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LONG-TERM CHANGE OF RIVER WATER TEMPERATURE FLOWING INTO RESERVOIRS IN JAPAN

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ABSTRACT

Reservoirs play an important role in flood control and water use. In particular, from the viewpoint of water use, they are responsible for the major resources of domestic water in Japan as well as agriculture and industrial waters. On the other hand, various impacts from climate change are becoming apparent in various areas in recent years. Eutrophication phenomenon, especially occurrence of water bloom by cyanobacteria, seems more frequent possibly because of changes in river water discharge and nutrient load affected by alteration of precipitation as well as rising water temperature. Water temperature is generally considered the principal factor to control water quality and ecosystem in natural water bodies. In this study, we investigated the long-term changes in water temperature observed over the past several decades in many dam inflow rivers in all parts of Japan. The observed date of water temperature and air temperature contain seasonal periodic components, which were removed using Fourier series approximation to extract long-term trend components. The relationship between the long-term trend of water temperature change, meteorological data such as air temperature and precipitation, and geographical data with respect to the watershed of the reservoir were then analyzed. The air temperature tended to rise at the most of the reservoirs. On the other hand, a number of inflowing rivers exhibited decreasing trends in water temperature. Besides, the changes of the water temperature and the air temperature were almost uncorrelated. In addition, although some correlation was observed between other meteorological data and geographic data, and water temperature, it was not sufficient to express the change tendency of water temperature.

Keywords: *climate change, river water temperature, regression analysis*

1 INTRODUCTION

The impact of climate change on the water environment in rivers and lakes is one of the most important issues in the area of water-related engineering. Numbers of influences which are becoming detectable are shown in the IPCC Fifth Assessment Report (2014) and other various research reports. One of the most frequently reported impacts is that the eutrophication phenomenon in lakes and reservoirs that will potentially caused by rise of water temperature and/or increase of nutrient load to those water bodies from more frequent occurrence of floods. The water temperature in inland waters is considered to be the most important water environmental element because its effect is usually the most dominant in biochemical reactions that affect water quality and growth and mortality of organisms inhabiting in the water.

Regarding the water temperature of lakes and reservoirs in Japan, Arai (2000) reviewed the examples of water temperature rise in several major lakes: raised water temperature since 1985 in Lake Biwa, ceased circulation during winter in Lake Ikeda, and a reduced frequency of ice coverage in Lake Suwa. Nagao and Suzuki (2010) investigated long-term changes of water temperature in nine selected reservoirs. They analyzed the trend of water temperature in the 1980s and 1990s, and found that the surface water temperature had risen in all reservoirs from 1993 to 2006. The both papers concluded that all of those changes appeared to be caused by the effects of global warming.

Reservoirs play an important role in flood control and water use. In particular, water supply from reservoirs accounts for more than half of tap water in Japan. On the other hand, the increase in water temperature seemingly caused by climate change as described above has been affecting the water environment such as water quality and ecosystem. For example, stoppage of tap water supply sometimes occurs because of severe musty odor and taste in the water induced by secretion of some kinds of cyanobacteria that excessively grow in eutrophied water.

We believed until recent years that such eutrophication problems in reservoirs were un likely to occur thanks to the lower temperature than that suitable for fast growth of cyanobacteria. However, several reservoirs in the Tohoku (Northeast) region of Japan experienced severe incidents of musty odor and taste to the tap water during the past decade. Umeda and Tomioka (2007) conclude from analysis of data collected from all over

Figure 1. Location of 28 reservoirs analyzed in this study

Japan that algal blooms tend to occur in high water temperature environments. Therefore, in order to secure stable water resources in the future, it is necessary to examine the signs of water temperature rise in the reservoirs.

In this study, we investigated long-term changes in water temperature of the inflow rivers in reservoirs for the purpose of tracing symptoms of potential aquatic environmental changes. We extracted long-term changes in water temperature at the reservoirs whose data were collected, analyzed the relationship with meteorological conditions and watershed properties, and investigated factors forming the changes of river water temperature.

