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# Proposal of Simple Measurement Method for Evaporation Rate by Using Oxygen Isotopic Ratio

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**ABSTRACT:** The purpose of this study is to develop simple method for estimating evaporation rates of water using oxygen isotopic ratio. From the laboratory test, strong negative correlation between average humidity and oxygen isotopic ratio change per unit evaporation rate was observed and humidity was clarified to be important parameter. The evaporation rate can be calculated from the amount of change of the oxygen isotopic ratio during evaporation. The amount of change of the oxygen isotopic ratio per unit the amount of change of evaporation rate estimated empirically under each humidity condition. The amount of evaporation per year in the Inawashiro Lake in Fukushima was estimated to be 590mm/year from the relation between humidity and evaporation rate and the estimated value was in agreement with the calculation result of previous research, 600mm/year. Therefore, the simple estimation method is effective for estimation of evaporation rate of an actual lake or a pond especially in a dried area because the measurement error is small under the low humid condition.

**Keywords:** Evaporation rate, Oxygen isotopic ratio, Humidity, Lake

## 1. INTRODUCTION

Recently, water shortage is caused by climate change such as Global warming. Therefore, estimation of amount of evaporation for dam, reservoir and irrigation water is important for preservation of water resources. There are various methods to calculate an amount of evaporation such as Thornthwaite method [1] and the Penman method [2], etc.

The relation between evaporation and isotope is discussed [3], [4]. The estimation method of evaporation rate using isotopic ratio was made by Allison et al. [5] or Gibson et al. [6]. However the method included many parameters such as humidity, partition coefficient, oxygen isotopic ratio of vapor, kinetic isotope effect, resistance of diffusion, and so on shown in expression (1) [7], [8] and then the some parameter is very difficult to measure or estimate. Therefore, estimation method of evaporation rate to calculate from isotope is very difficult because evaporation rate is controlled by many parameters as given by eq. (1).

$$\frac{d\,\delta_L}{d\ln f} = \frac{h_A(\delta_L - \delta_A)/(1+\delta_L) - \varepsilon^*}{(a - h_A)(a \cdot \alpha_{vap-liq} \cdot e_{i,L}/e + e_i/e)} \qquad (1)$$

$\delta_L$ : isotopic ratio of water
$f$ : ratio of water that remains for the first water
$\delta_A$ : isotopic ratio of vapor
$h_A$ : humidity
$a$ : water activity
$\varepsilon^*$ : $a\varepsilon + \triangle\varepsilon$ ($\varepsilon$ : equilibrium vapor pressure ratio, $\triangle\varepsilon$ : amount of change equilibrium vapor pressure ratio)
$\alpha_{vap-liq}$ : partition coefficient
$e_{i,L}$ : diffusion resistance of heavy water in water
$e$ : diffusion resistance of steam in atmospheric (Constant)
$e_i$ : diffusion resistance of heavy water in atmospheric

However, if there is some effective parameter to determine evaporation rate using isotope, we can estimate evaporation rate from limited parameter to measure easily. Therefore, the purpose of this study is to develop simple method for estimating evaporation rates of water using oxygen isotopic ratio and finding effective parameter for calculation of evaporation rate [9]–[11]. Then, we can estimate the oxygen isotopic ratio of residual water when the evaporation rate of water reaches 1%.

## 2. EXPERIMENT AND ANALYSIS

In laboratory test, amount of average evaporation of day, temperature, humidity, and saturation deficit were measured and then the relation of oxygen isotopic ratio of water and their parameters was analyzed. Table-1 shows the environmental condition and the actual measurement value of the test. The 33 evaporation tests were performed between 2005 and 2010 in the drying chamber with uniform temperature, the refrigerator with low temperature and the rooftop of the building in the Wakayama University. Fig.1 shows the pictures of evaporation experiment.

The water used for the experiment was tap water of Wakayama University. Both of the 5L (170 mm in the diameter, 300mm in the height, and 75 mm in the mouth diameter) and the 2L (126 mm in the diameter, 245 mm in the height, and 75 mm of mouth in the diameter) bottles were used for checking influence of difference of water volume on the relation between isotopic ratio of water and evaporation rate under the experiment.

