論文の内容の要旨
Abstract of Dissertation

# 論文題目　Modeling for Predictive Assessment and Mitigation of Cyanobacteria Toxins in a Eutrophic Lake

（富栄養湖における藍藻毒素の予測評価と緩和のためのモデルに関する研究）

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## 1. Introduction

### 1.1 Background

Lakes are very important property for all kinds of life. They provide water for consumption, fishing, irrigation, power generation, transportation, recreation, disposal of wastes, and a variety of other domestic, agricultural, and industrial purposes[1)]. However, the current scientific evidence shows that the coastal, marine and freshwater lakes or reservoirs ecosystem are vulnerable to the impact of harmful algal blooms in world. Toxic algal or cyanobacteria blooms have been known to kill fishes, waterfowl and livestock, and dogs have died after eating mats of cyanobacteria or licking their fur after swimming in bloom-infested waters. In some cases, humans have also died after exposure to harmful algal toxins[2)]. Unfortunately, not only Japan but also most of the developed and underdeveloped countries are not aware well enough about this issue. A very few studies have been conducted on algae transition behaviors[3)], their toxin production ability and mitigation strategies from a viewpoint of modeling.

### 1.2 Aims and objectives

The purpose of this study is modeling for predictive assessment and mitigation of cyanobacteria toxins in a eutrophic lake. The study area is the Lake Kitaura, Ibaraki Prefecture in Japan. Field samples were collected between July 2005 and September 2007.The major objectives of this study are: 1) to develop the vertical and horizontal transition of dominant algae model, 2) to develop toxin production model and their environmental mechanisms, and 3) to make a conceptual IMPACT (Integrating Mitigation Policies for Aquatic Cyanobacteria Toxins) model for controlling the nutrients that encouraged forming toxins.

## 2. Modeling of environment and algae transition

### 2.1 Hydrodynamic and ecosystem coupled model

The numerical model is based on the governing equations that are described in the Cartesian coordinate system[3)]. The time variation in the fields of current velocity, water level, water temperature, density can be described by the equations of momentum, the continuity equation, the advection-diffusion equation of heat, and the equation of the state. Time variation of chemical materials and planktons can be described by the advection-diffusion equation. The ecosystem model is based on the observed features of a eutrophic food web in Lake Kitaura. The ecosystem model contains nine state variables such as: phytoplankton, cell quota of phosphorus and nitrogen, zooplankton, particulate and dissolved organic carbon, dissolved inorganic phosphorus and nitrogen, and dissolved oxygen.

Major improvement on algae transition model from the existing model[3)] are: 1) calibration of the horizontal eddy viscosity and diffusivity coefficients, 2) conservation of phosphorus and nitrogen, 3) visible light for photosynthesis, 4) consistency of algal flotation model with growth model, 5) finer mesh size (from 500 m to 200 m), and 6) calibration of many parameters and values.

### 2.2 Computational condition

The governing equations were solved numerically by finite difference scheme. Numerical simulation was carried out between June 2005 and March 2009. The observations were used for the boundary condition of meteorology and river.

### 2.3 Results

#### 2.3.1 Water current velocity and temperature

The current velocity was reproduced well and strongly affected by the wind. Water temperature shows the longer stratification during June and July, and daily stratification in August. In terms of the annual variation in water temperature, the stratification was prolonged during June and July in 2008 since the atmospheric temperature increased rapidly during the same period.

#### 2.3.2 Water quality

The simulation showed that concentration of dissolved oxygen was lower for a longer period in 2008 due to the stronger stratification. The concentration of dissolved inorganic phosphorus was usually exhausted, while the release rate of phosphorus increases in summer because anoxic conditions are sometimes formed by instantaneous stratification. The period of stratification and resulting anoxic condition were longer in the summer of 2008. Higher concentrations of dissolved inorganic phosphorus were both observed and predicted off Kamaya during the same period (Fig.1). The concentrations of dissolved inorganic phosphorus and nitrogen were higher in the middle and north of Lake Kitaura, respectively (Fig.2). This is because the phosphorus and nitrogen are supplied from the bottom in deep water and through rivers in north, respectively.

