

A Preliminary Estimation on Carbon Footprint of Raw Water from the Reservoirs for Domestic Use in Taiwan

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Authors' contributions

This work was carried out in collaboration between all authors. Authors YHW, YDH and WLW designed the study, performed the measurement in all the reservoirs and performed the statistical analysis. Authors CYS and WCH wrote the protocol, performed the carbon inventory and finalized the subsequent analysis of the total carbon emission. Author CPC wrote the first draft of the manuscript. Authors YCK and YJC gave many valuable comments and modification of this manuscript. All authors read and approved the final manuscript.

Original Research Article

Received 30th April 2013
Accepted 7th December 2013
Published 10th March 2014

ABSTRACT

This study aims to evaluate the carbon footprint of raw water from reservoirs for domestic use in Taiwan. It also provides a preliminary measure and reference database for greenhouse gas (GHG) emission of reservoir systems in Taiwan. Four reservoirs, Feitsui (F.T.) and Liyutan (L.Y.T.) in subtropical zone and Nanhua (N.H.) and Tsengwen (T.W.) in tropical zone, were selected as the cases to be examined for carbon footprint inventory, including the GHG emission from the water body and from human activities. Carbon footprint inventory followed PAS 2050 (2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services). GHG emission from water body followed the instruction of UNESCO guidelines. The boundary of this inventory covers the water intake works, impoundment region, the dam, the affiliated hydroelectricity power plant, the administration center and other facilities. In this study, the floating chambers with gas chromatography (GC) were chosen to measure the GHG flux from the water body. For the emission of CH₄ and N₂O from the water body, there are no significantly difference between the fluxes during the daytime and nighttime. For

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carbon dioxide, the instantaneous flux during the nighttime is higher than the daytime flux. The two reservoirs in tropical zone emit more CO₂e from the water body than those in subtropical zone. Summarizing the direct and indirect GHG emission, for the four reservoirs, the annual emission quantities ranged from 653 ton of CO₂e to 23,146 ton of CO₂e. The carbon footprint of water supply for domestic use ranged from 0.002 kg CO₂e/m³ to 0.028 kg CO₂e/m³. Roughly speaking, the total GHG emission quantity of the 24 main reservoirs in Taiwan was estimated to be around 121,800 ton of CO₂e with the total yield of 4.35 billion m³ of water annually using the highest carbon footprint 0.028 kg CO₂e/m³.

Keywords: Carbon footprint; Raw water; Reservoirs; Greenhouse gas emission; Carbon dioxide; Methane; Nitrous oxide; Floating chamber method.

1. INTRODUCTION

1.1 Carbon Footprint of City Water for Domestic Use

After the adoption of United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [1], many countries have been promoting the inventory and reduction of greenhouse gas (GHG) emission, as well as the related energy management. The carbon management was first initialized from the quantification of GHG emission in the organization level. It was gradually expanded to the evaluation of carbon footprint of a specific product (or service), ranging from the upstream supply chain to the downstream products. This helps to comprehensively evaluate the GHG emission of the entire life cycle of this product or service and the potential environmental impacts.

Carbon footprint of city water supply has attracted academic interest and public attention in recent decades. The relevant data are an essential reference for the water authority not only to re-evaluate the current policy of water resource, but also to help assess the current effectiveness and potential environmental impacts of the operation of relevant facilities. From the aspect of entire life cycle assessment (LCA), carbon emissions of the entire water supply chain for domestic use include the emission of the following six stages: (1) water source, (2) water conveyance, (3) water treatment, (4) water distribution, (5) water use and (6) wastewater treatment. Fig. 1 illustrates the aforementioned six stages during the water supplying process. Based on the definition in PAS 2050 [2] (2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services), carbon footprint of water indicates the carbon emission of the operation/maintenance of aforementioned six stages ("A" denoted in Fig. 2).

To the best of the authors' knowledge, most literatures evaluate the carbon footprint covering from stage (2) to (6) [3,4,5,6,7]. The carbon footprint of water supply for domestic use ranged from 2.95 to 6.97 kg of CO₂e per cubic meter of water. Emission from stage (5) "water use" was reported as the largest in the water supply chain (83-89%), while the second was the sixth stage "wastewater treatment" stage (6-9%), as depicted in Fig. 3. Noticeably, the carbon footprints of stage (2) to (4) were combined as one value in these reports.

Carbon footprint of the water source (stage 1), that is "C" in Fig. 2, however has not been adequately surveyed. The item "water resource" possibly means taking raw water from the surface water (reservoirs, river weirs or lakes), groundwater wells, seawater desalination or

wastewater reclamation, where this study focuses on the reservoirs. The carbon emission in this stage includes the direct GHG's emission from water body emission or fuel combustion, as well as the indirect emission from the electricity consumption. Among the surface water sources, a constructed reservoir impounds water and becomes a kind of "flooded land". It may emit more GHG's from the water body and the rotten biomass in the sediment than the emission status before the reservoir was constructed. The proven GHG's emitted from the reservoir include carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) [8]. On the other hand, there are more manual operations in the reservoir system, so that more electricity is consumed than other water sources [5]. The carbon emission of raw water from a constructed reservoir may be significant. As aforementioned, in most studies, it could not be clearly segregated from the stages (2), (3) and (4) [5]. Some studies reported the carbon emission during the construction stage, mainly from the fuel combustion and engineering raw materials [9]. Some reported the GHG emission from the water body [10,11], without the indirect carbon emission, that is, the carbon dioxide released from the electric use of the human activities. So far there is no systematic study for one reservoir to consider the carbon footprint from both the direct carbon emission (scope 1) and indirect emission (scope 2) in the operation stage. None of emission from scope 1 and 2 can be ignored.