Fig.2 shows the flow of the experiment. The quantity of water was measured at the intervals of several days during evaporation period and then 20 ml water was sampled from the residual water for clarify relation between evaporation rate and the oxygen isotopic ratio. After the carbon dioxide equilibrium method, the oxygen isotopic ratio of the sampled water was measured with mass spectrometer (Finnigan Mat Delta Plus). The measurement

Table1 Environmental condition and actual measurement value of the evaporation experiment

| | Vessel | Evaporation Place | Average Temperature (℃) | Average Humidity (%) | Saturation Deficit ($g/m^3$) | Amount of average evaporation of day(mm/day) | Start Date | End Date |
|---|---|---|---|---|---|---|---|---|
| 1 | 5L | indoor | 8.8 | 68.7 | 2.3 | 0.8 | 2007/11/8 | 2008/4/11 |
| 2 | | | 9.9 | 65.3 | 2.7 | 0.7 | 2005/12/15 | 2006/4/28 |
| 3 | | | 19.3 | 74.3 | 3.6 | 1.4 | 2008/4/21 | 2008/7/9 |
| 4 | | | 23.8 | 74.6 | 4.7 | 1.4 | 2008/7/11 | 2008/9/17 |
| 5 | | | 24.8 | 47.3 | 11.2 | 3.6 | 2008/10/22 | 2008/12/1 |
| 6 | | | 24.9 | 42.3 | 12.5 | 3.5 | 2008/12/15 | 2009/1/23 |
| 7 | | | 29.9 | 41.1 | 17.2 | 3.5 | 2005/11/3 | 2005/12/5 |
| 8 | | | 24.6 | 68.0 | 6.3 | 2.0 | 2009/4/25 | 2009/8/5 |
| 9 | | | 24.9 | 39.8 | 13.1 | 3.3 | 2009/11/19 | 2010/1/28 |
| 10 | | | 10.4 | 73.4 | 2.1 | 0.6 | 2006/7/4 | 2007/1/4 |
| 11 | | outdoor | 7.8 | 60.0 | 2.8 | 0.7 | 2007/11/22 | 2008/4/8 |
| 12 | | | 13.1 | 62.1 | 3.7 | 1.0 | 2006/10/24 | 2007/1/4 |
| 13 | | | 24.7 | 66.5 | 6.7 | 0.7 | 2007/6/11 | 2007/10/29 |
| 14 | | | 27.2 | 67.5 | 7.5 | 1.5 | 2008/7/1 | 2008/9/17 |
| 15 | | | 23.9 | 65.5 | 6.6 | 2.4 | 2009/4/30 | 2009/8/27 |
| 16 | | | 7.1 | 59.9 | 2.6 | 0.6 | 2007/11/22 | 2008/3/11 |
| 17 | | | 24.7 | 66.5 | 6.7 | 0.7 | 2007/6/11 | 2007/10/29 |
| 18 | | | 13.0 | 61.9 | 3.7 | 0.9 | 2006/10/24 | 2007/1/4 |
| 19 | 2L | indoor | 9.0 | 69.0 | 2.3 | 0.8 | 2007/11/8 | 2008/2/27 |
| 20 | | | 19.8 | 72.8 | 3.9 | 1.4 | 2008/4/21 | 2008/6/23 |
| 21 | | | 24.8 | 74.8 | 4.9 | 1.4 | 2008/7/11 | 2008/9/17 |
| 22 | | | 24.9 | 53.8 | 9.7 | 5.5 | 2008/10/22 | 2008/11/18 |
| 23 | | | 24.9 | 42.1 | 12.6 | 5.7 | 2008/12/15 | 2009/1/22 |
| 24 | | | 24.7 | 59.2 | 8.3 | 3.6 | 2009/4/25 | 2009/6/5 |
| 25 | | | 25.0 | 42.6 | 12.5 | 4.2 | 2009/11/19 | 2009/12/21 |
| 26 | | outdoor | 7.1 | 59.9 | 2.6 | 0.8 | 2007/11/22 | 2008/3/11 |
| 27 | | | 27.6 | 67.6 | 7.6 | 1.9 | 2008/7/1 | 2008/8/29 |
| 28 | | | 21.7 | 63.5 | 6.1 | 2.2 | 2009/4/30 | 2009/8/3 |
| 29 | | | 7.1 | 59.9 | 2.6 | 1.0 | 2007/11/22 | 2008/3/11 |
| 30 | | | 17.2 | 64.5 | 4.5 | 2.3 | 2009/10/9 | 2009/11/9 |
| 31 | | | 17.2 | 64.5 | 4.5 | 2.6 | 2009/10/9 | 2009/11/9 |
| 32 | | refrigerator① | 4.6 | 25.3 | 4.6 | 0.4 | 2009/7/24 | 2010/3/8 |
| 33 | | refrigerator② | 5.5 | 89.6 | 0.6 | 0.2 | 2008/7/14 | 2009/1/20 |