2 STUDY AREA & METHODOLOGY

2.1 Study Area

The reservoirs managed by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) were analyzed in this study considering their thorough measurement scheme on regular environmental data.. The rivers the reservoir inflows to be examined were selected from dams constructed before 2000 so that the data analysis period could be long enough for our analysis. The Tohoku (Northeast) area in Japan especially focused for this study considering locality of the authors. We tried to collect select as many data as possible from the other areas of Japan. However, as described later, the water temperature data was extracted from the hydrological and water quality database, but it was not easy to determine the observation point directly upstream of each reservoir. Therefore, only reservoirs that were clearly discriminated from the materials published on the web or other accessible media were analyzed. As a result, 12 dams in Tohoku Region and 16 dams in other regions, namely a total of 28 dams, were selected for this study. **Figure 1** shows the location of the 28 reservoirs, and Table 1 shows data periods for the inflow rivers of each dam reservoir, along with a part of the analysis results described later. Data of air temperature was obtained from the observation conducted by the the Japan Meteorological Agency (JMA). The closest station to each dam was chosen among the meteorological measuring stations of JMA.

2.2 Analysis Method

The water temperature data used for the analysis was acquired from the hydrological and water quality database provided by the MLIT. When there were multiple inflow rivers, the average value of their water temperatures was taken. The river water quality measurement such as water temperature conducted by the MLIT is based on the frequency of once a month, so the data density is almost equal to this. However, some places in Hokkaido, Tohoku, and the mountainous areas include missing points in winter due to snow and ice, so there are inflow river points that are missing for about three months every year. Meteorological data such as temperature, precipitation and snowfall were extracted from past meteorological data retrieval provided by the Japan Meteorological Agency. Air temperature was calculated based on the monthly average (monthly average of daily average) to make the data arrangement method same as water temperature and to grasp long-term trends. In addition, period of the target data of the water temperature and air temperature were aligned at the same time in each dam reservoirs.

The following processing was performed on these water temperature and temperature data in order to capture the long-term trend of changes over time. The raw water temperature data used in this study is observation data of the frequency once a month as described above. Therefore, this time series is composed of three components: trend components that show long-term changes due to the effects of climate change, seasonal components of the annual cycle due to seasonal variations and random components that occur due to accidental conditions on the measurement date. So we first applied a process to remove seasonal components. If the observed water temperature on an observation day t is $T(t)$, the seasonal water temperature at that time is $N(t)$, and the deviation water temperature from the seasonal component is $d(t)$.

$$T(t) = N(t) + d(t) \tag{1}$$

Where $N(x)$ can be thought of as a periodic function with a period of one year. In this study, this is expressed by a periodic regression model using the finite Fourier series shown in the following **Eq.[2]** and **[3]**.

$$N(t) = a_0 + \sum_{k=1}^{n} a_k \cdot \sin(f \cdot t + b_k) \tag{2}$$

$$f = \frac{2\pi k}{365.25} \tag{3}$$

Where, a_0, a_k, b_k are constants determined for each reservoirs.

The advantage of this method is that even if the measurement interval is irregular or missing, it is possible to represent periodic components due to seasonal variations. In other words, the water temperature data used in this study may include several months of missing data every year, as described above. Even if there is no missing measurement, the measurement frequency is “once a month” and the number of days in the measurement interval is not always constant. Therefore, it was necessary to adopt a method that can deal with unequal interval data. In **Eq.[2]**, n was varied between 1 and 5, and the number of terms with the smallest Akaike Information Criterion (AIC) was judged to be optimal (1973), and was set for each dam as a model showing seasonal components. Also, in **Eq.[3]**, the denominator of f is set to 365.25 in order to consider leap years.

