Evaluation of algal growth potential in water resources reservoirs under future climate changes

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Reservoirs are important infrastructure because they occupy a major fraction of water resources in our society. In order to project potential influences from climate change on water quality in the future, a vertical 1-dimensional hydraulic numerical model was applied to multi-purpose reservoirs in Japan to make projections of the future conditions of stored water. Stratification intensity of surface layer of reservoirs were used as an index of algal growth potential. Future meteorological conditions were given using the output of GCMs. Our results predicted that eutrophication potential and effect of countermeasure has regional difference in Japan.

1. Introduction

Reservoirs are important infrastructure in that they occupy a major fraction of water resources in our society. However, influences of water quality deterioration tend to accumulate in reservoirs, because of their characteristics as closed water body. Therefore, effort to maintain and to improve water quality in lakes and reservoirs is essential for stable supply of fine water to citizens.

Climate change is one of the problems that draw the most serious concerns worldwide recently, especially in the area of aquatic science and engineering. One of the reasons is that climate change is expected to have many kinds of impacts on aquatic environment and water resources (Delpla et al, 2009).

Eutrophication is one of the most typical and sometimes very serious problems of water quality. There are several kinds of representative factors causing eutrophication. The most direct one is nutrient loading into water bodies from watershed. Strong relationship between algal biomass, which is an index of eutrophication grade of reservoirs, and nutrient concentration of inflow river has been revealed (e.g. Malmaeus et al. 2006). Another factor is meteorological conditions such as solar radiation and air temperature, and those can be affected by climate change.

This study focused on changes of algal growth potential in the future from a view point of nation wide tendency in Japan. Therefore, in this study, predictions of future water quality status are conducted on many water resources reservoirs in Japan. Most of the previous research works concentrate on only one or a couple of lakes or reservoirs for prediction and assessment, like Komatsu et al. (2007) and Molina-Navarro et al. (2014), etc. Those works conducted detailed examination and simulation for the investigated water area. Such posture is necessary when the purpose of study is to make definite plan on water quality preservation. However, overall tendency of water quality changes in the future influenced by climate change is still unknown and has much uncertainty. Therefore, obtaining such general change of water quality regime is tried in this study. Besides, not only future prediction of eutrophication situation estimated from algal biomass, but also assessment on effect of adaptation measure is conducted.

2. Methods

2.1 Reservoirs examined in this study

Water quality deterioration in reservoirs can affect water supply to the citizens. Therefore, assessment of water quality in water supplying reservoirs is required, and 37 multi-purpose reservoirs that have the purpose of domestic water supply were chosen from all over Japan. Figure 1 shows locations of the reservoirs. The reservoirs are managed by the national government and the Japan Water Agency. They have databases on the Internet and offer easy access to necessary data for our study.

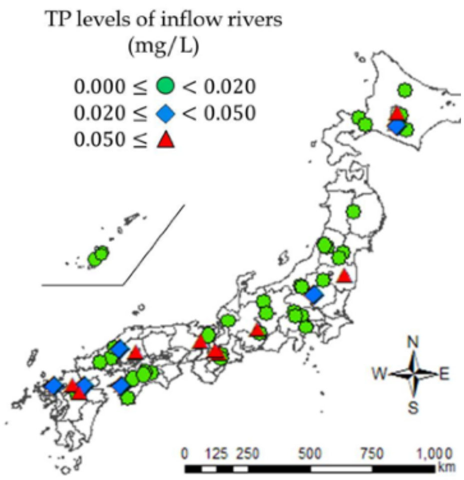

Figure 1. Locations of the reservoirs and TP levels of the inflow rivers

2.2 Modeling of water environment in reservoirs

Structure of water temperature in the reservoir was analyzed using a vertical 1-dimensional computation model (Umeda et al., 2010). The model is consisted of the following analysis procedures of water mass balance affected by inflow and outflow, heat balance through the water surface mostly influenced by meteorological conditions, and vertical diffusion and mixing of the heat inside the water body. The model computes temporal changes of thermal stratification in the reservoirs. This computational model has already been applied to a number of studies on water temperature simulation in reservoirs and water quality and temperature analysis in a lake. Therefore, verification of the model has already been well examined in those existing achievements.

Water balance in reservoirs was calculated from the continuity equation below:

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{1}$$

where V is the volume of stored water in a reservoir, Q_{in} and Q_{out} are inflow and outflow rate, respectively.