Fig.1 (a)【Drying chamber】

Fig.1 (b)【Refrigerator①】

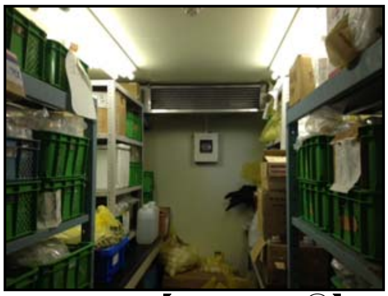


Fig.1 (c)【Refrigerator②】

Fig.1 (d)【Rooftop in the Wakayama University】

Fig.1 Pictures of evaporation experiment

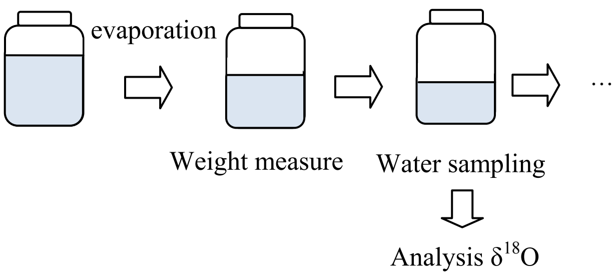



Fig.2 Flow of the evaporation experiment

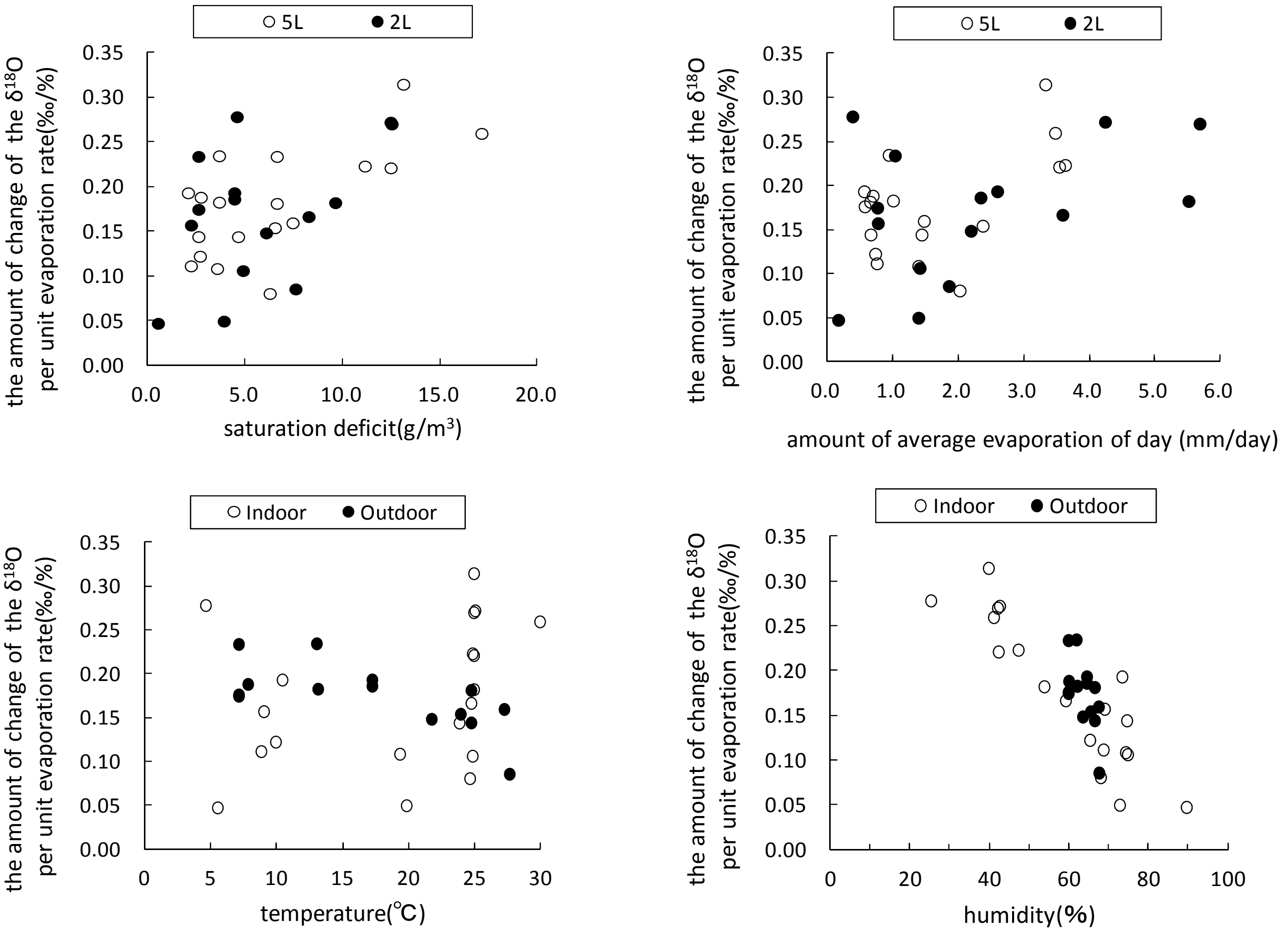



Fig.3 Relationship between the amount of change of the $\delta^{18}O$ per unit evaporation rate and each amount of average evaporation of day, saturation deficit, average temperature and average humidity

error of oxygen isotopic ratio ($\delta^{18}O$) is ±0.1‰. The temperature and humidity were every hour measured and the data was memorized with the storage meter (Sato meter factory SK-L200TH). Moreover, the temperature and the humidity of the outdoor experiment period were used the meteorological data of Wakayama City of the Meteorological Agency.

## 3. RESULT

### 3.1 Factor in which it affects oxygen isotopic ratio

Fig.3 shows relationship between the amount of change of the $\delta^{18}O$ per unit evaporation rate and each amount of average evaporation of day, saturation deficit, average temperature and average humidity.

From the test, negative correlation (R= -0.84) between the average humidity and the amount of change of the $\delta^{18}O$ per unit evaporation rate was found. In particular, the amount of change of the $\delta^{18}O$ per unit evaporation rate is sensitive to humidity under the low humidity condition and then the amount of change of the $\delta^{18}O$ per unit evaporation rate of residual water is large during evaporation process under a dry area.

