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Spring to summer nitrogen level in a brackish lake is higher in abundant snowmelt years: Correlation and causation

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Abstract

Eutrophication is an issue of concern in many brackish lakes with an agricultural watershed. The amount of snowfall in snowy areas is anticipated to decline because of global climate change. The aim of this study was to assess the impact of changes in the inflow of snowmelt on the nutrient concentrations of a downstream brackish lake. In Lake Ogawara, a brackish lake in a snow-covered agricultural area of Japan, we examined the relationships between inflowing river discharge (D/C) during spring and total nitrogen (TN) and total phosphorus (TP) concentrations in the mixolimnion of the lake ($[TN_{mix}]$ and $[TP_{mix}]$, respectively) using 29 yr of monitoring data. In addition, we assessed the causal relationship between the D/C and the lake nutrient concentrations. There was large year-to-year variation in D/C during April (D/C_{Apr}), which accounted for 7–31% of the mixolimnion volume. Significant positive correlations were observed between D/C_{Apr} and $[TN_{mix}]$ from the ensuing April to September. On an annual basis, 49% of the interannual variation of the mean $[TN_{mix}]$ during the ensuing April to September was explained by the interannual variation of D/C_{Apr}. Therefore, D/C_{Apr} could be useful as a simple index to $[TN_{mix}]$ in the ensuing spring to summer. It is notable that the relationships between D/C_{Apr} and $[TN_{mix}]$ from April to September was indicated to be acausal by statistical causal inference. Common climate conditions that increase D/C_{Apr} (i.e., a cold winter with a high level of precipitation) were found to drive other biogeochemical processes that increased $[TN_{mix}]$ during the ensuing spring to summer.

1 | INTRODUCTION

Eutrophication of lakes has become a problem worldwide. It degrades water quality and can drive the emergence and proliferation of cyanobacteria that are toxic or give the water an odd taste and odor. Eutrophication is caused mainly by an excess load of nutrients from the watershed. However,

Abbreviations: D/C, river discharge; DAG, directed acyclic graph; GAM, generalized additive model; MLIT, Ministry of Land, Infrastructure, Transport, and Tourism; TN, total nitrogen; TP, total phosphorus.

using a prediction model, Jeppesen et al. (2010) provided clear evidence that in addition to anthropogenic nutrient loading, eutrophication is often driven by climate change due to global warming. Global warming is predicted to increase the frequency and extent of extreme weather events and reduce the extent of snow-covered areas and glaciers (Stocker et al., 2013). As nutrient loading is extremely high during periods of high water discharge, such as storm events and snowmelt runoff, it is important to better understand the effects of climate change on the quality of lake water.

Snow plays a key role in the water cycle over a large area poleward of around latitude 40°N (Adam, Hamlet, & Lettenmaier, 2009). Climate change is expected to alter the timing and amount of snowmelt water. For example, Byun, Chiu, and Hamlet (2019) reported, based on a simulation study, that global warming altered the snowmelt pattern, shifting the peak-flow by up to 1 mo earlier in a snow-covered region. They also reported that global warming reduced the amount of snowfall during the winter season, thereby reducing the amount of snowmelt during early spring. Declines in snowfall are expected to be most significant in areas where the mean winter temperature is close to 0°C because a slight increase of the winter temperature changes snow into rain (Inoue & Yokoyama, 2003). In rivers flowing through snow-covered areas, the proportion of water discharge during snowmelt to the annual water discharge is often very high. In such cases, the nutrient load carried downstream during snowmelt can be significantly high (Liu, Elliott, Lobb, Flaten, & Yarotski, 2013; Rattan et al., 2017; Rattan, Blukacz-Richards, Yates, Culp, & Chambers, 2019). Thus, the amount of snowmelt strongly influences nutrient loading from the watershed and, consequently, the quality of the water in downstream lakes in snow-covered regions.

Although many studies have investigated the impacts of snowmelt water on stream water quality (Hatano, Nagumo, Hata, & Kuramochi, 2005; Woli, Hayakawa, Kuramochi, & Hatano, 2008), few studies have looked at the subsequent impacts on the nutrient levels of downstream lakes and reservoirs (Pierson, Samal, Owens, Shneiderman, & Zion, 2013). In particular, even though there are more brackish and saline lakes globally than freshwater lakes (Meybeck, 1995), almost no studies have investigated the impact of snowmelt on brackish lakes. In the context of anticipated changes in the amounts of snowfall in the near future, it is important to determine how snowmelt water affects the water quality of brackish lakes to assess properly the future changes in lake ecosystems. Therefore, our aim was to elucidate the impact of changes in the amount of snowmelt on the water quality in Lake Ogawara, a rural brackish lake in a snow-covered area of Japan. To this end, we studied the relationship between snowmelt runoff (river discharge [D/C] during April [D/C_{Apr}]) from inflowing rivers into Lake Ogawara and the total nitrogen (TN) and total phosphorus (TP) concentrations in the mixolimnion of the lake—hereafter [TN_{mix}] and [TP_{mix}], respectively—using 29 yr of monthly monitoring data. Further, since we found positive correlations between D/C_{Apr} and [TN_{mix}] from ensuing spring to summer, we investigated the causality of the relationship on the basis of statistical causal inference.

