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Predicting trophic state changes in the Yeongsan Reservoir, South Korea: modeling and management

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ABSTRACT

Eutrophication is a critical water quality issue in lake systems. Algal blooms, in particular, cause severe water quality deterioration leading to reduced water clarity, decreased biodiversity, and depleted oxygen. This study assesses the potential variation of chlorophyll-a (Chl-a) concentration caused by climate change in the Yeongsan Reservoir (YSR) using the CE-QUAL-W2 two-dimensional hydrodynamic and water quality model with up-to-date hydrodynamic, meteorological, and water quality data. The influence of climate change on Chl-a concentrations was investigated by considering the spatial characteristics of changes in air temperature. Spatiotemporal patterns in Chl-a concentrations were used as a key indicator to evaluate the future trophic status in the reservoir system under climate change conditions. The results revealed that air temperature in the 2050s was lower than 2008 in the summer season, whereas higher than that in the winter season; the air temperature in the 2090s was higher than 2008 in the entire year. The variations in air temperature resulting from climate change significantly influenced Chl-a concentrations in terms of change in algal growth. There were distinct changes in the distribution of Chl-a concentrations compared to the current distribution due to changes in reservoir hydrodynamics. Overall, this study presents the benefit of an evaluation approach to assess the impacts of climate change on the spatiotemporal concentration of Chl-a with a reasonable prediction of algal growth.

Keywords: Climate change; Chlorophyll-a; Air temperature; Water quality model; Trophic state

1. Introduction

Eutrophication is a major water quality problem in lakes and reservoirs globally due to increased levels of poorly treated sewage effluent and fertilizer/herbicide runoff in water systems. Eutrophication generally leads to excessive algal growth, causing water quality problems such as significant variations in diurnal dissolved oxygen levels and depletion of dissolved oxygen (DO) in bottom water, a foul taste and odor in the water supply, filter clogging in water treatment plants, and the prevention of water-contact sports and recreational activities [1]. To effectively manage eutrophication, it is necessary to identify potential cause and effect relationships between algal growth and various aquatic conditions.

Eutrophication has recently been significantly influenced by climate change (e.g., increasing temperatures), as biological processes are mainly temperature-sensitive. Increasing temperature can change organism growth rates. For example, phytoplankton growth rates double when the temperature increases by 10°C [2,3]. Although this does not apply to all phytoplankton species (some taxonomic groups are adapted to grow within specific temperature ranges), a temperature increase is a still significant factor for algal growth. In the North Sea, algal blooms mainly occur in late spring or summer, demonstrating growth in relatively high-temperature

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conditions [4,5]. Temperature increases related to climate change will, therefore, be beneficial to the harmful algae.

In addition to the direct effects of temperature on algal growth, the nutrient cycle is affected by climate change. Nutrient availability influences algal growth as the former is a dominant limiting factor. Phosphorus dynamics, in particular, are significant as it is the main limiting lake nutrient throughout most of the year [6]. Increasing water temperature can indirectly influence phosphorus release from sediment into water due to an increase upward flux of nutrients [7]. Therefore, these alterations caused by climate change must be evaluated using ecological models and detailed descriptions of the phenomena.

The objective of this study is to assess climate change impact on the trophic state of an estuarine reservoir (based on chlorophyll-a concentration changes) and suggest management strategies for maintaining current trophic states. This study provides preliminary insight into a range of factors that affect fecal-indicator bacteria concentration in coastal waters.

2. Materials and methods

2.1. Site description

The Yeongsan Reservoir (YSR) is an estuarine reservoir located in the southwestern region of Korea (Fig. 1). The YSR, built in 1981 to supply agricultural water and prevent flooding by damming the downstream end of the Yeongsan River, has a length of 23.5 km from the Mongtan Bridge to the Yeongsan estuarine dam; a surface area of 34.6 km^2; a water storage capacity of 253 million m^3; and an average depth of 10.1 m with a maximum of 21.9 m [8,9]. The main freshwater input into the reservoir is the Yeongsan River and the average inflow rate is 2,190 million m^3/year [8].