### 3.2 Variation of the amount of change of the $\delta^{18}O$ per unit evaporation rate

Fig.4 shows the variation of the indoor and outdoor

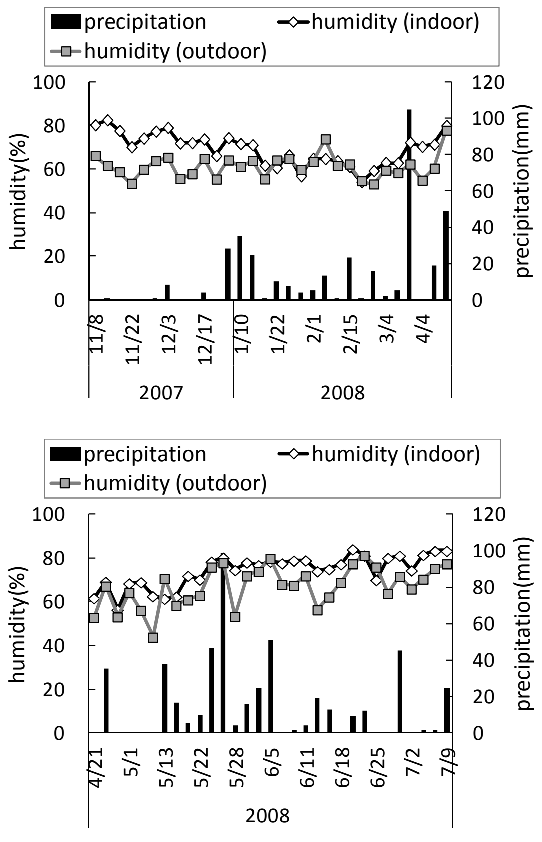



Fig.4 Variation of the humidity indoor and outdoor and precipitation

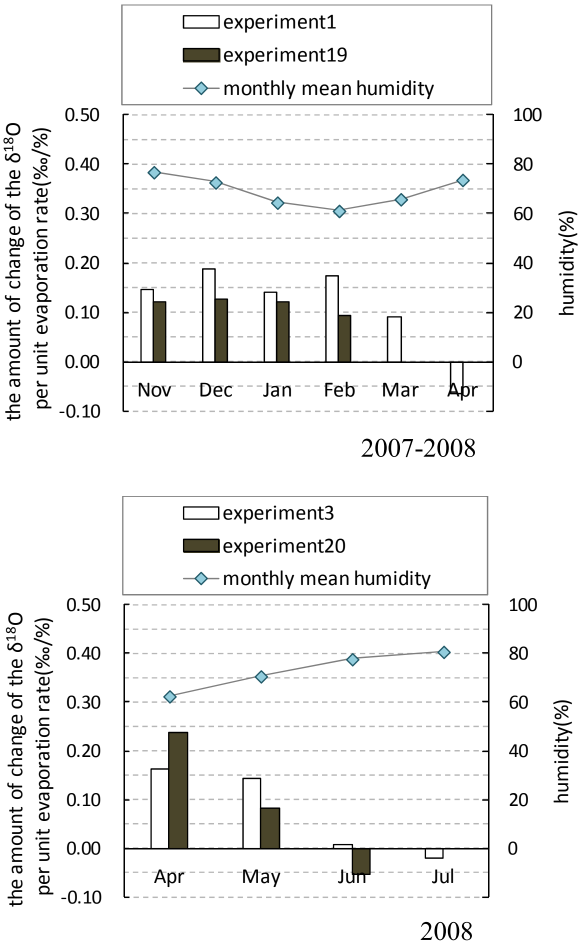



Fig.5 Monthly variation of the amount of change of the $\delta^{18}O$ per unit evaporation

humidity and precipitation in winter (2007.11～2008.04) and in summer (2008.04～2008.07). The humidity was high in summer and low in winter and the indoor humidity changed with outdoor humidity. Fig.5 shows the monthly variation of the amount of change of the $\delta^{18}O$ per unit evaporation in winter and in summer. The amount of change of the $\delta^{18}O$ per unit evaporation rate increased from -0.07 to 0.24 ‰ / % as humidity decreased from 80 to 60 %. Therefore, the humidity change accompanying seasonal change was clarified to affect apparently the amount of change of the $\delta^{18}O$ per unit evaporation rate.

Fig.6 shows relationship of the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate and humidity. The amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate changed from 0.2 to -0.2 ‰ / % with evaporation rate under the condition of more than 60 % humidity. Fig.7 shows variation of the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate under the condition of humidity from 20 to 80%. The amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate changed greatly as humidity increased. On the other hand, under the condition of less than 60 % humidity, the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate kept uniform although evaporation rate changed and then it was in agreement with the eq. (1).