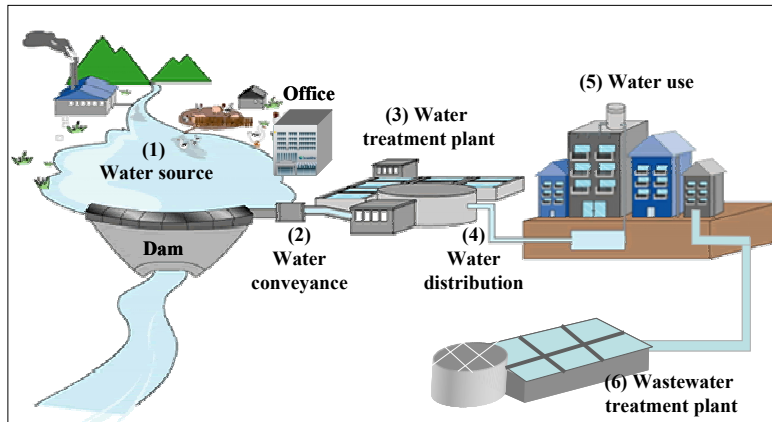


Fig. 1. Six stages in the life cycle of water supply for domestic use

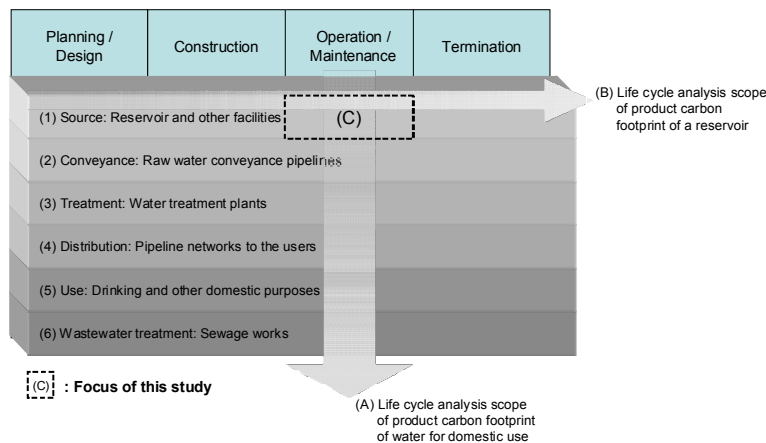


Fig. 2. Scope of life cycle analysis for carbon footprint calculation

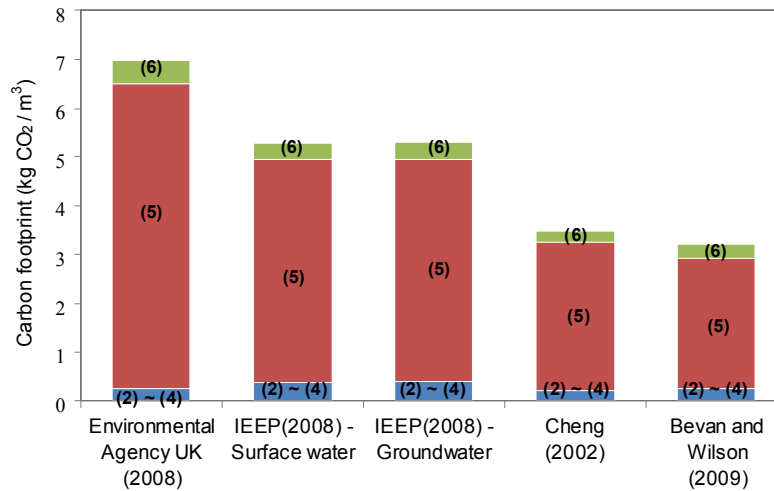


Fig. 3. Carbon footprint of domestic water use (excluding the water source stage)

1.2 Greenhouse Gas Emission from Water Body of Reservoirs

The investigations on GHG emission from flooded lands, including freshwater reservoirs, lakes and wetlands, have shown that flooded lands emit significant GHG's [12,13,14]. The reservoir may act as a carbon source, or on the contrary, a carbon sink, depending on the water quality, temperature and the reservoir depth [15,16,17,18]. Fig. 4 illustrates the two possible mechanisms of GHG emission. Mechanism I is the GHG released from the water-air interface in the reservoir. The plants die and are then immersed during the water impoundment. Microorganisms decompose the organic matters and produce carbon dioxide (CO₂) in aerobic environment, and in anaerobic environment, methane (CH₄) is produced. Nitrous oxide (N₂O) is produced in nitrification/denitrification process when the nutrients in aqueous phase are consumed [19]. On the other hand, carbonic acid reacts with alkali substances if pH is higher than 7 [20]. In this case, CO₂ is absorbed by the reservoir. Plants and algae in water also absorb CO₂ in the photosynthesis [21]. As many factors may be correlated with the GHG emission (or absorption), measurement of GHG emission at temperate zone and tropical zone may differ by one order of magnitude [16]. IPCC has reported the emission coefficient of CO₂ as 0.190 ~ 1.639 kg/m²/year and CH₄ as 0.0016 ~ 0.023 kg/m²/year for the flooded lands. Until 2012, IPCC has not reported systematic information for N₂O emission.

GHG's may be emitted during the water sluicing from the reservoir due to the dramatic change of pressure and temperature, as denoted as "Mechanism II" in Fig. 4 [22,23,24]. Abril et al. [22] reported that GHG emission through this mechanism only occurs when the dissolved CO₂ is higher than 250 μmol/L or when dissolved methane is higher than 25 μmol/L in the water. It ranged from 0.016~0.08 kg CO₂e per cubic meter in Barrage de Petit-Saut in Guyane of France from year 1994 to 2003. In this study, the GHG emission of mechanism II is categorized in the stage (2) (water conveyance), and is not counted as the GHG emission from the reservoir.

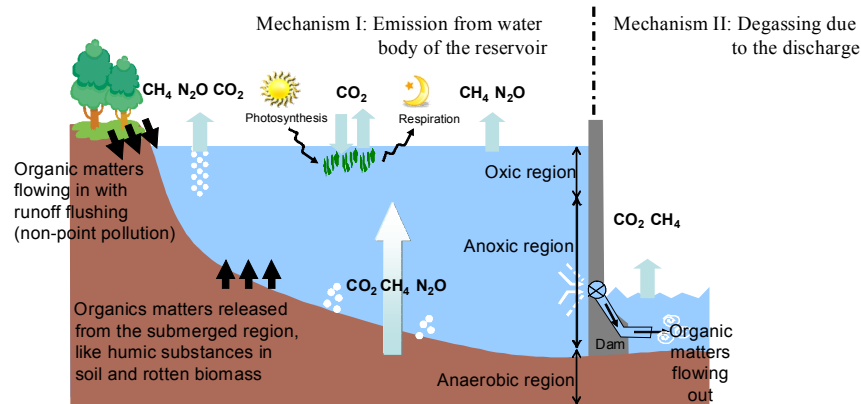


Fig. 4. The illustration of GHGs production and emission from reservoirs

1.3 Methods of GHG Emission Flux

In 2010, UNESCO published the methodology of GHG emissions flux measurement, “GHG Measurement Guidelines for Freshwater Reservoirs” [25]. It introduced several important ways to measure the flux, including thin-film method (also known as “thin boundary layer method”), floating chamber method and eddy-covariance method. The quantitative assay of GHG concentration includes gas chromatography (GC), Fourier-transformed infrared (FTIR), and the other gas analyzers.