The water temperature $d(t)$ of the deviation component extracted in this way was separated into the trend component water temperature $s(t)$ and the random component water temperature $\varepsilon(t)$, and the long-term change tendency of the water temperature was investigated.

$$d(t) = s(t) + \varepsilon(t) \tag{4}$$

The probability component $\varepsilon(t)$ is considered to follow a normal distribution if the seasonal component and the trend component can be removed. Therefore, the normality was confirmed by performing the Shapiro-Wilk test (2011). The trend component indicating long-term change in water temperature is assumed to be a straight line, and the following **Eq.[5]** is used as a regression equation.

$$s(t) = \alpha \cdot t + \beta \tag{5}$$

$$\alpha_{10} = \alpha \times 365.25 \times 10 \tag{6}$$

Where α and β in **Eq.[5]** are constants determined for each reservoirs. The results were organized using this α as the rate of change in water temperature per 100 years as **Eq.[6]**.

The method of calculating the separation of change components and the change rate described was applied to the temperature as well. On the other hand, although precipitation and snowfall are seasonal, there is a large amount of short-term random fluctuations. Therefore, a regression line is set for the annual total time series and the rate of change is obtained.

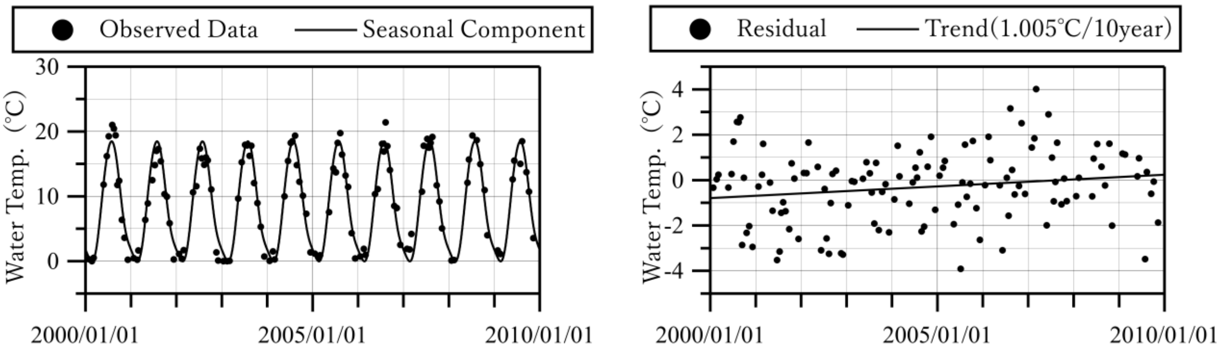

Figure 2 Example of water temperature time series component division (Takisato dam, 2000−2010)
(Left) Observed Data and Seasonal component (Right) Redidual component and Trend component

Table 1 Reservoirs to be considered, data period, and results of variable component division