The heat balance components considered in the model are short wave radiation, long wave radiation from the water body itself and the atmosphere above it, latent and sensible heat:

$$\phi = \left(1 - r\right) b \phi_I - \phi_L - \phi_e - \phi_c \tag{2}$$

, where r = reflection rate at the water surface, b = absorption rate at the surface of water. Heat transfer through long wave radiation, and latent and sensible heat were estimated using empirical formulas such that

$$\phi_L = 0.97k\left(T_w^{\ 4} - 0.937 \times 10^{-5} T_a^{\ 6} \left\{1.0 + 0.17 C_d^{\ 2}\right\}\right) \tag{3}$$

$$\phi_e + \phi_c = \left(0.000308 + 0.000185W\right) \rho \left(e_s + \Psi e_a\right) \left(L_v + CT_s + \frac{269.1\left(T_w - T_a\right)}{\left(e_s - \Psi e_a\right)}\right) \tag{4}$$

, respectively, where k is the Stefan - Boltzmann's constant, T_w is water temperature at the surface, T_a is air temperature, C_d is cloudiness, W is wind speed, e_s and e_a are saturation water vapor pressure at the water surface temperature and the air temperature, respectively, Ψ is relative humidity, and L_v is evaporation heat of water. Heat conveyance via the transmission of short wave radiation below the water surface with regard to the depth direction is calculated based on the law of Lambert - Beer:

$$\phi_{IZ}\left(z\right) = \left(1 - r\right)\left(1 - b\right) \phi_I \exp\left(-\eta z\right) \tag{5}$$

, where ϕ_{IZ} is intensity of short wave radiation at the depth of z, η is attenuation coefficient.

Based on the bulk heat balance evaluated with the above conditions, vertical distribution of water temperature is computed with the diffusion equation:

$$\frac{\partial T}{\partial t} = \frac{K_z}{A} \frac{\partial^2 AT}{\partial z^2} \tag{6}$$

where T is water temperature, Kz is diffusion coefficient, A is horizontal area of the reservoir at each vertical location. Diffusion coefficient Kz was evaluated considering local density stratification conditions.

One of the most frequently observed water quality problems in reservoirs is eutrophication phenomena, which are basically caused by excess growth and existence of phytoplankton. A common index of biomass of phytoplankton is concentration of chlorophyll-a (Chl-a), and there are many simplified or complicated methods to estimate Chl-a concentration in reservoirs by considering inflow loading of nutrients into reservoirs and/or hydraulic characteristics of reservoirs. In this study, by combining the hydraulic modeling shown above paragraphs that has been developed for estimation of thermal structure environment in reservoirs with empirical statistical knowledge of phytoplankton growth conditions in reservoirs, an evaluation method of phytoplankton growth potential is adopted.

Many existing studies have shown that the most common water bloom forming algae of cyanobacteria tend to appear in higher water temperature conditions, and *Microcystis*, especially, has been reported that events in which abundant growth of *Microcystis* were observed when the surface water temperature is higher than 20 ℃. Besides, several studies have suggested that density stratification condition near the water surface can play an important roll in generation and maintenance of water bloom by cyanobacteria, as well as the water temperature in the surface layer itself.

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Surface gradient of water temperature K is used in this study to evaluate water temperature environment and growth potential of cyanobacteria, which is defined as

$$K = \frac{T_1 - T_z}{z} \qquad (7).$$

T_1 is surface water temperature, T_z is water temperature at the depth of z. The evaluation depth z is usually considered 3 - 5 m. Some studies such as Nagayoshi et al. (2006) have reported that when measurement of water temperature distribution in a reservoir is conducted during daytime, water quality problem cased by excess growth of cyanobacteria tends to occur if K ≧ 0.5 ℃/m.

The purpose of this study is to evaluate mean condition of algal growth under future environmental changes in decadal time scale, and prediction of short term changes, such as daily or weekly, of algal biomass is not our target. On the other hand, assessment of annually averaged condition is more focused in this study, because prediction of meteorological conditions from climate change does not have enough resolution to rate short term changes, but focus on mean trend of meteorological situation around intended period of some years. Therefore, yearly basis evaluation is suitable for projection of future algal growth potential in wide areal range of reservoirs. Taking favorable water temperature conditions for cyanobacteria to grow densely and to form blooming into account, two criteria of evaluation were considered: one is the number of days in a year when the surface water temperature exceeds the cyanobacteria growth condition demarcation of 20 ℃, and the other is the number of days in a year when surface water temperature gradient K ≧ 0.5 m/℃. In this study, those two indexes were combined to evaluate algal biomass in a reservoir by counting the number of days that exceeds the both criteria.

The surface water temperature indexes introduced above can be basically applied for evaluation of algal growth potential if nutrient conditions in reservoirs are sufficient. To use this index for evaluation of algal biomass or potential of water bloom formation, information on nutrient concentration level in reservoirs is also essential. According to past investigations, most of the reservoirs in Japan were diagnosed as phosphorus limitation rather than nitrogen. In this study, total phosphorus concentrations (TP) in inflow rivers were used. The measurement data in reservoirs were basically taken monthly basis, and the data used in this study for algal growth assessment were the average at each reservoir for one year or more depending on availability of measurement data.