Core Ideas

- Spring to summer total N concentration in a brackish lake correlated significantly with snowmelt.
- The snowmelt–total N concentration ([TN]) relationship was not necessarily causal.
- Other processes influencing spring to summer [TN] were also present.
- The colder the winter, the higher the [TN] during the ensuing spring to summer.
- Snowmelt can be a useful predictor of the [TN] during the ensuing spring to summer.

2 | MATERIALS AND METHODS

2.1 | Study area

Lake Ogawara is a brackish lake in the northernmost part of the main island of Japan (Figure 1). The region is located in a cool-temperate climate. The annual and winter (December–February) mean temperatures of the last 30 yr were 9.9°C (SD = 0.5°C, minimum = 9.0°C, maximum = 11.1°C) and −0.3°C (SD = 0.9°C, minimum = −2.2°C, maximum = 1.0°C), respectively (Supplemental Figure S1). Similarly, the annual and winter (cumulative amount during December–February) precipitation were 1291 mm (SD = 178 mm, minimum = 929 mm, maximum = 1668 mm) and 230 mm (SD 55 mm, minimum = 143 mm, maximum = 355 mm), respectively (Supplemental Figure S2). The watershed land use is dominated by forest in the upper reaches (52%) and by paddy fields (18%) and upland fields (13%) in the lower reaches (Figure 1). The loads of TN and TP from the watershed were estimated to be 1.31 and 0.0298 g m^{-2} yr^{-1}, respectively (calculated from Nishida & Suzuki, 2007). The relative TN and TP loads by land use were estimated as follows: 45% agriculture, 22% natural, and 12% domestic and livestock for TN; and 28% livestock, 25% natural, 24% domestic, and 11% agriculture for TP (Aomori Prefecture, 2017).

The physical and hydrological characteristics of Lake Ogawara are as follows: mean and maximum depths of 11 and 26 m, respectively; surface area of 63.2 km^2; lake volume of 714 × 10^6 m^3; annual flux of 695 × 10^6 m^3; residence time of ∼1 yr; and watershed area of 805.4 km^2 (Aomori