The principle of thin-film method is used to estimate the convective flux of GHG using the interfacial mass transfer coefficient k_x and the concentration difference between the atmosphere and aquatic phase. The GHG flux F_a is calculated as

$$F_a = k_x (C_{water} - C_{air}) = k_x (K_0 \times pGas - C_{air}) \quad (1)$$

In eq. (1), the variables are defined as:

- F_a : GHG flux (mg/m₂/day)
- C_{water} : Dissolved GHG concentration in surface water (μmol/L)
- K_0 : Solubility of GHG in water (mole L⁻¹atm⁻¹)
- $pGas$: Partial pressure of GHG in the dark glass bottle (μatm)
- C_{air} : GHG concentration in atmosphere (μ mol/L)

In eq. (1), k_x is estimated using semi-empirical equations, mainly correlated with wind speed:

$$k_x = k_{600} \left(\frac{Sc}{600} \right)^{-x} \quad (2)$$

k_{600} : Normalized interfacial mass transfer coefficient (cm/h) [26,27,28].

$\frac{\mu}{\rho D}$
 Sc: Schmidt number ($\frac{\mu}{\rho D}$)
 μ : Viscosity of GHG (kg/m/s)
 ρ : Density of GHG (kg/m³)
 D: Diffusivity of GHG in air (m²/s)
 x: an empirical constant; it is 0.66 when the wind speed is less than 3 m/s and is 0.5 if wind speed is more than 3 m/s.

Water at 0.5 m under the surface is manually sampled and placed in a dark glass bottle. The dissolved GHG is released to the headspace in the bottle (Fig. 5) and then measured to estimate the gas concentration in the water. Although the procedure is simple, it is relatively difficult to manually apply in night time in the reservoir due to security concerns. On the other hand, this method only considers the mechanism of convective mass transfer driven by the concentration difference between aqueous phase and atmosphere, while the other factors that drive the mass transfer, such as photosynthesis and respiration of algae, are not counted if this method is applied.



Fig. 5. The dark glass bottle used in the thin-film method

The principle of floating chamber method is used to measure the accumulation of GHG's in the floating chamber in one specific period, and then to calculate the flux crossing the air/water interface. Fig. 6 shows the illustration of the instruments. The flux is calculated in the following equation:

$$F_a = \left(\frac{V}{A} \right) \left(\frac{\Delta C}{\Delta t} \right) \left(\frac{P \times F1 \times F2}{R \times (273.15 + T)} \right) \quad (3)$$

In eq. (3), the variables are defined as (Goldenfum, 2010):

- F_a : GHG flux (mg/m²/d)
- V: Chamber volume (m³)
- A: Bottom surface of floating chamber (m²)
- Δt : Time (min)
- ΔC : Gas concentration variation during Δt (ppmv)
- P: Atmosphere pressure (kPa)
- F1: Molecular weight; CO₂: 44; N₂O: 44; CH₄: 16 (gmole⁻¹)
- F2: Conversion factor of minute to day, 1440
- R: Gas constant 8.3144 JK⁻¹mole⁻¹
- T: Temperature (°C)

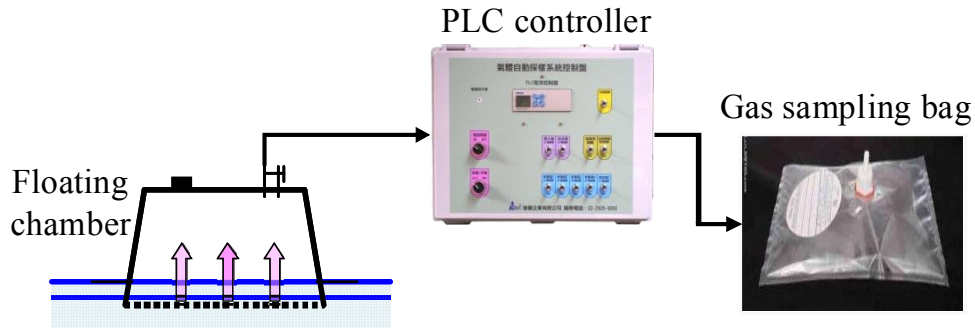


Fig. 6. Floating chamber method

Many literatures suggest that Δt should be a 30 minute span for this measurement [11,22,29]. The sampled gas is then quantitatively analyzed using gas chromatography, direct reading meter, or closed-cell Fourier-transfer infrared analyzer. It can measure the actual flux crossing the interface without the assistance of empirical equations like thin-film method. It is also possible to be collocated with auto-sampler to measure in the night time. The drawback is similar to the thin-film method that it needs manual operation to measure the gas concentration and then calculate the flux in most studies [14,29].

The principle of eddy-covariance method is to measure the fluctuation of gas concentration and vertical velocity above the surface of water body (Fig. 7). It has been widely applied on measuring GHG emission of terrestrial ecosystems, with a flux tower of height more than 5 m high (or no interfering objects surrounded) [30,31,32]. The GHG flux can be obtained by multiplying the gas concentration and vertical velocity using eq. (4) [25]:

$$F_a = \overline{w'c'} \times \frac{P \times F1}{R \times (273.15 + T)} \quad (4)$$

In eq. (4), the variables are defined as:

F_a : GHG flux ($\text{mg}/\text{m}^2/\text{s}$)

$w' = w - \bar{w}$ (m/s)

$c' = c - \bar{c}$ (ppmv)

w : wind speed in the vertical direction (m/s)

\bar{w} : The 30-min average of w (m/s)

c : GHG concentration (ppmv)

\bar{c} : The 30-min average of c (ppmv)

P : Atmosphere pressure (kPa)

$F1$: Molecular weight; CO_2 : 44; N_2O : 44; CH_4 : 16 (gmole^{-1})

R : Gas constant $8.3144 \text{ JK}^{-1}\text{mole}^{-1}$

T : Temperature ($^{\circ}\text{C}$)

$\overline{w'c'}$: The 30-min average of $w'c'$ ($\text{mg}/\text{m}^2/\text{s}$)