	Dam Reservoirs	Prefecture	Length of Year	Water Temperature			Air Temperature		
				n	Shapiro-Wilk Test		*n*	Shapiro-Wilk Test	
					W	*p*		W	*p*
1	Iwaonai	Hokkaido	1977/10-2018/11	3	0.997	0.906 *	3	0.997	0.655 *
2	Kanoko		1983/1-2018/11	3	0.977	0.000	2	0.997	0.686 *
3	Takisato		1999/2-2016/11	3	0.976	0.000	1	0.992	0.291 *
4	Hoheikyou		1984/7-2017/11	3	0.993	0.476 *	2	0.995	0.161 *
5	Nibutani		1997/1-2017/12	4	0.986	0.002	2	0.997	0.907 *
6	Pirika		1992/5-2017/11	2	0.989	0.000	1	0.991	0.063 *
7	Aseishigawa	Aomori	1988/1-2018/12	2	0.994	0.154 *	1	0.996	0.489 *
8	Shijushida	Iwate	1970/1-2019/3	4	0.998	0.496 *	1	0.997	0.367 *
9	Gosho		1981/1-2019/3	4	0.994	0.047	1	0.995	0.102 *
10	Tase		1976/11-2019/3	4	0.991	0.009	1	0.994	0.064 *
11	Yuda		1976/2-2019/3	2	0.980	0.000	4	0.998	0.798 *
12	Naruko	Miyagi	1976/12-2019/3	2	0.987	0.000	1	0.997	0.513 *
13	Kamafusa		1976/11-2019/3	4	0.976	0.000	1	0.995	0.089 *
14	Shichikashuku		1992/10-2019/3	2	0.984	0.001	1	0.993	0.141 *
15	Tamagawa	Akita	1990/1-2019/3	2	0.977	0.000	1	0.996	0.409 *
16	Sagae	Yamagata	1990/1-2019/1	2	0.996	0.481 *	2	0.996	0.423 *
17	Shirakawa		1981/1-2019/1	1	0.986	0.000	3	0.998	0.887 *
18	Miharu	Fukushima	1997/1-2016/12	3	0.994	0.409 *	2	0.992	0.256 *
19	Ikari	Tochigi	1979/8-2011/5	4	0.996	0.500 *	2	0.998	0.850 *
20	Kawamata		1977/11-2019/3	3	0.972	0.000	2	0.998	0.672 *
21	Futase	Saitama	1974/5-2019/3	4	0.971	0.000	2	0.997	0.557 *
22	Amagase	Kyoto	1979/2-2018/12	4	0.995	0.164 *	1	0.997	0.494 *
23	Saruya	Nara	1979/1-2018/12	3	0.992	0.010	3	0.998	0.869 *
24	Shimajigawa	Yamaguchi	1981/4-2016/12	4	0.996	0.330 *	1	0.999	0.984 *
25	Yabakei	Oita	2001/1-2018/12	2	0.974	0.000	2	0.995	0.651 *
26	Matsubara		1972/1-2018/12	3	0.982	0.000	3	0.999	0.990 *
27	Henoki	Okinawa	1988/5-2017/12	1	0.974	0.000	3	0.995	0.251 *
28	Fukuji		1987/7-2017/12	4	0.990	0.011	3	0.995	0.236 *

* indicates $p>0.05$.

3 Results

As an example of the analysis results on the separation of fluctuating components, **Figure 2** shows the water temperature change of the inflowing river of Takisato Dam. When $n = 3$, the water temperature of the Takisato Dam has the minimum AIC in the periodic regression model in **Eq.[2]**. The change in water temperature was about 1.005 °C per 10 years. In the same way, temperature change and water temperature change were calculated for 28 reservoirs. **Table 1** shows the results of the Shapiro-Wilk test for the terms n and $\varepsilon(t)$ of the finite Fourier series $N(t)$. Focusing on the number of terms n, we can see that the seasonal variation is modeled with the number of terms having a lower temperature than the water temperature. Because the water temperature is 0 °C as a threshold, and it is difficult to express it with a simple trigonometric function. Also, looking at the results of the Shapiro-Wilk test, $p>$ 0.05 for all dam inflow rivers with probability component $\varepsilon(t)$ in terms of temperature, the null hypothesis that the distribution is normal distribution was not rejected. On the other hand, regarding the water temperature, $p>$ 0.05 was limited to about 1/3 of the inflowing river. This is because the monthly average value was used for the temperature, but the water temperature was observed at the time of still water once a month. In this study, it was judged that no more deterministic components could be removed from the water temperature, and the same data processing method was used for the water temperature.

Figure 3 shows the trend components. First, the rate of change in temperature was positive except for several dams, indicating a warming trend. On the other hand, the rate of change in water temperature was about half