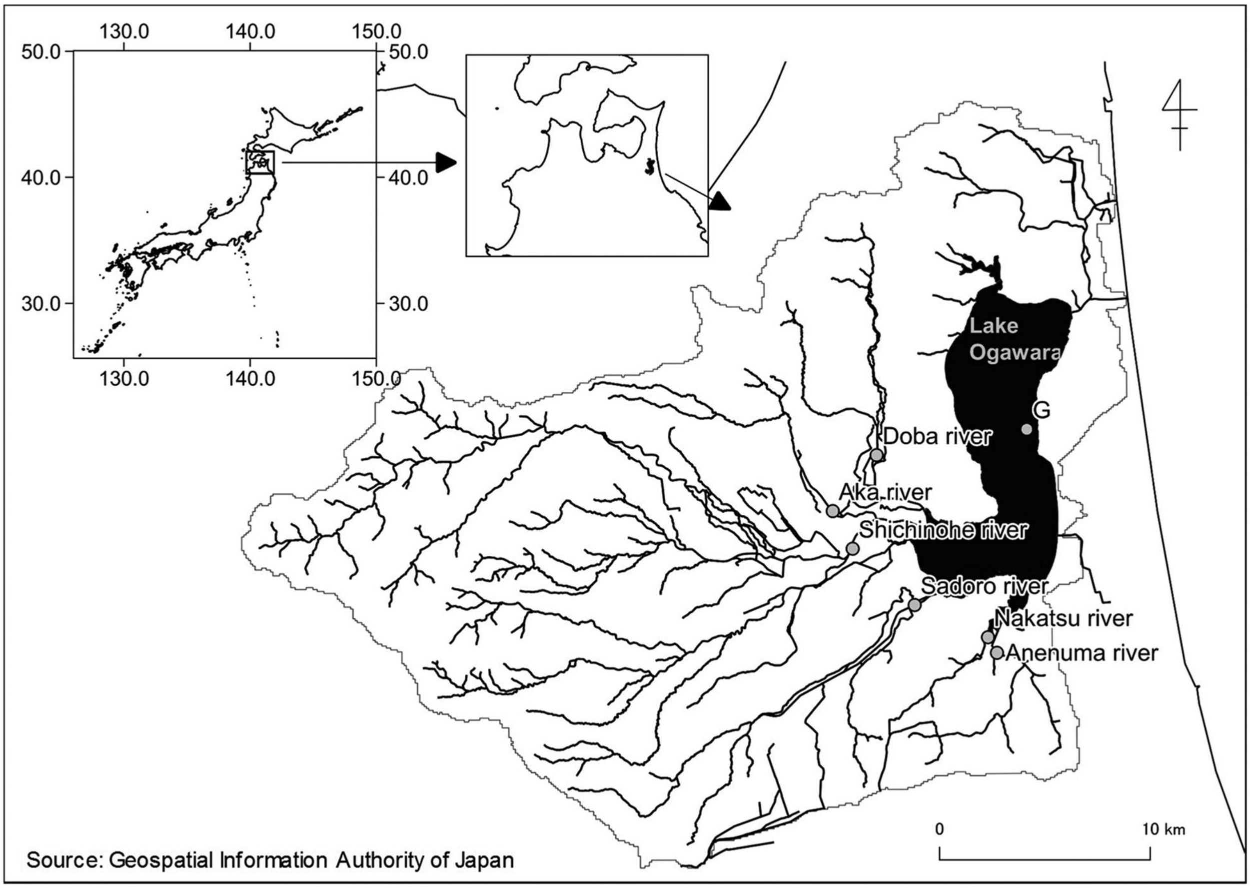

FIGURE 1 Location of Lake Ogawara and the monitoring stations of the dataset. The river system and watershed boundary are also included

Prefecture, 2017). Most of river water inflows from the south and outflows to the north. Pacific Ocean seawater reaches Lake Ogawara mainly during winter. The surface and bottom layers' salinities are 0.6–2.6 and 9.5–15.9, respectively. A halocline is formed throughout the year. Until the beginning of 2000, the halocline was 20 m below the surface, but this had reduced to 15 m by 2008 (Kinoshita, Akoh, Ishikawa, & Tsuruta, 2014) and has remained between 15 and 18 m since 2010. During summer (July–September), Lake Ogawara stratifies at ~8 m. The lake surface freezes completely or partially during December to March, depending on the year.

2.2 | Dataset used for the analysis

Data of [TN_{mix}], [TP_{mix}], chlorine concentration of mixolimnion ([Cl_{mix}]), and water discharge from inflowing rivers to Lake Ogawara from 1989–2017 were obtained from publicly available data in the Water Information System (http://www1.river.go.jp/), collected by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), Japan. The [TN_{mix}] in water samples was determined using ultraviolet spectrophotometry after alkaline peroxodisulfate digestion according to Japanese Industry Standard JIS K0102 2016 45.2 (quantitative range = 0.05–2.0 mg L^{-1} with CV < 10%). The [TP_{mix}] was determined using the molybdenum blue method following oxidative digestion with acidic peroxodisulfate according to JIS K0102 2016 46.3.1 (qualitative range = 0.003–0.5 mg L^{-1} with CV < 10%). The [Cl_{mix}] was determined by titration with silver nitrate according to Japanese Standard Drinking Water Examination Methods (qualitative range = 2–10 mg L^{-1} with CV < 10%; JWWA, 2011). Station no. G, which is in the center of the lake, was used as a representative site for the lake (Supplemental Table S1). We calculated monthly D/C by summing the daily discharge of the following six main inflowing rivers: the Doba River, Shichinohe River, Sadoro River, Anenuma River, Aka River, and Nakatsu River (Figure 1). Eighty-one percent of the total watershed area of Lake Ogawara was covered with these six rivers. As there were missing values (<0.5% of the dataset) in the daily discharge monitoring data, they were estimated using regression equations based on the river concerned and a river with the highest correlation coefficient during 30 d before and after the missing data (r^2 > .67).

2.3 | Processing of the river discharge data

River discharge data from 1989–2017 was separated into "seasonal," "trend," and "remainder" using the stl function (Cleveland, Cleveland, McRae, & Terpenning, 1990) in the statistical software R (version 3.4.1; R Core Team, 2017; hereafter referred as R). Then the means of "trend" from April to September in each year (hereafter referred to as $[\overline{TN}_{lake}]_{Apr}^{Sep}$) was calculated. The Pearson's product–moment correlation coefficient between D/C and $[TN_{mix}]$ or $[TP_{mix}]$ was calculated by R with the cor.test function. The augmented Dickey–Fuller (ADF) test was conducted to check the presence of unit root in time series data by R with the ndiffs function in the "forecast" package. Where unit roots existed, correlation analyses were performed after converting them into stationary data by taking differential values (i.e., $\Delta y_t = y_t - y_{t-1}$, where y_t and y_{t-1} are data at time t and its previous month, respectively). As the relationship between D/C and $[TN_{mix}]_{Apr}$ seemed to be curvilinear (Figure 2), generalized additive model (GAM) analysis, which is described in detail in the supplemental file, was performed to evaluate this relationship using the mgcv package (Wood, 2017) in R.