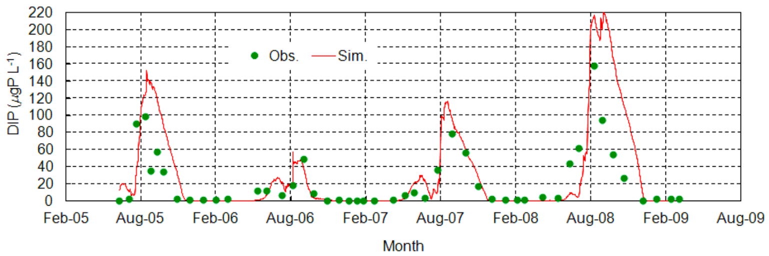



Fig.1 Observed and simulated dissolved inorganic phosphorus off Kamaya station.

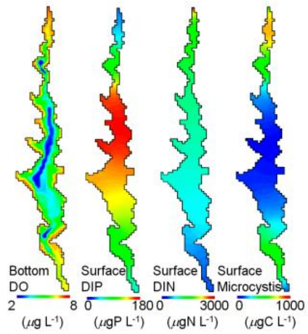



Fig.2 Simulated water quality and *Microcystis* concentration in August 2005

#### 2.3.3 Algal transition and its mechanism

The numerical model could reproduce the seasonal variation in dominant algae; *Planktothrix* spp. in early summer, *Microcystis* spp. in late summer, and *Cyclotella* spp. between autumn and spring. The sudden increase in *Planktothrix* spp. in 2008 was also represented in the numerical simulation (Fig. 3). From several scenario simulations, it could be predicted that the exchange of water from other connecting lakes and rivers have the effect on algae transition in Lake Kitaura. The sudden increase in *Planktothrix* spp. is likely caused by the transfer of water containing *Planktothrix* spp. from Lake Nishiura via Wani River.

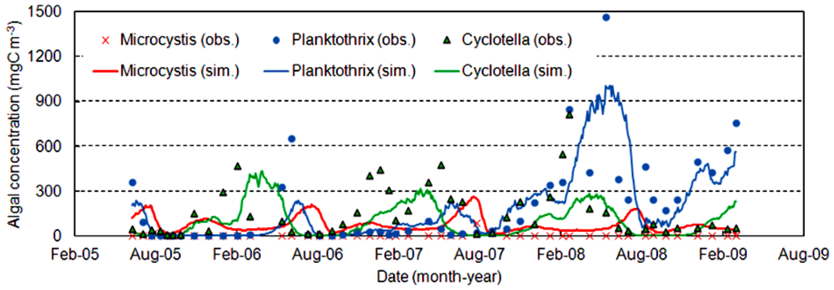



Fig.3 Simulation and observational transition of dominant species of algae off Kayama Station 2005-2009.

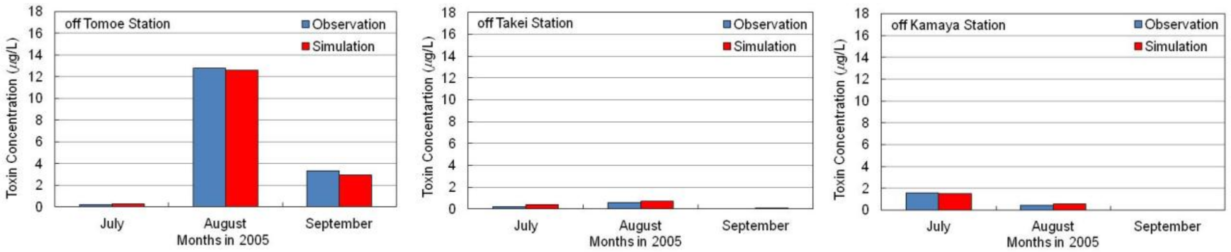
## 3. Modeling of toxic algae/cyanobacteria toxin production

### 3.1 Toxin production model

The timing and duration of the cyanobacteria blooms depends on the ability to make scum or colonies, light intensity, temperature, stratification, presence of nitrogen and phosphorus limited cyanobacteria. In the present study, toxin production is made by *Microcystis* spp., and is proportional to the growth of algae, while it depends on whether phosphorus or nitrogen limits the algal growth. The toxin remains in the cell for respiration. Toxin is released with extracellular release and mortality, and advects and diffuses with the surrounding current and turbulence. The degradation of toxin was taken into account by the decay coefficient which crosses the concentration of toxin. Numerical simulation was also tried under the assumption that phosphorus or nitrogen always limits the algal growth.