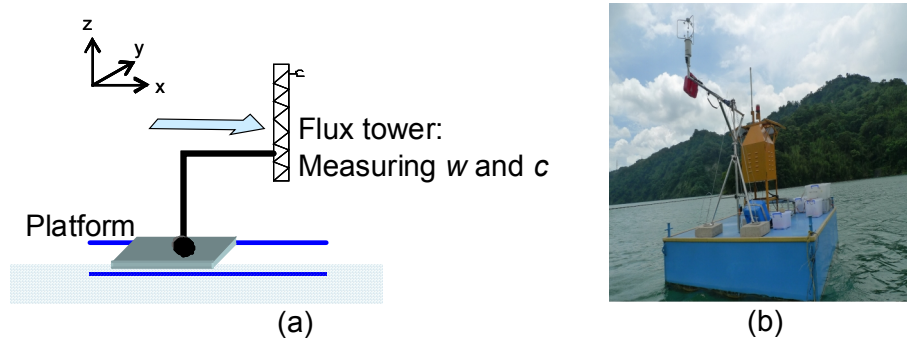


Fig. 7. Eddy-covariance method

The obtained data require further modification to remove the interference. More details are available in Black et al. and Aubinet et al. [33,34]. The major constraint on applying this method to aquatic system is that it is difficult to install a flux tower bearing the instruments on a stable platform on the reservoirs. Even slight waving and vibration in the vertical direction lead to measuring uncertainty of vertical wind velocity. For measurement on the reservoir, it is difficult to install a platform without vibration.

Among the three methods, the floating method directly measures the GHG flux across the water/air interface. Considering the requirements, constraints and measurement results of the aforementioned methods, the floating chamber method with GC analysis would be the most recommended approach of measuring GHG flux in reservoirs in Taiwan [14,29]. TBL method is suitable for measuring the GHG emission during the sluicing, but not suitable for measuring the flux crossing the water surface.

1.4 Target of This Study

In Taiwan, 20% of water is used in domestic consumption, whereas 9% is for industrial use and 71% is for agricultural use [35]. The studies on the carbon footprint of water supply chain for domestic use have begun since the beginning of this century [3]. The scattered results are required for further integration, and studies on carbon footprint of raw water (stage 1) in Taiwan are still lacking. Between year 2000 and 2009, in Taiwan, 24% of raw water (4.35 billion m³ per year) is from the reservoirs, whereas 56% is from the river water diversion with 20% from groundwater [35]. To comprehensively assess the potential environmental impacts of reservoir, the developers of water resource now begin to estimate the emission, and collect related information for policy making. This study is the first survey integrating the carbon emission from the water body and the human activity of the reservoir system in Taiwan, and is to give a reliable estimation of carbon footprint to “raw water” in the water supply chain. Noticeably, the floating chamber accompanied with a patented auto-sampler of Sinotech was used to measure the GHG emission from water body every four to six hours, and to observe the emission pattern during the daytime and nighttime.

2. METHODOLOGY

2.1 Four Reservoirs of This Study

This study selected four reservoirs in Taiwan to evaluate the carbon footprint in the stage (1) (water source) when the raw water comes from reservoirs. The evaluation included direct GHG emission from the water body and direct / indirect GHG emission during the reservoir operation. The four reservoirs, Feitsui (F.T.), Liyutan (L.Y.T.), Nanhua (N.H.) and Tsengwen (T.W.), were selected as the cases to be studied for GHG measurement. The main function of the four reservoirs is for the public water supply, and the volume of impounded water all exceed 50 million tons. At least 20% of public water supply in Taiwan comes from the previous four reservoirs. The locations are depicted in Fig. 8. F.T. and L.Y.T. are located in the subtropical zone, and N.H. and T.W. are located in the tropical zone.

2.2 Inventory of Carbon Footprint

The inventory followed the ISO/DIS14067 [36] (Greenhouse gases -- Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals), PAS 2050 [2] (2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services), and Taiwan carbon footprint calculation guidance for products and services [37]. The geological boundary of this inventory is illustrated in Fig. 9, including (1) water intake works, (2) impoundment region, (3) the dam, (4) the affiliated hydroelectricity power plant, (5) the administration center and other facilities (pipelines and penstocks for sluicing, and the tunnel to hydroelectricity plants). The upstream watershed area, the downstream receiving water, and the GHG emission through the water sluicing (mechanism II in Fig. 4) are excluded.

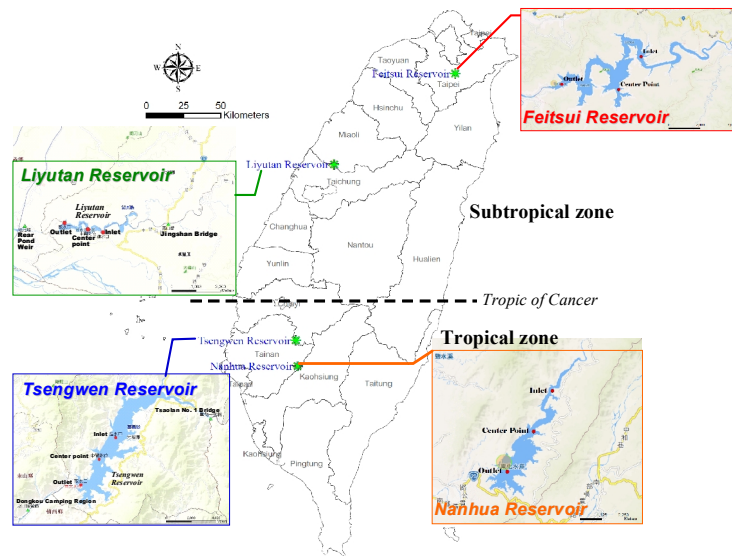


Fig. 8. The Positions of Four Selected Reservoirs in This Study

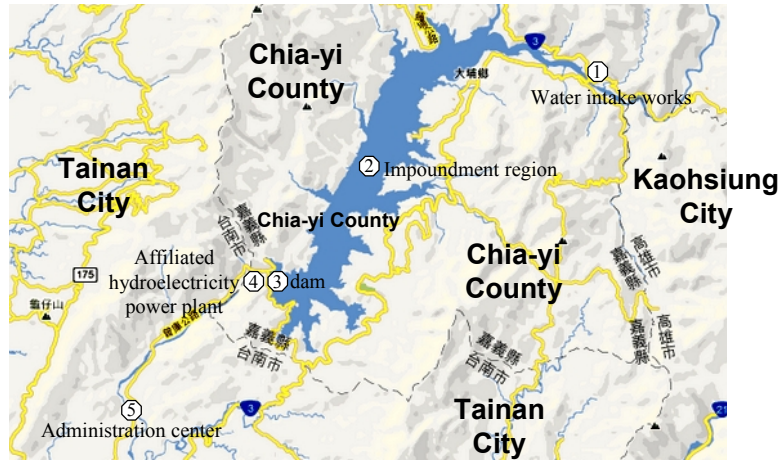


Fig. 9. The geological boundary of this inventory (taking T.W. reservoir as an example)