2.4 | Causal inference and confounding adjustment

The water in Lake Ogawara, which is a brackish lake, is often stratified because of the density differences regulated by water temperature and salinity. A high-salinity water layer is formed at the bottom, which is characterized by a high nutrient salt concentration and a dysoxic or anoxic environment. Nutrients in the mixolimnion are supplied from external loads from inflowing rivers and internal loads from the monimolimnion through entrainment and/or diffusive mixing at the boundary layer (Nishida & Suzuki, 2007, Nishida, Suzuki, & Nakatsuji, 2006). Climatic conditions such as temperature and precipitation influence not only external loads but also vertical mixing, which regulates internal loads through ice formation during winter (Sugihara & Hirai, 2016). Although our study originally aimed to determine the influence of snowmelt (an external load) on nutrient concentrations in the mixolimnion, climatic conditions that influence snowmelt may also influence internal loads through the abovementioned processes, creating spurious correlations. Consequently, it is important to remove possible confounding effects to evaluate the causal effect of snowmelt on nutrient concentrations in the lake.

Therefore, a directed acyclic graph (DAG) was proposed, based on previous studies (Shu, Sun, Podgurski, & Cao, 2013) and/or statistical analyses (Le et al., 2016), to examine the existence of confounding. A DAG is defined as follows: (i) factors connected with arrows that represent the direction of the causal relationship, and (ii) an absence of a directed path that forms a closed loop, as a factor cannot cause itself. A more detailed description of DAGs can be found elsewhere (Suttorp, Siegerink, Jager, Zoccali, & Dekker, 2014). An introduction to back-door criteria is supplied in the supplemental file. In this study, DAG is used solely to identify confounders based on a "back-door criterion," and quantification of each path is beyond our scope (Pearl, 2009). A proposed DAG is shown and explained in Supplemental Figure S3.

Adjustment of possible confounders was conducted by a multivariate regression model using a GAM. A GAM was used because correlations between $[TN_{mix}]$ and explanatory variables can be curvilinear. A GAM is a better choice than a linear regression model for reducing residual confounders when their relationship is nonlinear (synonymous with curvilinear in this article; Benedetti & Abrahamowicz, 2004). Note that a GAM contains a linear regression model. A GAM analysis was performed with applying a smoothing spline to all the variables, using the mgcv package on R. Detailed explanation of GAM analysis is described in the supplemental file.

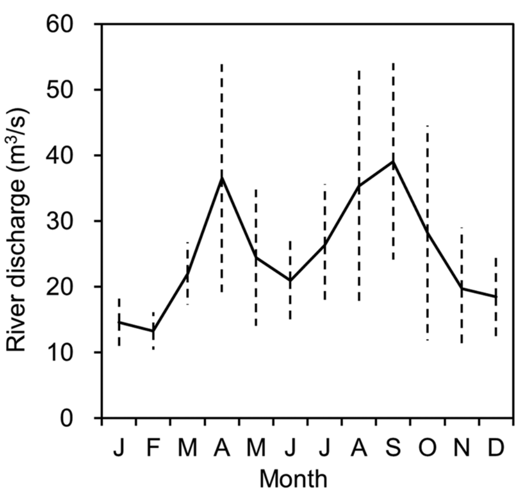

FIGURE 2 Seasonal variation of river discharge into Lake Ogawara. Solid line shows the mean of monthly river discharge from 1989–2017. Dashed bars show standard deviation. Letters on *x*-axis indicate months (January–December)