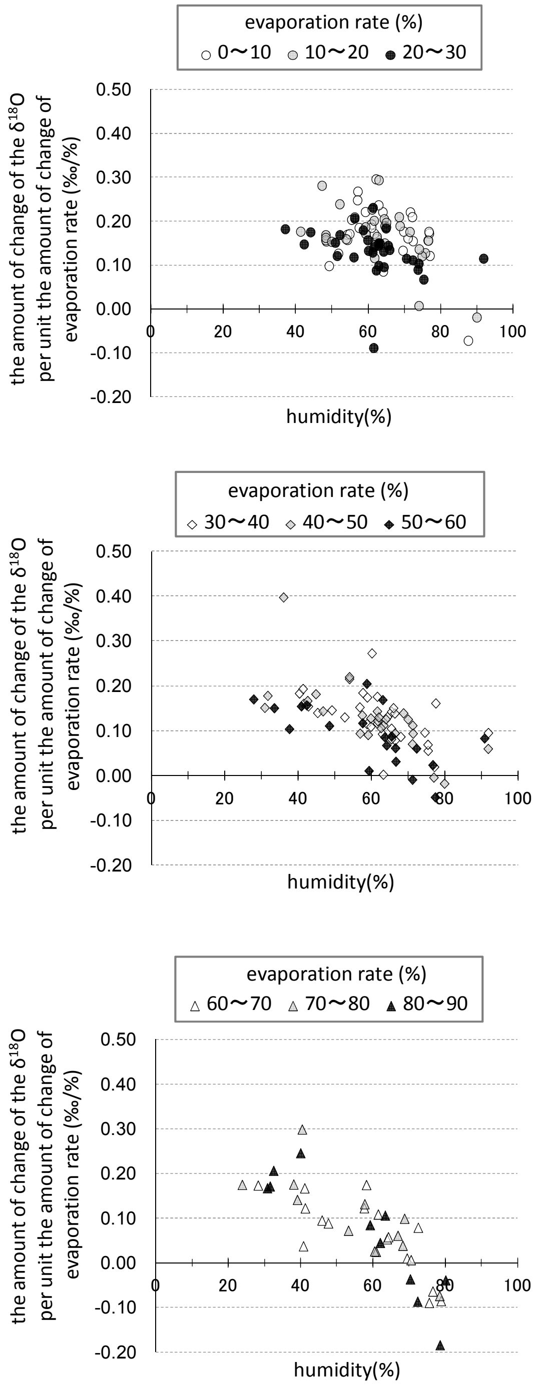



Fig.6 Relationship of the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate and humidity

### 3.3 Variation of $\delta^{18}O$ with evaporation under the high humidity condition

Fig.8 shows variation of $\delta^{18}O$ with evaporation under the high humidity condition of more than 70%. Although $\delta^{18}O$ for water increased with evaporation rate at the beginning of evaporation, the $\delta^{18}O$ for water gradually became uniform values or decreased with evaporation rate in drying chamber (experiment-1, 3, 8). Uniform or decrease process of $\delta^{18}O$ value with evaporation rate in the condition of more than high humidity is in agreement with the previous

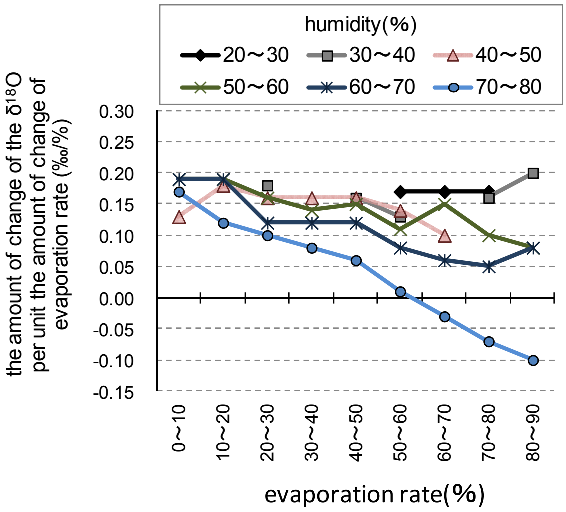



Fig.7 Variation of the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate about humidity from 20 to 80%

research (Gonfiantini,1965) [12]. And the $\delta^{18}O$ in refrigerator (experiment-33) decreased until -9.1‰ from -7.9 ‰ at the beginning of evaporation and then the $\delta^{18}O$ increased under the condition of more than 80% humidity. The estimated volume of vapor was about 18 $m^3$ because the volume of the refrigerator was about 20 $m^3$ and the refrigerator was filled with samples. Then, there was a lot of vapor and the $\delta^{18}O$ in water was apt to be influenced by the $\delta^{18}O$ in vapor. On the other hand, the volume of the drying chamber was about 0.10 $m^3$ and the estimated volume of vapor was about 0.07 $m^3$ and the $\delta^{18}O$ in vapor was apt to be influenced by the $\delta^{18}O$ in water.

The vapor caused by evaporation was exchanged with the vapor in the drying chamber and refrigerator. When $\delta^{18}O$ for original vapor was lower than those for vapor evaporated from liquid sample, $\delta^{18}O$ for original water did not increase but decreased. On the other hand, when $\delta^{18}O$ for original vapor was higher than those for vapor evaporated from liquid sample, $\delta^{18}O$ for original water increases. However, under the condition of exchanging outdoor air with lower isotope than those evaporated from water, $\delta^{18}O$ for original water increases at the beginning of evaporation but the increase gradually becomes low and reaches uniform values and then decreases because of low isotope vapor inflow.

### 3.4 Verification of the measurement method in the Inawashiro Lake in Fukushima

The amount of evaporation per year in the Inawashiro Lake in Fukushima was estimated from the relationship of the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate and humidity.