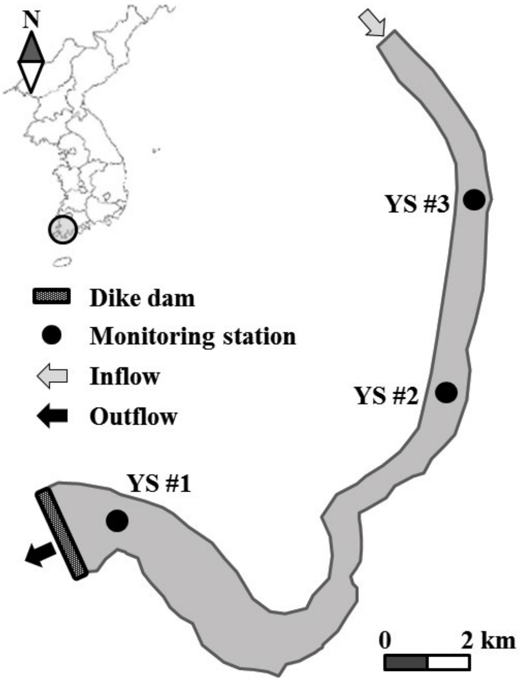

Fig. 1. Water quality monitoring stations within the Yeongsan Reservoir (YSR).

The water quality in the YSR has been drawing researcher attention in recent years because of the aggravated state of the aquatic ecology, which was caused by a structural deficiency (i.e., the estuarine dam) and pollutant load from the Yeongsan watershed. As the dam was constructed at the outlet of the Yeongsan River, it has prohibited natural water circulation and caused poor water quality as a result of anoxic and hypoxic conditions in the bottom layer of the reservoir.

2.2. Model application

Fig. 2 presents a conceptual diagram to assess the change of the trophic state of the YSR in terms of predicted air temperature changes. The CE-QUAL-W2 ("W2") model was used to simulate hydraulic processes and water quality in the YSR; W2 is a two-dimensional (i.e., longitudinal and vertical) hydrodynamic and water quality model developed by the Environmental and Hydraulics Laboratories of the U.S. Army Engineer Waterways Experiment Station [10]. As W2 assumes homogeneity in a lateral flow direction, it is suitable for relatively long and deep water bodies that have measurable longitudinal and vertical water quality gradients [10].

To set up the W2 model, model domain data and boundary conditions were required. Bathymetry data, generated by measuring bottom depths, were applied to the model to produce the computational grid. The daily outflow and channel flow rates of the YSR, recorded by the Korea Rural Community and Agricultural Corporation from January 1, 2007 to December 31, 2008, were used as the upstream and downstream boundary conditions, respectively. Daily meteorological data (e.g., air temperature, dew point temperature, wind direction, wind speed, and cloud cover), collected by the Korea Meteorological Administration from January 1, 2007 to December 31, 2008, were used to calculate the heat balance in the reservoir. Monthly water quality data, monitored by the Yeongsan River Basin Environmental Office from January 1, 2007 to December 31, 2008, were used for inflow and vertical profiles. The detailed process for setting up the W2 model in the YSR is documented in Park et al. [8].

2.3. Predicting future climate conditions

The Hadley Centre Global Environment Model version 3 - regional atmospheric (HadGEM3-RA) [11] model was used to simulate the regional climate over Korea during two future periods (i.e., 2051–2060 and 2091–2100). The boundary conditions of this regional model were obtained from the HadGEM2-AO (atmosphere-ocean) model projected with a representative concentration pathway (RCP) 6.0 scenario in the Intergovernmental Panel on Climate Change (IPCC) [12]. The resolution of the HadGEM3-RA model is 12.5 km for the spatial scale and daily for the temporal scale. The daily average air temperatures for the two periods (2050–2059 and 2090–2091) were applied to a laterally averaged two-dimensional reservoir model for simulating water quality and hydrodynamic quality. The current air temperature data were replaced with the future air temperature data that