The details of GHG emission measurement of the water body is described in the next section. The GHG emission of individual human activities, including electricity consumption of the administration center, fuel combustion, the routine operations of the reservoir, maintenance works (for example, the excavating, dredging and mudslide prevention works) and waste disposal, are estimated using the annual records of raw materials, fuels and electricity consumption (from year 2011 to 2012). The carbon emission of aforementioned activities is calculated using the emission factors announced by EPA Taiwan and the database, such as ELCD 2.0 (European Commission-Joint Research Centre) and Ecoinvent 2.2 (Life Cycle Inventory). The aforementioned data is summarized and using the following equation to calculate the carbon footprint:

$$CF = \frac{1}{Q_R} \sum_i (S_i \times C_i + F_a \times A_R) \quad (5)$$

$$CF_{CO_2e} = CF_{CO_2} \times 1 + CF_{CH_4} \times 25 + CF_{N_2O} \times 298 \quad (6)$$

In eq. (5), the variables are defined as:

CF : Carbon footprint of raw water from the reservoir (mg/m^3)

S_i : Human activity strength (units of activity/d)

C_i : Carbon emission strength ($mg/units$ of activity)

F_a : GHG emission flux of water body ($mg/m^2/d$)

A_R : Impoundment area of reservoir (m^2)

Q_R : Reservoir yield (m^3/d)

In eq. (6), 1, 25 and 298 are the global warming potentials (GWP) for a 100-year horizon of CO_2 , CH_4 and N_2O , respectively (IPCC, 2007). The three items are summarized to obtain the CO_2 equivalent (CO_2e).

2.3 Floating Chamber Method for Measuring the Direct GHG Emission

The design of the floating chamber and the measurement followed UNESCO/IHA GHG Measurement Guidelines for Freshwater Reservoirs. The appearance of floating chamber is shown in Fig. 10a, with height of 30 cm, diameter of 43 cm, bottom area of 0.15 m² and effective volume of 43 liters. There are four valves on the chamber top, functioning in gas sampling and pressure balancing (between inner space and the atmosphere). The volume of gas sampling bag is 1 liter, which is made of the material Tedlar®. CO₂, CH₄ and N₂O were analyzed using GC/TCD, GC/FID and GC/ECD, respectively. At all the sampling points, three floating chambers were installed for triplicate tests (Fig. 10b) beside a stable platform (Fig. 10c). It measures the concentration difference between the 0 sec and 30 sec in the chamber, and then calculates the flux using eq. (3). GHG concentration variation in the chamber can be measured in two ways, either on-line using portable gas analyzers continuously, such as direct-reading CO₂ detector or closed-cell FTIR, or by taking air samples for gas chromatography (GC) analysis in the laboratory. It is shown that the measurement results using GC, CO₂ detector and closed-cell FTIR coincided well (Fig. 11). In this study we chose GC for the quantification.

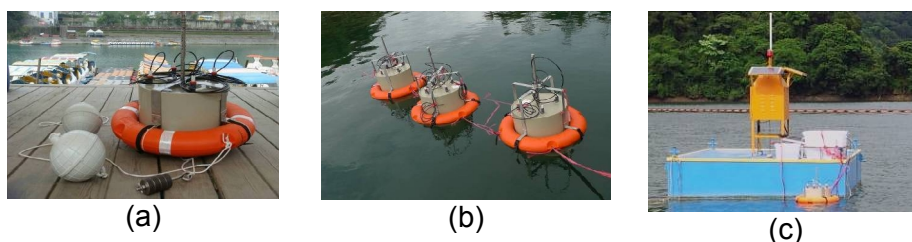


Fig. 10. The method of measuring the GHG emission flux crossing the water-gas interface of the water body by floating chamber.

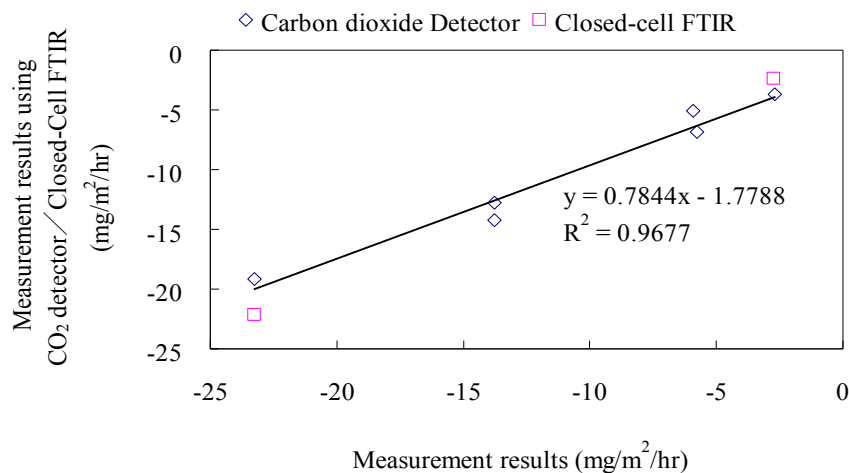


Fig. 11. The measurement results of GC, CO₂ detector and closed-cell FTIR.

In order to clarify the difference in GHG emission variation during daytime and nighttime, the floating chamber is connected with the patented auto-sampler of Sinotech to conduct 24-hr survey. The GHG flux at certain specific location is the GHG emission in 24 hours per

square meter ($\text{mg}/\text{m}^2/\text{day}$) by integrating the instantaneous flux ($\text{mg}/\text{m}^2/\text{hr}$), as shown in eq. (7).

$$F_{a,24} = \frac{1}{24 \text{ hours}} \int_{0:00}^{23:59} F_a(t) dt \quad (7)$$

The flux at the inlet, center point and outlet were then averaged to obtain the flux of one reservoir, as shown in eq. (8):

$$F_a = \frac{F_{a,\text{inlet}} + F_{a,\text{center point}} + F_{a,\text{outlet}}}{3} \quad (8)$$

The values were then averaged to obtain the GHG flux of this reservoir. The monitoring began from July 2011 to August 2013.