Fig.9 shows distribution of $\delta^{18}O$ of the water in the Inawashiro Lake and rivers surrounding the lake. The area is 103 $km^2$. Pondage is 3.9 billion $m^3$. Maximum depth is about 94 m. The surrounding length is 55 km. It is amount 10300 million $m^3$ / year of the inflow during the year to the lake. The detention period is estimated by dividing the amount of reservoir during year by the amount of the inflow, and the estimated value is about 3.7 years. As the $\delta^{18}O$

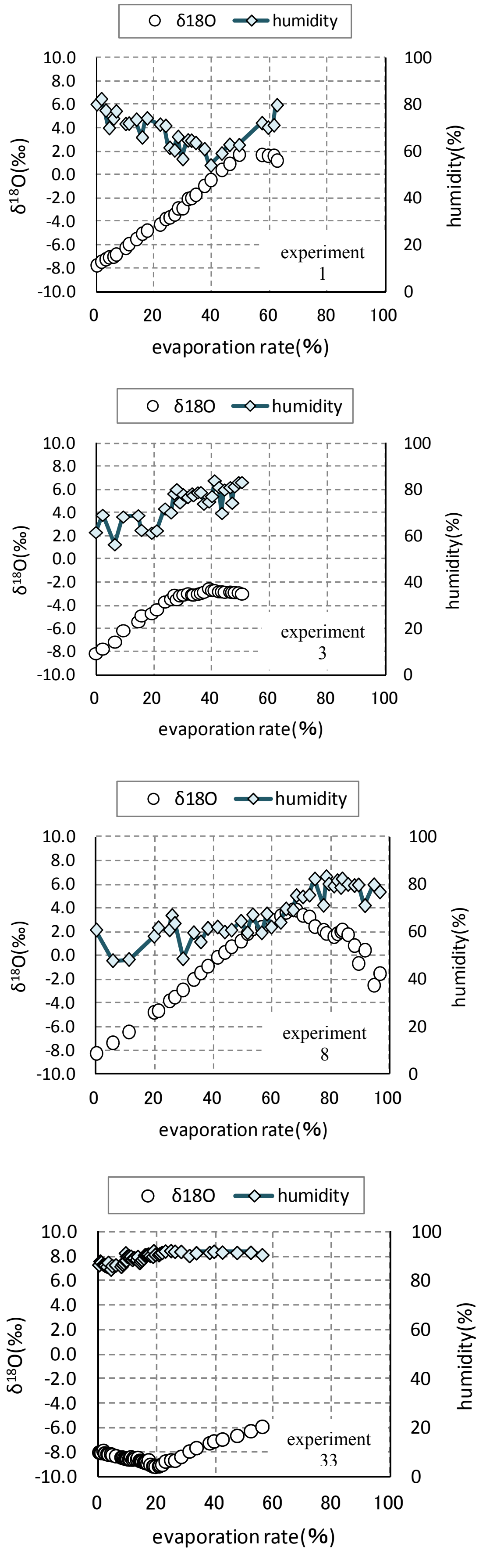
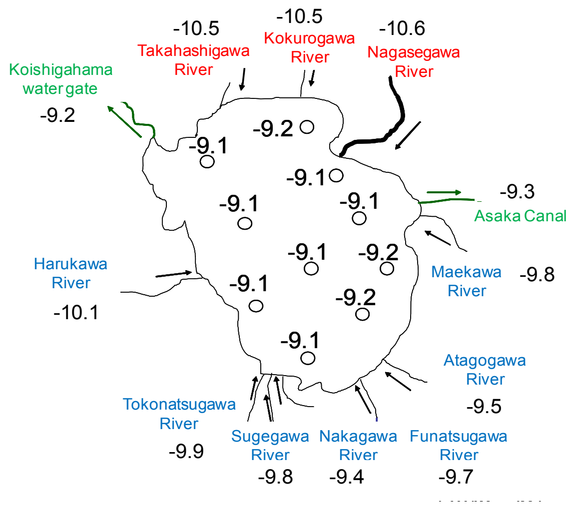



Fig.8 Variation of $\delta^{18}O$ with evaporation under the high humidity condition of more than 70% experiment1(8.8℃) , experiment3(19.8℃), experiment 8(24.6℃) and experiment33(5.5℃)




- area: 103 $km^2$
- pondage: 3.9 billion $m^3$
- amount of the inflow during the year to the lake: 10300 million $m^3$ / year
- detention period: 3.7year
- average humidity: 74%
- $\delta^{18}O$ of lake before evaporation: -10.3‰
- $\delta^{18}O$ of lake after evaporation: -9.3‰

