.8	386	573

(1) mean (TSI_{KR})–stdev (TSI_{KR}); (2) mean (TSI_{KR}); (3) mean (TSI_{KR}) + stdev (TSI_{KR}).

4. Conclusions

The GHG emissions from wetlands including reservoirs have received less attention from researchers in spite of their enormous impact on global warming mainly because of the low data availability. The 2019 Refinement has been adopted to embrace recent technological development and scientific advances in improving the national GHG inventories. This study is aimed at demonstrating the application of refinement for estimating the methane emissions from reservoirs in Korea. More specifically, the results from tropic state assessment for individual reservoirs are accounted for by deriving the adjusted emission factors. The Korean trophic state index TSI_{KR} is used for identifying the trophic class of reservoirs to take regional environmental characteristics into account. Additionally, the trophic state assessment is performed season by season in an effort to include the seasonal variations in the estimation of methane emissions from reservoirs. It is observed that the magnitude of seasonal variations greatly differs among reservoirs and the emissions are highly dependent upon the main use of reservoirs which affect their management practice for water quality. The differences in methane emissions are tested for their statistical significance by means of confidence intervals, and the statistically significant differences are confirmed for the reservoirs which exhibit greater seasonal variations in the trophic state assessment. Furthermore, it is shown that the emission estimates can effectively be obtained by employing the regression analysis, which may render the functional relationship between emission estimates and trophic state indices. It is thus expected that, given the surface area and seasonal trophic state index, the emission estimates of methane from the reservoir can be predicted from the statistical perspective.

To the best of authors' knowledge, this study is one of the first attempts to apply the refinement for estimating methane emissions from wetlands. However, one of the major limitations of this study comes from the lack of validation procedure for emission estimates. Even though carried out as per the guidelines provided by IPCC, the emissions estimation still needs to be validated against the actual measurement data on the methane emissions from reservoirs. Another limitation of this study is the deficiency of uncertainty assessment to explain the sources of variations in emission estimates except for the trophic states of reservoirs. Further research efforts thus need to be directed towards securing data availability from a wide variety of different geographical contexts. In addition, more accurate estimations and even predictions on methane emissions from wetlands may be enabled by applying advanced analysis methods of statistics and data analytics. Despite unaccounted for uncertainties and opportunities for potential improvement, the procedure outlined above may provide useful tips and guidelines for an effective estimation of methane emissions from reservoirs with the considerations of regional and seasonal variations in emissions behavior.

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Abbreviations

ANOVA	Analysis of Variance
BN	Bunam Reservoir (Name)
BR	Boryeong Reservoir (Name)
Chl-a	Chlorophyll-a
CI	Confidence Interval
COD	Chemical Oxygen Demand
DH	Daeho Reservoir (Name)
GHG	Greenhouse Gas
G-Res	Greenhouse Gas Reservoir Tool
IPCC	Intergovernmental Panel on Climate Change
SD	Secchi Depth
SG	Sapgyo Reservoir (Name)
SM	Seokmum Reservoir (Name)
TI	Trophic Index
TJ	Tapjeong Reservoir (Name)
TN	Total Nitrogen
TP	Total Phosphorus
TSI	Trophic State Index

Nomenclature

α_i	Emission adjustment factor for trophic state in reservoir *i* within a given climate zone
$A_{totj,i}$	Total area of water surface for reservoir *i* located in climate zone *j* (in hectare)
$EF_{CH_4 age>20,j}$	Methane emission factor from reservoirs more than 20 years old located in climate zone *j* (in kg CH_4/year/hectare)
$F_{CH_4 res}$	Annual reservoir surface emissions of methane from all reservoirs more than 20 years old (in kg CH_4/year)
$F_{CH_4 downstream}$	Annual emissions of methane originating from all reservoirs but emitted their downstream (in kg CH_4/year)
$F_{CH_4 tot}$	Total annual methane emission from all reservoirs more than 20 years old (in kg CH_4/year)
$nres_j$	Number of reservoirs more than 20 years old in climate zone *j*
R_d	Ratio of total downstream emission of methane to the total flux of methane from the reservoir surface
TSI_{KR_Chl-a}	Korean Trophic State Sub-Index based on the measurement of Chl-a
TSI_{KR_COD}	Korean Trophic State Sub-Index based on the measurement of COD
TSI_{KR_TP}	Korean Trophic State Sub-Index based on the measurement of TP
TSI_{KR}	Overall Korean Trophic State Index

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