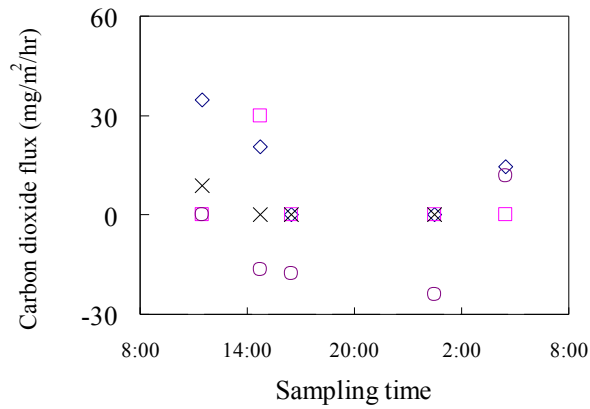
3. RESULTS AND DISCUSSION

3.1 The Measurement of Direct GHG Emission from Water Body

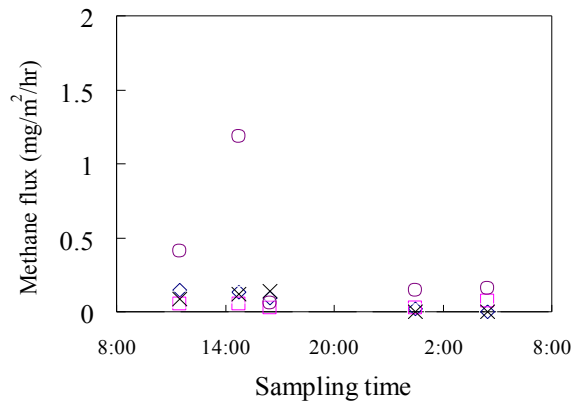
Fig. 12 demonstrates a typical measurement of instantaneous flux of GHG emission in a 24-hr cycle in January 2013. Fig. 12a, 12b and 12c are the results of CO_2 , CH_4 and N_2O , respectively. Noticeably, instantaneous flux of CO_2 may be positive or negative, but CH_4 and N_2O fluxes were always positive. For the four reservoirs, except some data scattering, during the daytime (6:00 to 18:00), most measured CO_2 fluxes were negative and ranged from -15 to 0 $\text{mg}/\text{m}^2/\text{hr}$ (Fig. 12a). Water body absorbed carbon dioxide from the atmosphere, possibly because of the photosynthesis of algae and plants, or because of the high pH of water body. There was no significant difference between the reservoirs in the tropical zone (N.H. and T.W.) and those in subtropical zone (F.T. and L.Y.T.).

During nighttime, at all reservoirs (18:00 to 6:00 on next day), the flux became less negative, or even became positive. It ranged from -6 to 15 $\text{mg}/\text{m}^2/\text{hr}$. By comparison, the nighttime flux of CO_2 was roughly 5~20 $\text{mg}/\text{m}^2/\text{hr}$ higher than the daytime flux. The release of CO_2 from the respiration of plants and algae at night may be the main factor, though it requires more studies to elucidate the correlation. Again, the difference between the reservoirs in tropical and subtropical zones was not significant.

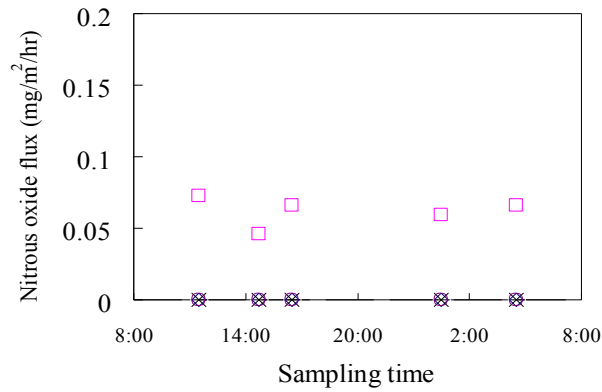
Fig. 12b depicts the results of instantaneous CH_4 flux at the same measurement. Using the hypothesis test, it showed no significant difference between the daytime flux and nighttime flux at a 95% confidence level. Most data points ranged from 0 to 0.2 $\text{mg}/\text{m}^2/\text{hr}$. In some extreme cases, the instantaneous flux was more than 0.5 $\text{mg}/\text{m}^2/\text{hr}$, possibly implying that there was plenty of rotten biomass in the sediment. Fig. 12c depicts the results of instantaneous N_2O flux. Similar to CH_4 flux, it also showed no significant difference between the daytime flux and nighttime flux at a 95% confidence level. Most data points ranged from 0 to 0.04 $\text{mg}/\text{m}^2/\text{hr}$.



(a) ◇ F. T. Reservoir □ T. W. Reservoir × N. W. Reservoir ○ L. Y. T Reservoir



(b) ◇ F. T. Reservoir □ T. W. Reservoir × N. W. Reservoir ○ L. Y. T Reservoir



(c) ◇ F. T. Reservoir □ T. W. Reservoir × N. W. Reservoir ○ L. Y. T Reservoir

Fig. 12. A Typical 24-hour measurement of GHG instantaneous flux in the selected reservoirs: (a)CO₂, (b) CH₄ and (c) N₂O

The results in Fig. 12 show a large fluctuation of GHG instantaneous flux in a 24-hour span, also reported by Wang et al. [19]. It is then difficult to compare the emission pattern between two reservoirs if only instantaneous fluxes data are obtained. Apparently using the instantaneous flux as a basis of carbon footprint calculation may be misleading. Using the daily average flux may better represent the emission pattern. By using eq. (7) and eq. (8), Fig. 13 demonstrate the seasonal variation of daily average GHG emission of T.W. reservoir as an example (in unit of $\text{mg}/\text{m}^2/\text{day}$). For methane and nitrous oxide, the emission is relatively stable than that of carbon dioxide. Noticeably, flux of three GHG's in January and May, usually with a lower water table in Taiwan, is higher than those fluxes in other seasons. Similar trends occurred in other reservoirs, too.