2.5 | Directed acyclic graph construction

Supplemental Figure S3 shows a DAG that was proposed to assess the causal relationship between snowmelt (D/C_{Spg}) and $[TN_{mix}]$ from spring to summer with reference to previous reports and correlations between factors. Based on the DAG, three factors ($[TN_{mix}]_{Mar}$, $[Cl_{mix}]_{Mar}$, and $[TP_{mix}]_{Mar}$) that satisfy back-door criteria were selected, and confounding adjustments were made using a GAM. The main three back-door paths are as follows: (i) TN loaded from rivers during winter affects $[TN_{mix}]$ in March (hereafter, the month is written in subscript to the right of [TN_{mix}]; e.g., [TN_{mix}]$_{Mar}$), and thus that of the ensuing spring to summer; and (ii) D/C during winter (D/C_{Wtr}) can affect the salinity of the mixolimnion and therefore the salinity gap (or the water density gap) between the mixolimnion and the monimolimnion. The salinity gap affects the susceptibility of vertical mixing between the mixolimnion and the surface of the monimolimnion. Convective diffusion of nitrogen from the monimolimnion into the mixolimnion may increase [TN_{mix}] because [TN] in the monimolimnion is approximately eight times higher than that of [TN_{mix}] (calculated from 1993–2017 monitoring data from the Water Information System). However, as the monimolimnion is anoxic to dysoxic, mixing of the two layers may induce denitrification (Brettar & Rheinheimer, 1991), thereby reducing [TN_{mix}]. The latter process is supported by the negative relation between [Cl_{mix}] of March to May and most of the [TN_{mix}] of spring to winter, which suggests that the more the monimolimnion is mixed with the mixolimnion, the lower the [TN_{mix}] of spring to winter (Supplemental Table S2). The salinity of the monimolimnion was ∼10 times that of the mixolimnion, and [Cl_{mix}] serves as a good indicator of mixolimnion–monimolimnion mixing. No such relationship was observed between [Cl_{mix}] and [TP_{mix}]. (iii) Freezing of the lake weakens vertical mixing and reduces P supply from the monimolimnion to the mixolimnion. The [TP_{mix}] has a strong influence on the primary production of Lake Ogawara, which is under P limitation (Nishida et al., 2006). As TN is also incorporated into primary production products, sedimentation of these products removes TN from the mixolimnion (Nishida et al., 2006). When [TP_{mix}] is higher in spring, [TN_{mix}] decreases in the ensuing months (Supplemental Table S2).

In this study, a DAG was constructed to select variables (*Z*) that satisfy back-door criteria. Not all causal structures located upstream of *Z* were validated because of insufficient data. However, as long as the factors located upstream of *Z* affect *Y* (objective variables) through *Z*, confounding adjustments can be made with *Z*. In other words, causal relationships can be evaluated without verifying or quantifying all the variables located upstream of *Z* (Hayashi & Kuroki, 2016).

2.6 | Selection of variables in generalized additive model to adjust confounding

Given these possible back-door paths described in the supplemental file (Supplemental Figure S5), the causal relationship between D/C and [TN_{mix}] during spring to summer was assessed. We restricted potential confounding bias by adding [TN_{mix}]$_{Mar}$, [Cl_{mix}]$_{Mar}$, and [TP_{mix}]$_{Mar}$, which satisfied the back-door criterion, as explanatory parameters of the GAM. The following GAM was fitted by month to control for confounding on [TN_{mix}]:

$$\left[\mathrm{TN_{mix}}\right]_i = \alpha_i + f\left(\mathrm{D/C_{Apr}}\right) + f\left(\left[\mathrm{TN_{mix}}\right]_{\mathrm{Mar}}\right) + f\left(\left[\mathrm{Cl_{mix}}\right]_{\mathrm{Mar}}\right) + f\left(\left[\mathrm{TP_{mix}}\right]_{\mathrm{Mar}}\right) + \varepsilon_i$$

where [TN_{mix}]$_i$ is a [TN_{mix}] of month *i*; *f*(D/C_{Apr}), *f*([TN_{mix}]$_{Mar}$), *f*([Cl_{mix}]$_{Mar}$), and *f*([TP_{mix}]$_{Mar}$) are smooth functions of each covariates; and α_i and ε_i are the intercept and residue of month *i*, respectively. Under this condition, the significance of each variable can be used to assess the causal effect on [TN] after spring.

3 | RESULTS AND DISCUSSION

3.1 | Intra- and interannual trend of river discharge

Figure 2 depicts intraannual variations in the D/C. There were two distinct peak discharges in April and August to September; these were, to a great extent, attributed to snowmelt runoff for the former and typhoons or tropical or extratropical cyclones for the latter. Note that D/C_{Apr} did not have significant correlation with rainfall in April ($r = -.1$, $p > .05$); instead, it had significant correlation with snow depth in March ($r = .66$, $p < .001$). There were large interannual variations in the D/C of April (hereafter, the month or period is written in subscript to the right of D/C; e.g., D/C_{Apr}) (36.5 ± 17.3 $m^3\ s^{-1}$), D/C_{Aug} (35.3 ± 18.1 $m^3\ s^{-1}$), and D/C_{Sep} (39.1 ± 14.9 $m^3\ s^{-1}$). The D/C_{Apr} ranged from 4.7×10^7 to 2.1×10^8 $m^3\ mo^{-1}$, equivalent to approximately 7 and 31% of the mixolimnion volume, respectively (above the halocline layer, 18 m deep). Thus, nutrient loading from D/C_{Apr} was anticipated to have a significant impact on the water quality in Lake Ogawara.