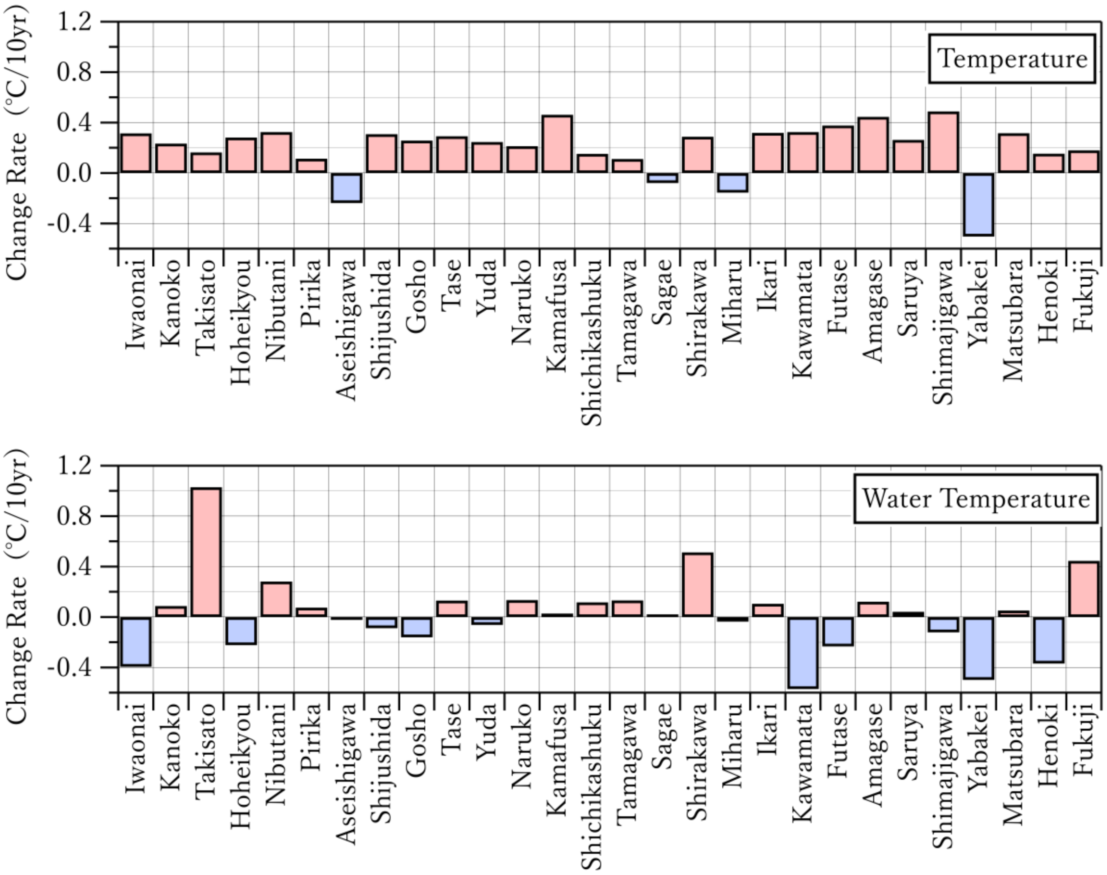

Figure 3 Temperature change rate (upper) and water temperature change rate (lower) for each reservoirs

Table 2 Correlation of main variables

	Water Temp. change	Temp. change	Elevation	Precipitation change	Total Precipitation	Basin Area
Water Temp. change	1.000					
Temp. change	0.126	1.000				
Elevation	-0.383	0.139	1.000			
Precipitation change	-0.375	-0.077	0.370	1.000		
Total Precipitation	-0.115	-0.199	0.016	0.280	1.000	
Basin Area	0.297	0.267	-0.351	-0.138	-0.246	1.000

of the points showing positive and negative values, and the overall trend could not be grasped. As can be seen from the relationship between the water temperature change rate and the temperature change rate (**Figure 4**), there is no correlation.

Table 2 shows the results of correlations between changes in water temperature and other variables. As shown earlier, there is almost no correlation between water temperature change and air temperature change. On the other hand, elevation and precipitation change are items that have some degree of correlation with water temperature change. Both are negatively correlated, and dams with lower elevations and dams with decreasing precipitation tend to have higher water temperatures.