Fig.9 Distribution of $\delta^{18}O$ of the water in the Inawashiro Lake and rivers surrounding the lake

humidity (%) ▶ the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate (‰/%)

▼

evaporation rate (%) = the amount of change of the $\delta^{18}O$(‰) / the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate (‰/%)

▼

amount of evaporation (mm/year) = the amount of the inflow during the year to lake ($km^3$/year) × evaporation rate (%) / the area of lake($km^2$)

Fig.10 Flow of the calculation of the amount of evaporation

value of the lake was uniform, -9.3 ‰ because mixing season and the $\delta^{18}O$ value of the inflow rivers was -10.3 ‰, the $\delta^{18}O$ of water increased from -10.3 ‰ to -9.3 ‰ by evaporation process [9]. The amount of change of the $\delta^{18}O$ evaporation process was 1 ‰. Also the amount of evaporation of the lake was calculated from the method of Jacobs (1975) with the aerodynamical technique and the estimated value was 600 mm/year [13]. In the Inawashiro Lake, the average humidity for a year was 74 %. And then, the amount of change of the $\delta^{18}O$ per unit evaporation rate with 74 % humidity was adopted.

Fig.10 shows a flow of the calculation of the amount of evaporation.

1) The amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate is determined from the Fig.7 and average local humidity.
2) The evaporation rate is calculated from the amount of change of the $\delta^{18}O$ and the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate (‰ / %)
3) The amount of evaporation for a year was calculated from the amount of the inflow during the year to lake, evaporation rate, and the area of lake.

The amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate was calculated from relationship between the amount of change of $\delta^{18}O$ per unit the amount of change of evaporation rate and humidity. And then, the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate with 74 % humidity, average humidity in the Inawashiro Lake was 0.17 ‰ / % under the evaporation rate 0～10 %. The evaporation rate was calculated from the amount of change of the $\delta^{18}O$ and the amount of change of the $\delta^{18}O$ per unit evaporation rate. Therefore, evaporation rate in the Inawashiro Lake was calculated to be 5.9% from 1 %, the amount of change of the $\delta^{18}O$ and 0.17 ‰ / %, the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate shown in expression (2).

$$1\ (‰) / 0.17\ (‰ / \%) \fallingdotseq 5.9\ (\%) \qquad (2)$$

$$10300 \text{ million } (m^3 / year) \times 5.9\ (\%) / 103\ (km^2) = 590\ (mm / year) \qquad (3)$$

The amount of evaporation for a year was calculated from the amount of the inflow during the year to lake, evaporation rate, and the area of lake. Therefore, the amount of evaporation for a year in the Inawashiro Lake was calculated to be 590 mm / year from 10300 million $m^3$/ year, the amount of the inflow during the year to lake and 6.7 %, evaporation rate and 103 $km^2$, the area of the lake shown in expression (3). The estimated value was about 590 mm / year in agreement with the calculation result of the previous research using the method of Jacobs, 600 mm / year.

However when the evaporation rate in the lake exceeded 10%, evaporation rate in the lake could not be calculated using only 0.17 ‰ / % because of the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate changed with evaporation rate under the condition of more than 60 % humidity. Therefore, if evaporation rate in the lake exceed 10 %, the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate needs to use depending on the evaporation rate. On the hand, under low humidity condition, it is easy to apply this method because $\delta^{18}O$ for water increase with evaporation rate uniformly.

## 4. CONCLUSION

The purpose of this study is to develop simple method for estimating evaporation rates of water using oxygen isotopic ratio. From the empirical results, negative correlation (R= -0.84) between the average humidity and the amount of change of the $\delta^{18}O$ per rate of unit evaporation was clarified. And the amount of change of the $\delta^{18}O$ per unit the amount of change of evaporation rate changed with evaporation rate under the condition of more than 60 % humidity. The amount of evaporation per year in the Inawashiro Lake in Fukushima was estimated to be about 590 mm / year from the relation between humidity and evaporation rate and the estimated value was in agreement with the calculation result of the previous research using the method of Jacobs, 600 mm / year.

It is difficult to estimate the evaporation rate under high humidity condition because $\delta^{18}O$ does not always increase with evaporation rate from the experiments result. On the other hand, $\delta^{18}O$ increases with evaporation rate in low humidity condition. Therefore, the simple estimation method using only oxygen isotopic ratio and humidity is very effective for estimation of evaporation rate of an actual lake or a pond.

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