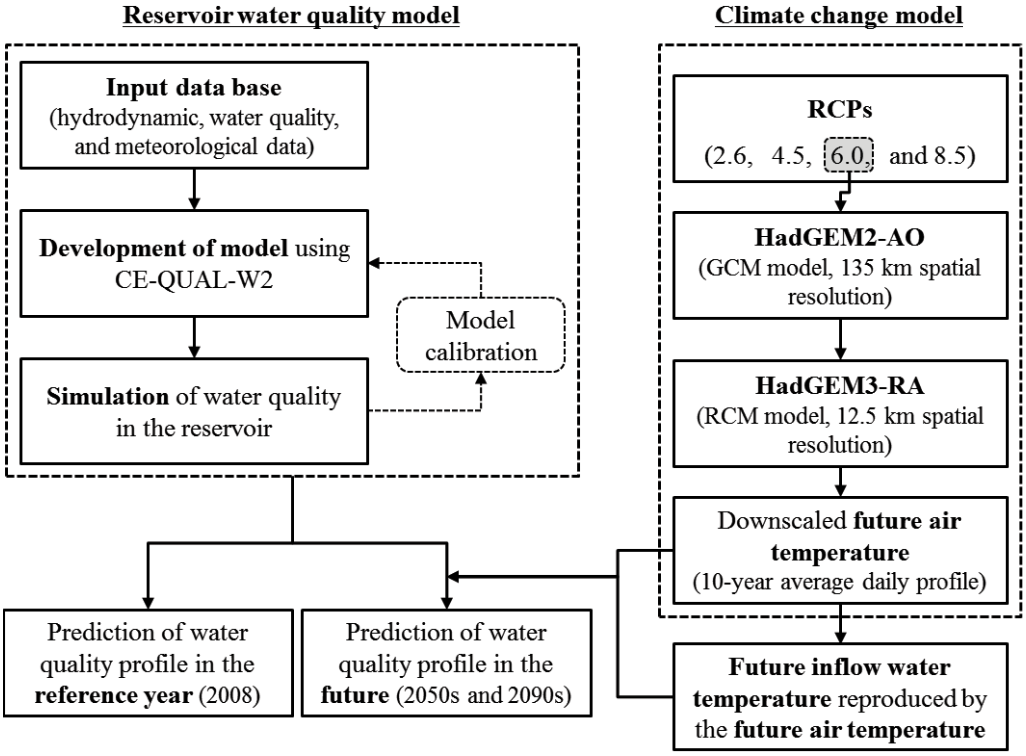

Fig. 2. Flow chart for assessing the change of future trophic states based on future air temperature changes; RCP is the representative concentration pathway.

were obtained from the climate model in the input file of the reservoir.

2.4. Trophic state change management

In this study, chlorophyll-a (Chl-a) concentration was used to classify the trophic state of the YSR (we used the trophic state index of [13]). The current trophic state of the YSR is mesotrophic based on mean Chl-a concentration in the growing season (May to October). Considering the temperature increase due to climate change and, therefore, increased algal activity, the trophic state may change from mesotrophic to eutrophic. Based on the predicted temperature changes, we determined whether the trophic state changed from mesotrophic to eutrophic. If the trophic state did change, we applied a management strategy to maintain the current trophic state by controlling the input nutrient concentration.

3. Results and discussions

3.1. Hydrodynamic and water quality calibration

The W2 model was calibrated using the YSR daily water surface elevation and monthly temperature. The model parameters calibrated included the horizontal eddy viscosity, horizontal eddy diffusivity, Chezy bottom friction factor, wind sheltering fraction, solar radiation absorbed at the water surface, light extinction for pure water, and coefficient of the bottom heat exchange [8,14]. The predicted water surface elevation and water temperature values compared favorably with the observed values (result not shown).