When the altitude and precipitation change are used as explanatory variables, and the change in water temperature is used as the objective variable, the following regression **Eq.[7]** is obtained.

$$T_w = 2.34 + (-4.62 \times 10^{-3})H + (-2.15 \times 10^{-1})P \qquad [7]$$

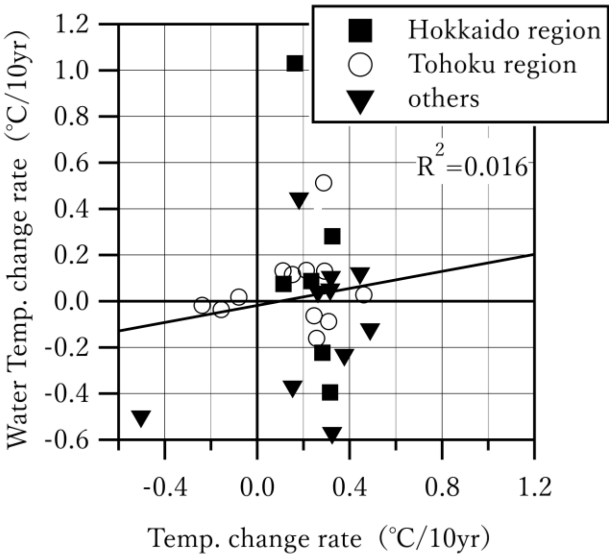

Figure 4 Relationship between the water temperature change rate and the temperature change rate

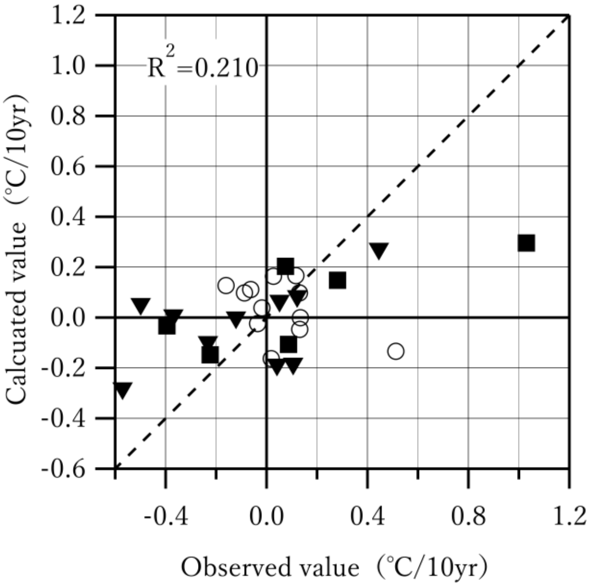

Figure 5 Reproducibility evaluation of regression equation

Where T_w is the water temperature [°C], H is the altitude [m], and P is the rate of precipitation change [mm/10 years]. Using this result, the relationship between the water temperature change obtained from the observed values and the water temperature change obtained from the regression equation is as shown in **Figure 5**. Since the coefficient of determination is $R^2 = 0.210$ and lacks explanatory power, it is necessary to investigate other factors that influence the changing tendency of the water temperature.

4 CONCLUSIONS

In this study, we analyzed the long-term water temperature change of the inflowing river in the dam lake with the purpose of grasping the effect of climate change on the water environment of the reservoir. The target reservoirs (rivers) were 28, and although the total number was not necessarily large, a nationwide (but focused on the Tohoku region) analysis was conducted. The main conclusions of this paper are as follows.

1) Long-term changes have been made in order to carry out analyzes on river water temperature observation data, which are non-uniformly spaced time-series data that are mostly conducted once a month and sometimes missing. We created a method to divide the data into three components: the trend component shown, the seasonal component showing the annual cycle, and the highly random component generated by the accidental condition of the measurement date.

2) As long-term changes in temperature, 24 out of 28 locations showed an upward trend. The average value was about 2.0 °C in 100 years. On the other hand, the water temperature varied widely, with 16 rising trends and 12 decreasing trends, with an average rate of change of about 0.19 °C. That is, the correlation between long-term changes in river water temperature and temperature was low.
3) The long-term fluctuation tendency of the water temperature was examined by trial and error using the meteorological and basin conditions as explanatory variables. As a result, it was found that some explanations can be given by two variables: elevation of reservoir and change in precipitation. However, the coefficient of determination was as low as about 0.2. In the future, it will be necessary to consider more detailed weather or basin conditions.

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