### 3.2 Results

The simulation results compare the toxin (the sum of *MC-LR*, *MC-RR* and *MC-YR*) production of three stations in the Lake Kitaura with the observational data in the month of July, August and September for 2005, 2006 and 2007. The simulation results show a good agreement with the observation and simulation all the stations and months in 2005 (Fig.4). If toxin production is assumed to be always limited by phosphorus, it is overestimated off Takei and off Kayama Stations where algal growth is limited by dissolved inorganic nitrogen. If toxin production is assumed to be always limited by nitrogen, it is underestimated off Tomoe Station where algal growth is limited by dissolved inorganic phosphorus. Consequently, toxin production strongly depends on what nutrient limits the algal growth. In 2006 and 2007 there is no toxin produced by cyanobacteria (dominant species by *Microcystis ichthyoblabe* is toxic/nontoxic) in the ecosystem of Lake Kitaura, however toxin is detected during this period in numerical simulation. This discrepancy may be attributed to the species of *Microcystis*.




(a) off Tomoe Station (b) off Takei Station (c) off Kayama Station

Fig.4 Simulation and observation toxin production are shown at the months of July, August, September in 2005 in off Tomoe, off Takei and off Kamaya stations in Lake Kitaura respectively.

## 4. Modeling of toxic algae mitigation strategies

The proposed IMPACT (Integrating Mitigation Policies for Aquatic Cyanobacteria Toxin) model assumes for preparing scenarios for alternative policy states like ideal state, moderate ideal state, poor state and very poor state (Fig.5). According to IMPACT model the scenario of Lake Kitaura is reflected the Scenario 2 (S-2). That means the nutrients management is not ideal.

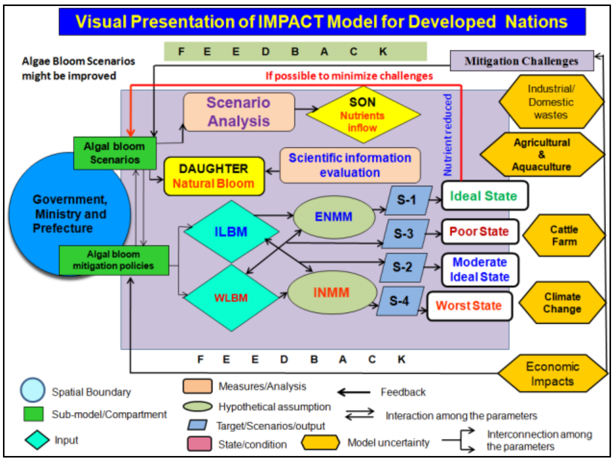



Fig.5 Mitigation strategies IMPACT model

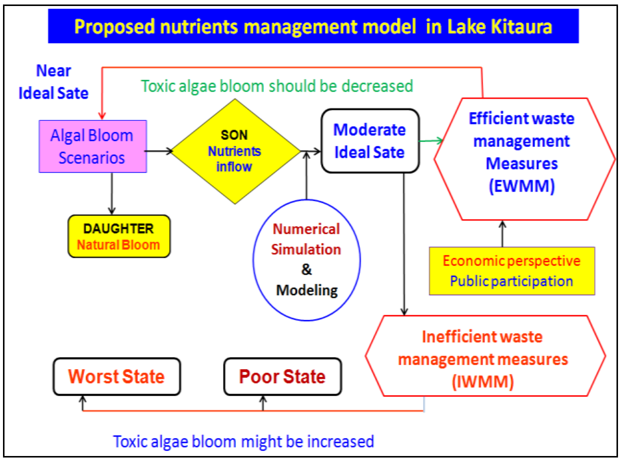



Fig.6 Nutrients management strategies flow chart.

If the national and prefectural government takes initiative for mitigation strategies with efficient nutrients management measures (Fig.6), and integrating lake basin management measures, then the actual condition of cyanobacteria mitigation policy will be 'optimum situation and ideal state' (Scenario 1). The finding of this study suggests that successful mitigation of cyanobacteria toxins is highly dependent on multi-functional, multi-stakeholder involvement, and relevant intergovernmental policy.

## 5. Conclusion

The environmental factors were not the key parameters explaining the transition of dominant algae in 2008, which was caused by the flux of algae due to water exchange between the lakes via Wani River. The toxin production behaviors are affected by the algae growth, nutrients limited condition and toxin decay coefficient. Toxin production in Lake Kitaura depends on whether phosphorus or nitrogen limits the algal growth. The ideal long term strategies for dealing with toxic algae are to prevent or reduce the occurrence of blooms. In this context, the proposed IMPACT model could be a decision framework for identifying suitable policies that mitigate cyanobacteria impacts.

## References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