The water quality variables were calibrated using its associated model parameters. Overall, the predicted DO, NH_3–N, NO_3–N, and PO_4–P concentrations reproduced the spatiotemporal variations of the observed values, capturing the seasonal fluctuations (Fig. 3). However, the simulated DO in the middle and bottom layer predicted a far lower DO concentration than that measured; vertical mixing of the waterbody significantly influenced the DO concentration near the reservoir bottom. This underestimation of DO concentration led to an overestimation of phosphorous during the summer season at mid-depth and near-bottom; the underestimated DO enhance phosphorus release from the sediment bed.

3.2. Predicted climate change from the HadGEM3-RA

Predicted air temperatures are compared with current air temperatures in Table 1. The HadGEM3-RA outputs within RCP 6.0 indicated that the 10-year daily average air temperature in the 2050s was higher than in 2008 in the winter season (e.g., November to February). Air temperatures in the 2090s were higher than those in 2008 over the entire year. Interestingly, the predicted temperature in the 2050s is lower during the summer season, relative to 2008.

3.3. Comparison of Chl-a state between current and predicted conditions

Obtaining an accurate prediction of Chl-a concentration is generally difficult due to a lack of monitoring data and

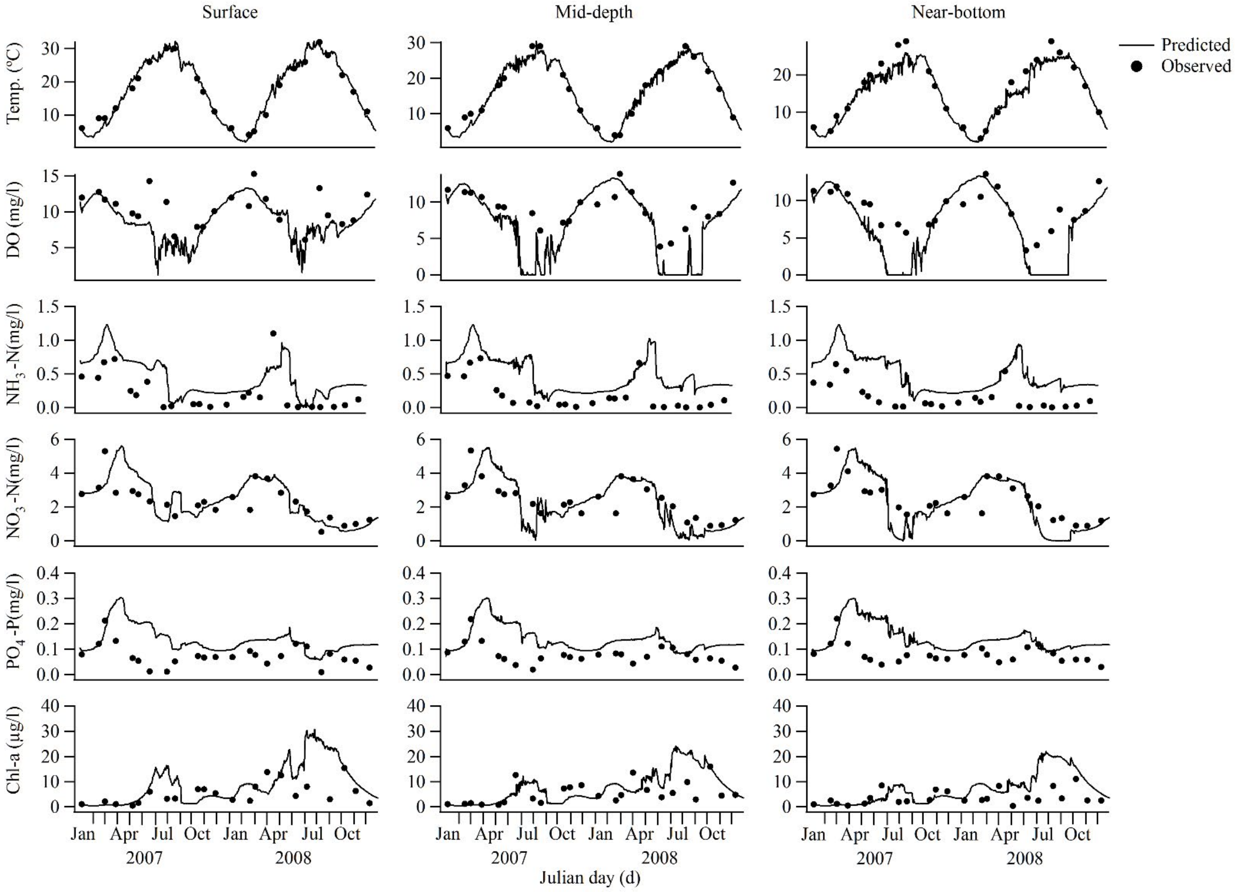

Fig. 3. Time-series plots of predicted and observed water temperatures, DO, NH_3–N, NO_3–N, PO_4–P, and chlorophyll-a (Chl-a) at the surface, mid-depth, and near-bottom during 2007 and 2008 at YS#1.

Table 1
Comparison of 2008 and predicted (2050s, 2090s) air temperatures based on monthly mean

Month	2008	2050s		2090s	
	Air temp. (°C)	Air temp. (°C)	Rate of change	Air temp. (°C)	Rate of change
1	1.98	2.98	0.50	5.37	1.71
2	1.51	4.13	1.73	6.30	3.16
3	7.60	7.36	–0.03	9.48	0.25
4	13.17	11.54	–0.12	13.74	0.04
5	17.16	15.98	–0.07	17.80	0.04
6	20.72	19.64	–0.05	21.90	0.06
7	25.93	23.03	–0.11	25.26	–0.03
8	25.45	24.78	–0.03	26.75	0.05
9	23.06	22.33	–0.03	24.84	0.08
10	17.88	18.37	0.03	20.46	0.14
11	10.52	12.39	0.18	14.43	0.37
12	4.93	6.48	0.31	8.22	0.67

algal community complexity. To consider all algal species as significant variables in the water quality model is not trivial because the dominant algal species change with spatiotemporal variation. Despite these limitations for interpreting algal dynamics, temporal Chl-a concentrations were accurately reproduced at the YS#1 station (Fig. 3). Overall, data trends indicate that there is a cyclic response of algae to water temperature, with rapid growth from May to October; however,