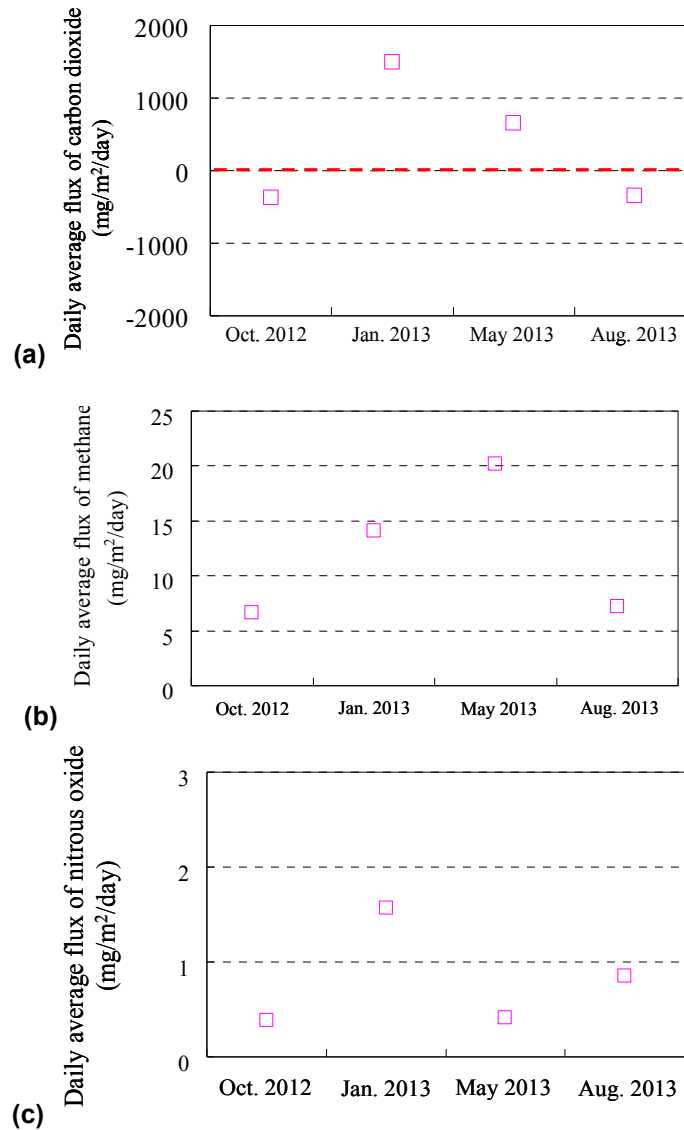
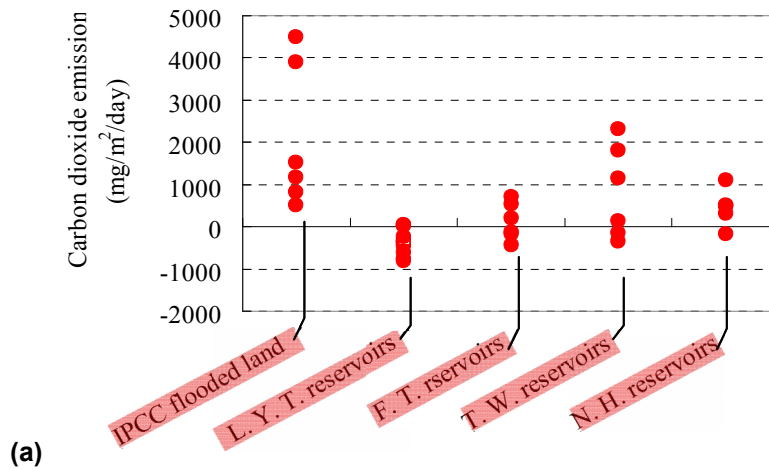


Fig. 13. A seasonal variation of daily average GHG emission of T.W. reservoir (a)CO₂, (b) CH₄ and (C) N₂O

Fig. 14 compare the GHG emission measured in this study and the flux of flooded lands reported by IPCC (only CO₂ and CH₄) [25]. For CO₂ (Fig. 14a), the flux of two reservoirs at tropical zone (T.W. and N.H.) ranged from -800 to 2,100 mg/m²/day, higher than that of those reservoirs in subtropical zone (F.T. and L.Y.T., ranged from -900 to 900 mg/m²/day). CO₂ flux of L.Y.T. reservoirs at most times during the monitoring was negative, and the reasons require more studies. Although Taiwan is just located on the Tropic of Cancer, CO₂ fluxes measured in this study are much lower than the IPCC reported values (from -200 to 4,500 mg/m²/day) [38,39,40]. It is closer to the values of reservoirs at temperate zone.

For CH₄, there was no significant difference among the CH₄ fluxes of the four reservoirs. They ranged from 0 to 15 mg/m²/day (Fig. 14b). The fluxes reported in this study were again much lower than the IPCC reported values (from 3 to 62 mg/m²/day). For N₂O, IPCC did not report the corresponding results and emission flux. For T.W. Reservoir, the N₂O fluxes ranged from 0.2 to 1.8 mg/m²/day, higher than the other reservoirs (ranged from 0 to 0.5 mg/m²/day) (Fig. 14c). Summarizing the emission of the three GHG's using eq. (6) to obtain carbon dioxide equivalents (CO₂e), Fig. 14d depicts the results. T.W. Reservoir emits the highest amount of carbon dioxide equivalents among the four reservoirs (50 to 3,000 mg/m²/day), while L.Y.T. Reservoir nearly emits no carbon dioxide equivalent. The two reservoirs in tropical zone emit more CO₂e than those in subtropical zone. The difference possibly comes from the water quality variation, though more evidence is required. Though the conceptual model is illustrated in literatures to describe why GHG was emitted from the reservoir, there are few studies conducting quantitative analysis. The possible factors influencing the GHG emission are the climate, water quality, ambient and human activities. Summarizing the survey in literatures, the reported factors may include the organics, nutrients, temperature, dissolved oxygen, planting density, aqua ecology, water retention time in the reservoir, wind speed, the reservoir type and water depth. Our studies are still ongoing.