3.2 | Correlation between river discharge and the concentrations of TN_{mix} and TP_{mix}

Significant correlations were observed between D/C during spring (D/C_{Spg}) and [TN_{mix}] over ensuing several months (Table 1). In particular, from April to September, there were significant positive correlations between D/C_{Apr} and [TN_{mix}]. Figure 3 shows the relationship between the mean [TN_{mix}] from April to September (hereafter referred to as $[\overline{\mathrm{TN}}_{\mathrm{lake}}]^{\mathrm{Sep}}_{\mathrm{Apr}}$) and D/$C_{Apr}$. The value of the effective degree of freedom of the fitting model was 2.0, which indicated that the relationship was curvilinear. The GAM explained 49% of the variation of $[\overline{\mathrm{TN}}_{\mathrm{lake}}]^{\mathrm{Sep}}_{\mathrm{Apr}}$ (p <.05) as follows: the $[\overline{\mathrm{TN}}_{\mathrm{lake}}]^{\mathrm{Sep}}_{\mathrm{Apr}}$ (1.01 mg L^{-1}) in the year with maximum D/C_{Apr} (82 $m^3\ s^{-1}$) was 1.3 times higher than that in the year with minimum D/C_{Apr}

TABLE 1 Pearson's product–moment correlation coefficients between monthly river discharge (D/C) and the concentrations of total N ($[TN_{mix}]$) and total P ($[TP_{mix}]$) in the mixolimnion of Lake Ogawara in ensuing months

	River discharge				River discharge		
$[TN_{mix}]$	March	April	May	$[TP_{mix}]$	March	April	May
Mar.	0.36			Mar.	0.11		
Apr.	0.47*	0.62***		Apr.	0.17	0.02	
May	0.39*	0.63***	0.55**	May	0.02	−0.11	0.04
June	0.06	0.44*	0.39*	June	−0.08	−0.23	−0.08
July	0.03	0.44*	0.41*	July	0.03	−0.06	0.10
Aug.	0.34	0.41*	0.29	Aug.	0.24	0.00	0.05
Sep.	0.43*	0.48**	0.27	Sep.	0.22	0.23	0.38*
Oct.	0.21	0.30	0.10	Oct.	0.05	−0.29	−0.13
Nov.	0.36	0.27	0.08	Nov.	0.12	−0.13	−0.01
Dec.	0.14	0.16	0.13	Dec.	−0.24	0.09	0.33

*,**,***Significance at the .05, .01, and .001 probability levels, respectively.

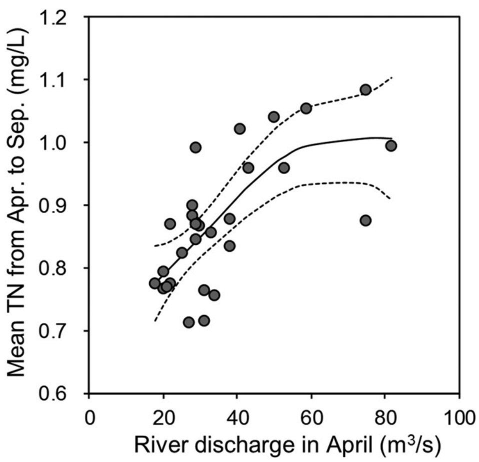

FIGURE 3 Relationship between river discharge in April (D/C_{Apr}) and mean TN concentration of mixolimnion from April to September ($[\overline{TN}_{mix}]_{Apr}^{Sep}$). Solid line represents mean predicted value. Dashed lines represent confidence interval of 95%

($18\ m^3\ s^{-1}$, $[\overline{TN}_{lake}]_{Apr}^{Sep} = 0.776\ mg\ L^{-1}$). There was little correlation between D/C_{Spg} and $[TP_{mix}]$. The reasons for this could be as follows: most phosphorus inflow from the rivers into Lake Ogawara comes in particulate form; thus, most TP was precipitated in the lake, and internal loading of phosphorus from monimolimnion is much higher than the amount of TP inflow during spring. In addition, unlike nitrogen, phosphorus does not change into a gas under reduced conditions (this process is described below). Therefore, the impact of D/C_{Spg} on $[TP_{mix}]$ was not considered further.

3.3 | Statistical causal inference

Figure 4 shows the marginal effect of each variable on $[TN_{mix}]$ elucidated by GAM analysis. There were significant relationships between $[TN_{mix}]$ from April to August and variable(s) that differed by month. Interestingly, a significant positive relationship was observed between D/C_{Apr} and $[TN_{mix}]$ only in May. This result was different from that obtained between D/C_{Apr} and $[TN_{mix}]$ using a single regression (Table 1). This discrepancy indicated that the spring to summer relationship between D/C_{Apr} and $[TN_{mix}]$ was generally correlation but not causation—different factors influenced on the $[TN_{mix}]$ in respective months, as described below.