Considering those conditions of water temperature and nutrient, the following empirical equation was made

$$C_a = aD + bP \qquad (8)$$

, where C_a is annual mean Chl-a concentration at the surface of a reservoir, D is number of days in a year when the surface water temperature is above 20 ℃ and the surface water temperature stratification is above 0.5 m/℃. P is mean TP concentration of inflow rivers of the reservoir. D is obtained from numerical simulation, while P is calculated from existing measurement data at each reservoir entrance points. The coefficients a and b are determined from multi-regression analysis. Although the data of TP and the coefficients of a and b are obtained based on baseline (current or past) conditions, the equation (8) with the coefficients is assumed applicable in the future environmental conditions.

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Adaptation of expected water quality deterioration affected by climate change in the future is also considered in the projection. The adaptation methods is destratification system in reservoirs, which is one of the most common countermeasures against algal bloom caused by cyanobacteria. Destratification system in reservoirs is classified as flow controlling method against eutrophication phenomena. The intended mechanism of the system is to destroy thermal stratification, especially around the water surface where water bloom tends to develop, and bring phytoplankton that grow and gather around the surface into deeper depth by mixing the water body (Lorenzen & Mitchell, 1975) using bubble emitting facilities. The effect of mixing the density stratification in a reservoir is modeled (Umeda, 2005) applying the double plume model developed by Asaeda & Imberger (1993), and the effect of reducing algal biomass is indirectly expressed by the equation (8) from decreased values of D.

2.3 Computation conditions

GCM (Global Circulation Model) outputs from Model for Interdisciplinary Research on Climate (MIROC) 5.0 were used as future meteorological conditions. The periods of computation applied in this study were baseline period (1981 - 2000), mid-future period (2031 - 2050), and far future (2081 - 2100), in which RCP 8.5 of CMIP 5 (Riahi et al., 2011) was used as the emission scenario. The GCM results were downscaled using LARS-WG (Semenov & Stratonovitch, 2010) accompanied with past meteorological data measured closed to the locations of each reservoir.

Inflow river water temperature is another important factor that determines water temperature structure in a reservoir. It is estimated from empirical correlation with air temperature around the reservoir. By collecting water temperature data measured around inflow points of the reservoirs and air temperature data, following relationship is established for each of the reservoirs:

$$T_W = cT_A + d \tag{9}$$

,where T_W is inflow water temperature, T_A is air temperature, c and d are constant coefficients obtained for each reservoir from regression analysis.

3. Results and Discussion

Figure 2 shows the results of prediction on chlorophyll-a concentration at all the 37 reservoirs selected in this study. The map on the left shows the results without adaptation countermeasure against increased potential of algal growth in reservoirs implemented by destratification system, and the right-hand chart shows the results with adaptation measure. The locations of the bar graphs in the map correspond to the actual locations of the reservoirs, and the hight of the bars show predicted Chl-a concentrations for each period. As found more clearly in the left chart, results of Chl-a prediction results increase as the period proceeds at most of the reservoirs. Comparing the left and the right charts, effects of adaptation measure is observed, which is more recognizable in west areas of Japan.

To evaluate the responses of algal growth potential in reservoirs in regard to regional characteristics and differences between consideration of adaptation measure, Figure 3 is plotted. Although absolute air temperature is different between east-north and west-south regions of Japan, increasing response of Chl-a to that of air temperature is similar, in case without adaptation, showing comparable slope of

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the regression lines. On the other hand, effect of destratification system as adaptation measure can be estimated from reduced slope in the right side chart, as well as the levels of predicted Chl-a concentration. The slope of the regression line of the west region show less than half of that of the east. Therefore, destratification system as adaptation to climate warming against enhancement of algal growth potential is more effective in west-south regions of Japan.