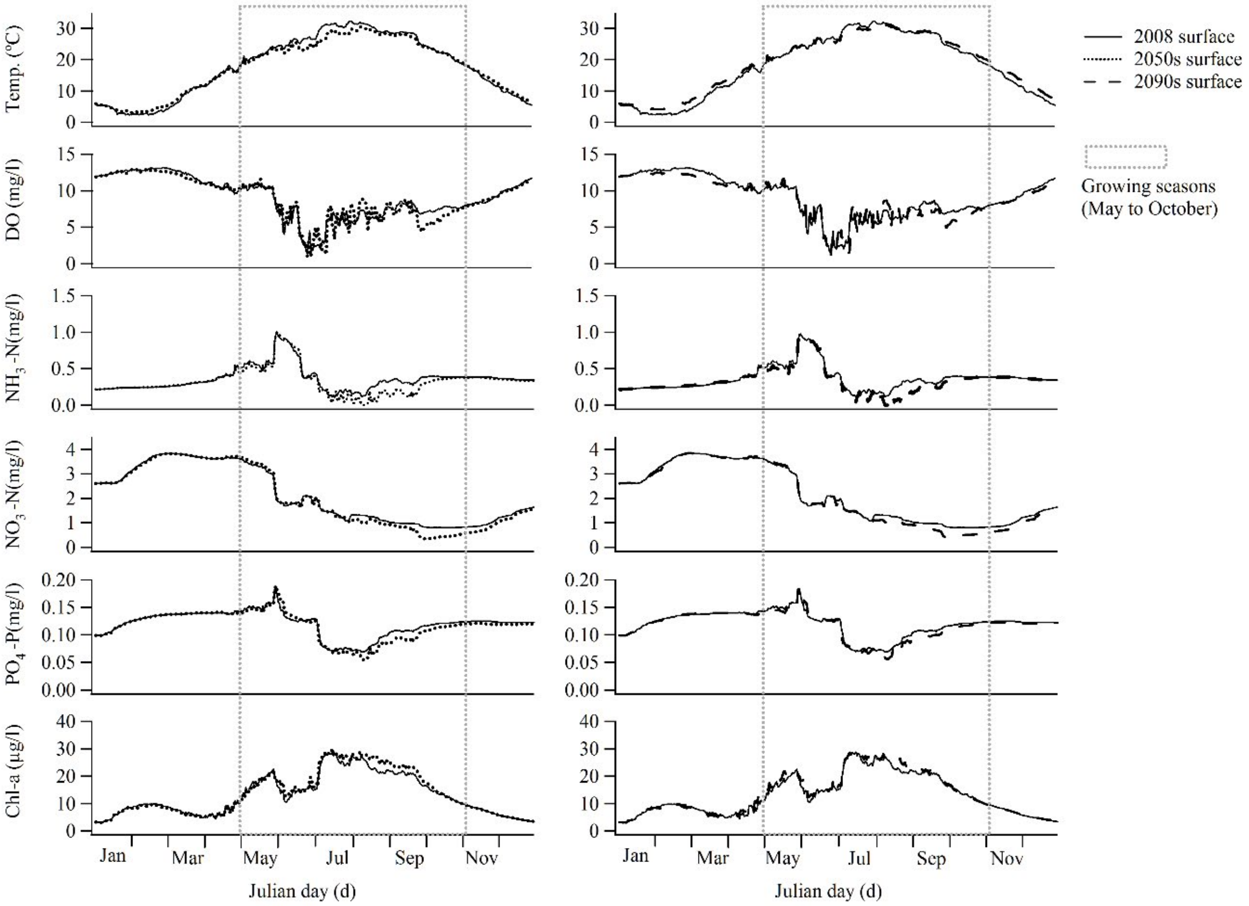

Fig. 4. Time-series plots of predicted water temperatures, DO, NH_3–N, NO_3–N, PO_4–P, and Chl-a at the surface in 2008, the 2050s, and 2090s at YS#1.

the peak summer concentration of Chl-a is underestimated in the model.

Relative to 2008, Chl-a concentration is slightly higher during three months (July–September) in both the 2050s and 2090s (Fig. 4). Despite the predicted lower summer temperatures in the 2050s, algal activity increased compared to 2008. This phenomenon is due to the amount of vertical mixing by thermal stratification influencing algal blooms [15]. Mean Chl-a concentration in the growing season is highest in the 2050s, among the three periods; the values were 19.04, 20.34, and 20.11 ug/l in 2008, the 2050s, and the 2090s, respectively.

Based on the mean Chl-a concentration, the trophic state in both the 2050s and 2090s is eutrophic; climate change has, therefore, altered the trophic state of the YSR from mesotrophic to eutrophic. To maintain the current YSR trophic condition in the 2050s and 2090s, a management scenario was implemented. When the NO_3–N concentration of inflow was maintained at 1.0 mg/L during the growing season the trophic state in both the 2050s and 2090s remained mesotrophic.

4. Conclusions

In this study, a two-dimensional hydrodynamic and water quality model was applied to assess the predicted trophic state in the YSR based on chlorophyll-a (Chl-a) concentration changes due to climate change. The major conclusions are as follows:

- Air temperatures in the 2050s, predicted by the climate change model, are lower than 2008 in the summer season, but higher in the winter season.
- Although the summer air temperature for the 2050s was lower than in 2008, the mean Chl-a concentration increased during the May to October growing season.
- Due to climate change, the trophic state of the reservoir in the 2050s and 2090s changed from mesotrophic to eutrophic.
- Maintaining an inflow nitrate concentration of 1.0 mg/L during the growing season keeps the trophic state mesotrophic in the 2050s and 2090s.

Overall, this study demonstrates that a water quality model, coupled with a management strategy, can control reservoir systems.

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