From April to June, there were positive relationships between $[TN_{mix}]_{Mar}$ and $[TN_{mix}]$, representing an autoregression, as was assumed in DAG (Supplemental Figure S3). From April to July, there were significant negative or V-shaped relationships between $[Cl_{mix}]_{Mar}$ and $[TN_{mix}]$. This indicated that up to a certain point, the rate of denitrification increased as the vertical mixing increased, but the rate of the nitrogen supply from the monimolimnion exceeded denitrification after that point. In particular, in May and June, a negative correlation was found between $[TN_{mix}]$ and $[Cl_{mix}]_{Mar}$ when the concentrations were $<1100\ mg\ L^{-1}$, but it changed to a positive correlation when the concentrations were $\geq 1100\ mg\ L^{-1}$. This bidirectional result agrees with the assumption that vertical mixing of two layers may lower $[TN_{mix}]$ by increasing denitrification rate in mixolimnion, since monimolimnion is anoxic on one hand, but on the other hand increases the $[TN_{mix}]$ because the TN concentration is much higher in the monimolimnion. From May to July, there was a significant negative relationship between $[TP_{mix}]_{Mar}$ and $[TN_{mix}]$. As was assumed in DAG, this relationship represents an increase of nitrogen sedimentation accompanied by an increase of primary production fueled by the supply of phosphorus. Different from a simple correlation between D/C and $[TN_{mix}]$, no significant relationship was observed between $[TN_{mix}]$ and any variables in September for GAM. This may be ascribed to dilution of the effect by each factor with time. However, as