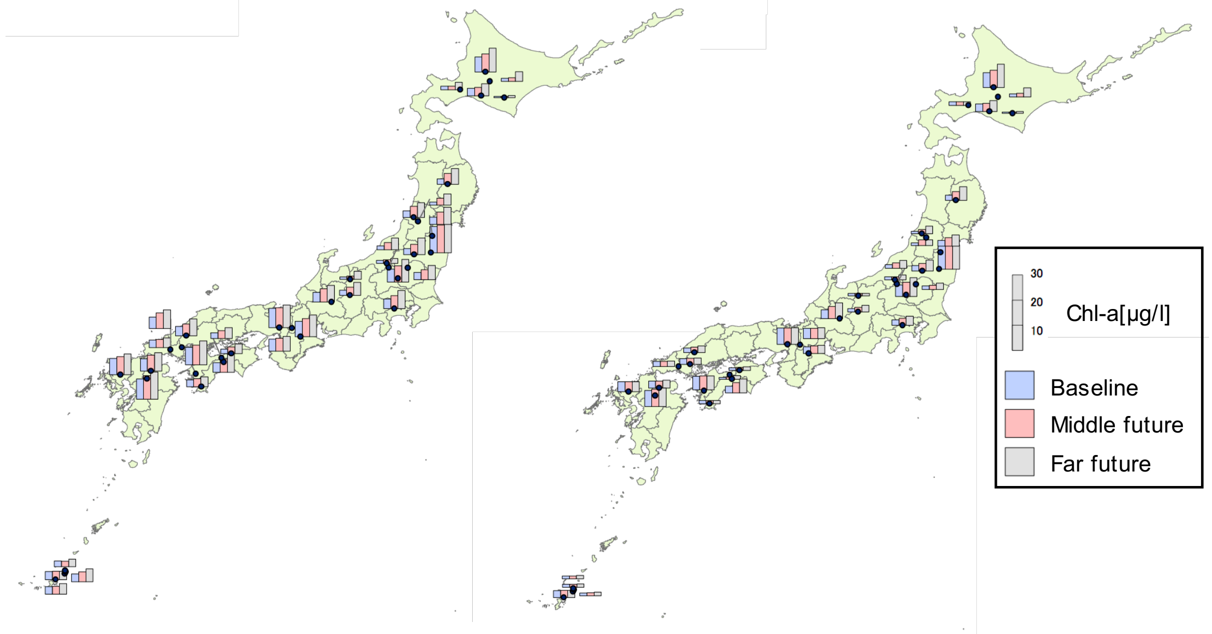

Figure 2. Modeling results of Chl-a concentration in the reservoirs under the conditions of emission scenario RCP 8.5. Left and right charts show results without, and with adaptation measure, respectively.

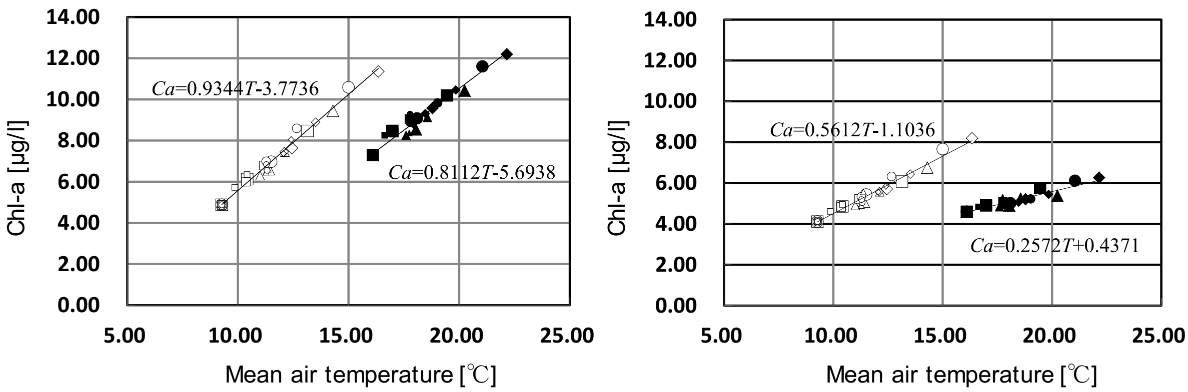

Figure 3. Relationship between Chl-a concentration and air temperature based on prediction results. White and black marks show the results of reservoirs in east and west regions of Japan, respectively. Left and right charts show results without, and with adaptation measure, respectively.

4. Conclusions

Climate change in the future can influence on many aspects of water-related environments. Water quality change in reservoirs that supply domestic drinking water

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is one of the examples, but closely related to our daily lives. Therefore, it ought to be carefully examined before influences from climate change become prominent. Water temperature rise caused by future climate change can increase certain kinds of algae that can cause water quality problems. Therefore, it is essential to assess such risks, and to prepare for it if the risk is sufficiently high. In this study, by using 1-dimensional hydraulic model to simulate water temperature stratification structure in reservoirs, combined with measurement data of total phosphorus as nutrient condition, growth potential of water bloom forming algae, assuming cyanobacteria, is projected. Besides, destratification system in reservoirs is also considered as adaptation measure against increased potential of algal growth. The results of the predictions show that the algal biomass will increase in the future at most of the reservoirs investigated in this study, and that the adaptation method will have sufficient effect for reducing algal biomass. However, the effect of adaptation tends to be more conspicuous in the west-south regions of Japan than in the east-north. Therefore, in north areas of the country, other adaptation measures need to be considered for preparation against boosted risk of water quality problems potentially caused by algae predominance in reservoirs.

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