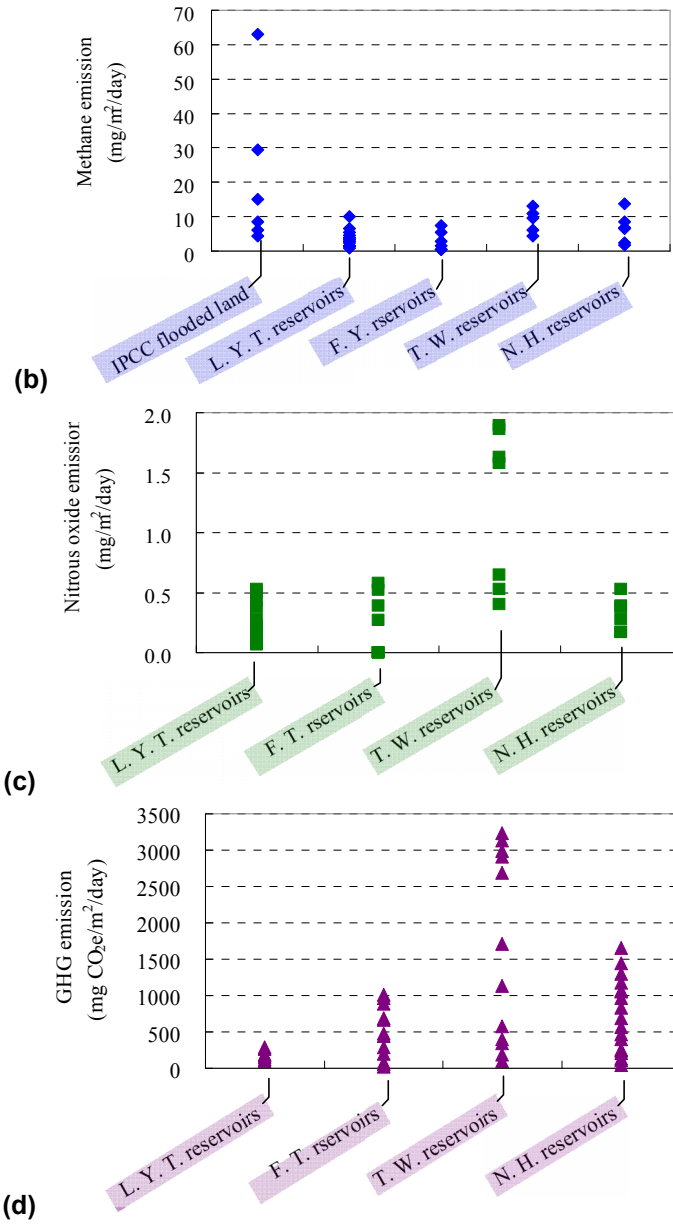


Fig. 14. Comparison of GHGs emission flux of the selected reservoirs from July 2011 to January 2013: (a) CO₂, (b) CH₄, (c) N₂O and (d) CO₂e

3.2 Carbon Footprint of the Four Reservoir System

Table 1 summarizes the background of the four reservoirs, as well as the carbon emission from water body and human activities based on the data during 2011 to 2012. Due to the strong variation of GHG fluxes in reservoirs, the GHG fluxes listed in Table 1 conservatively take the maximum values depicted in Fig. 14d. Among the four reservoirs, the annual emission quantities were 653 ton CO₂e for L.Y.T. Reservoir, 4,630 ton CO₂e for F.T.

Reservoir, 23,146 ton CO₂e for T.W. Reservoir and 6,212 ton CO₂e for N.H. Reservoir. The carbon footprint calculation used per cubic meter water output as the functional unit. The carbon footprint of water supply for domestic use were 0.002 kg CO₂e/m³ for L.Y.T. Reservoir, 0.004 kg CO₂e/m³ for F.T. Reservoir, 0.028 kg CO₂e/m³ for T.W. Reservoir and 0.027 kg CO₂e/m³ for N.H. Reservoir.

Noticeably, direct emission from water body was the major emitting source, which is about 41%~73% of the carbon footprint. As F.T. and T.W. have hydroelectric function, and they require more maintenance, they emit more GHG in the operation stage. On the other hand, N.H. and T.W. have larger catchment, and require more dredging and mudflow prevention. They also require more effort to remove the wooden waste, and this leads to larger carbon emission in the maintenance works.

Relative to the carbon footprint covering from stage (2) to stage (6) reported in literatures (2~8 kg CO₂e/m³) (Cheng, 2002; Environmental Agency UK, 2008; IEEP, 2008; Bevan and Wilson, 2009), the carbon footprint in stage (1), during which raw water comes from reservoir, is less than 1%. Roughly speaking, the total GHG emission quantity of 24 main reservoirs in Taiwan was estimated to be around 121,800 tons of CO₂e with the total yield of 4.35 billion m³ of water annually using the highest carbon footprint at 0.028 kg CO₂e/m³. This value is somehow smaller than the emission from one typical petroleum factory or one fossil-fuel power plant. Although building a reservoir raises the controversy of ecological destruction, taking raw water from reservoir system may cause relatively low carbon footprint.

Table 1. Carbon footprint of reservoir systems

Item	L. Y. T.	F. T.	T. W.	N. H.
Reservoir Yield (10 ⁶ m ³ /year)	327.8	1236.5	829.6	227.6
Impoundment Area (10 ⁶ m ²)	4.48	9.22	12.3	4.55
Maximum GHG Flux of Water Body (g CO ₂ e/m ² /year)	66.95	368.3	1,109	563
Carbon Emission (kg CO ₂ e/year)				
Direct Emission from Water Body	299,936	3,394,253	13,673,970	2,561,650
Emission of Routine Operation	240,226	888,706	696,356	425,024
Emission of Maintenance Works	112,844	347,244	8,776,043	3,226,195
Total Emission	653,006	4,630,203	23,146,369	6,212,869
Carbon Footprint of Raw Water from the Reservoir (kg CO ₂ e/m ³)	0.002	0.004	0.028	0.027

Based on the aforementioned information, carbon reduction strategies for reservoir systems may be proposed, including the strategies for reservoirs' planning and design, operation, water body management, and the customized solutions for the individual reservoirs. The main consensus was to optimize water storage and distribution process, maintain storage space of reservoirs (preventing the flow-in of suspended solids as much as possible), reduce water wastage, and reduce the use of desalination or recycled water derived from highly energy-intensive facilities. Furthermore, it is also recommended to take carbon emission inventory into the engineering contract in the future to more accurately assess GHG emission from reservoirs' construction and operation. Efficient and effective GHG emission

control of the reservoir system may be effectively practiced if the emission status and quantities are comprehensively informed.

4. CONCLUSION

In this study, the carbon footprint of the raw water from the Taiwanese reservoirs for domestic use was estimated based on the PAS 2050 and UNESCO guidelines. It focused on the carbon emission on the boundary of a reservoir, including the water intake works, impoundment region, the dam, the affiliated hydroelectricity power plant, the administration center and other facilities. The first part of this study is to measure the GHG flux from the water body in a 24-hr span, using the floating chamber methods with a patented auto-sampler of Sinotech. For the four reservoirs, the instantaneous flux of CO₂ was generally negative during the daytime, and it became positive or less negative during the nighttime. This is possibly related to the respiration of algae and plants. Noticeably the results here are closer to the reported values of reservoirs within temperate zone. The second part is the carbon inventory of the human activities. The inventory covers the consumption of fuels, electricity and raw materials during the routine operation and the maintenance works such as dredging. Summarizing the carbon emission of part 1 and part 2 and divided by the annual yield of the reservoir, one may obtain the carbon footprint of the raw water from the reservoir. For the four reservoirs, the carbon footprint of water supply for domestic use ranged from 0.002 kg CO₂e/m³ to 0.028 kg CO₂e/m³. It is roughly 1% of the entire supply chain of water for domestic use. This study is the first survey integrating the carbon emission from the water body and the human activity of the reservoir system in Taiwan.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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