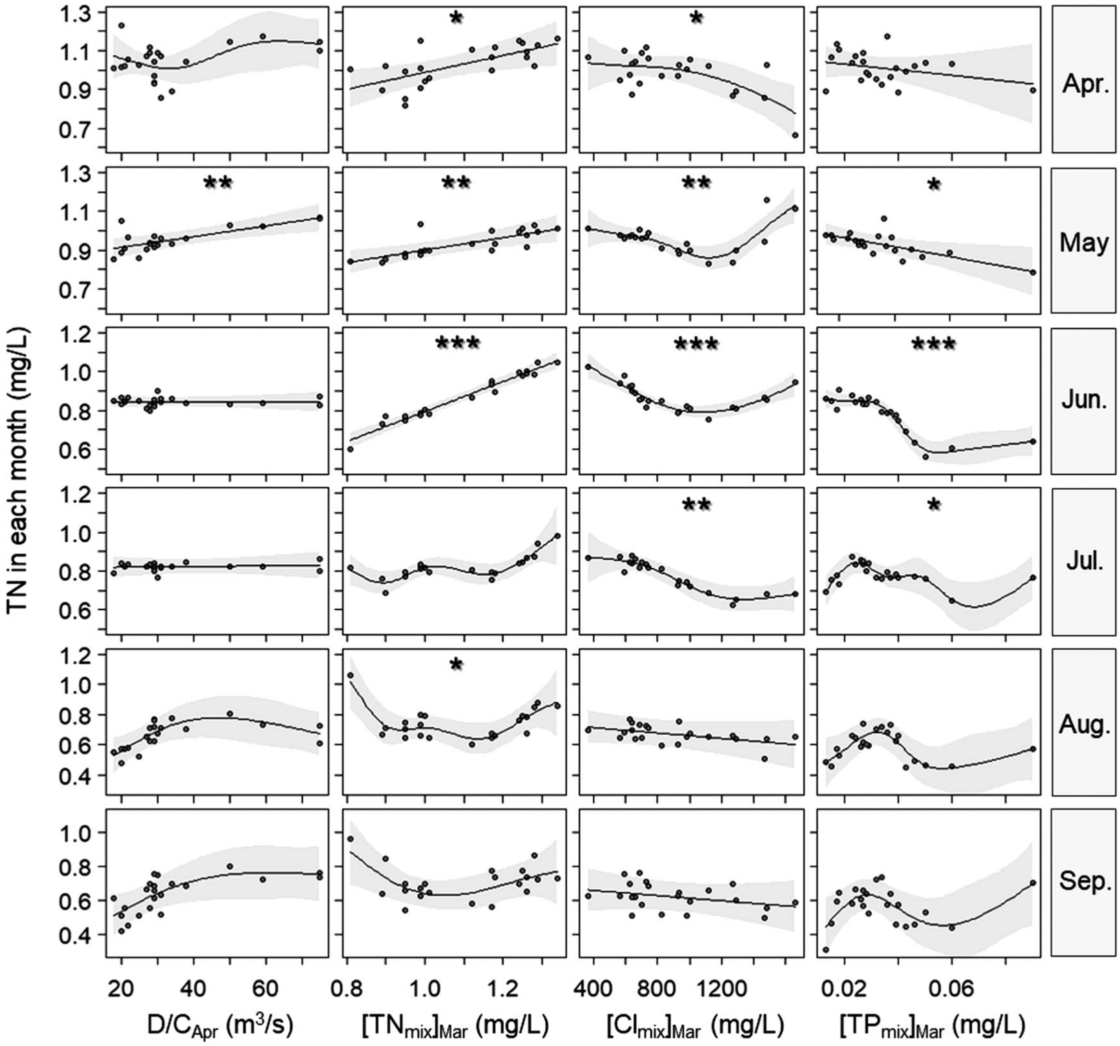

FIGURE 4 Plots of marginal effect of each variable on the total nitrogen concentration in the mixolimnion of Lake Ogawara ([TN_{mix}]) calculated by a generalized additive model. Asterisks (*, **, ***) refer to statistical significance at p levels of <.05, <.01, <.001, respectively. Solid lines represent the mean predicted value. Gray bands represent the confidence intervals of 95%. D/C_{Apr} refers to river discharge in April. The [TN_{mix}], [TP_{mix}], [Cl_{mix}] refer to total nitrogen, total phosphorus, chlorine concentrations in the mixolimnion, respectively

the impacts of these factors all increase [TN_{mix}] under common climate conditions, as described below, combination of the factors boosts the effects—GAM showed good prediction of the [TN_{mix}] from April through September with the above-mentioned variables (Supplemental Figure S6).

3.4 | Biogeochemical processes affecting [TN_{mix}] of ensuing spring to summer

The D/C_{Apr} accounted for 7–31% (mean 14%) of the mixolimnion volume of Lake Ogawara. Since there were positive correlations between D/C_{Apr} and [TN_{mix}] from April to September (Figure 3), interannual variations in snowmelt were considered to have the potential to affect the [TN_{mix}] of the ensuing spring to summer. However, during these months, other factors as well as snowmelt, which are influenced by winter temperature and winter precipitation, were found to influence the [TN_{mix}]. A winter with abundant D/C_{Apr} can be characterized as a cold winter with a higher number of subzero days (see Supplemental Figure S1 for winter temperature of this area). Under such climate conditions, the following processes, which all direct to increase [TN_{mix}], are considered to occur (Supplemental Figures S3 and S5): (i) higher D/C supplies more nitrogen from watershed to the lake; and (ii) ice cover of the lake weakens vertical mixing and decreases transfer of salts, phosphorus, and anoxic water, from monimolimnion to mixolimnion. As this is the case, primary productivity during the following spring decreases due to low [TP_{mix}], thereby reducing the settling out of nitrogen (biomass) from the mixolimnion. Also, denitrification rate will decrease due to more aerobic conditions of mixolimnion.

Inoue and Yokoyama (2003) predicted that an increase in winter temperature by a few degrees would considerably reduce the depth of snow in the study region because the precipitation would change from snow to rain. According to Stocker et al. (2013), there has been a 1.6% (∼0.8–2.4%) decline in the snow-covered areas in the northern hemisphere per decade from 1967–2012. Lake Ogawara is a meromictic lake with a halocline. In this lake, the type of mixing changes from dimictic to monomictic and snowmelt decreases when the winter air temperature increases by a few degrees as the mean winter temperature is near 0°C (Supplemental Figure S1). Therefore, increase in winter temperature will decrease [TN_{mix}] of the ensuing spring to summer.

4 | CONCLUSION

The influence of snowmelt–winter climate on nitrogen level in a brackish lake in snowy area was investigated on Lake Ogawara in Japan. The D/C_{Apr} accounted for 49% of the variation of $[\overline{TN}_{lake}]_{Apr}^{Sep}$, suggesting that D/C_{Apr} can serve as a simple indicator of [TN_{mix}] during the ensuing spring to summer in Lake Ogawara. In general, the relationship between D/C_{Apr} and [TN_{mix}] during spring to summer was correlation, but not causation. Statistical causal inference has illustrated the importance of considering confounding factors. Common climatic conditions that increased D/C_{Apr} (i.e., a colder winter with a high level of precipitation) were found to drive biogeochemical processes that all increase [TN_{mix}] in Lake Ogawara during spring to summer. On the contrary, an increase in winter temperature in association with global warming decreases [TN_{mix}] and thus also the nitrogen/phosphorus ratio. This may change the community structure of phytoplankton by increasing cyanobacteria (Smith, 1983), which in turn alters the ecosystem of the lake (Havens, 2008). Emergence of a musty odor by 2-methylisoborneol (2-MIB) and cyanobacteria are becoming a problem in Lake Ogawara, which supports a fishing industry. Given the relationship between [TN_{mix}] and their emergence, D/C_{spg} may be useful as a simple index to predict the emergence of undesirable conditions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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