Long-term light environment variability in Lake Biwa and Lake Kasumigaura, Japan: Modeling approach

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Abstract Light environment variability was investigated in the two Japanese Lakes Biwa and Kasumigaura, which offer a broad range of optical conditions in the water bodies due to their diverse morphometries and limnological characteristics. To elucidate their light environments, Secchi depths (SDs) were connected with the long-term monitored datasets of concentrations of optically active substances (OASs) by using two approaches based on statistical and mechanistic models. The good estimation of the non-phytoplanktonic suspended solids (NPSS) concentration using a monthly factor δ (that represents the phytoplanktonic portion in total suspended solids) from a long-term analysis helped to develop robust models. Using the mechanistic model, the OAS contributions to SD can be understood and further investigated in detail than would be possible with the statistical approach, but on the other hand the statistical model presented better results in terms of SD prediction. From the analysis of OAS contributions to SD, it was clear that NPSS was the most influential component that controlled the light environments in the two lakes; in this respect, this study supports other studies showing the importance of the suspended inorganic particles as the main contributors to SD in inland waters. Using ANOVA we analyzed how specific inherent optical properties (SIOPs) might have changed spatially and temporally, indicating that the temporal (monthly) effect was primarily responsible for the loss of accuracy in the models. In addition, the ANOVA analysis suggested the grouping of data to improve the prediction performance of the statistical models. Finally, we concluded that the combination of the two models could lead to the most reliable results in terms of SD prediction and OAS contributions to SD at present.

Keywords Secchi depth, Chlorophyll-a, NPSS, DOC, optical properties

Introduction

Light penetration has important ecological and water quality implications, as it influences many aspects in lakes ecosystems such as primary production, species composition of phytoplankton, the depth distribution of submerged macrophytes and the heat budget of waterbodies (Reinart et al. 2003). Besides, studies provided evidence that the light environment can affect the bacterial numbers and composition e.g. decreasing the abundance of phototrophic microorganisms (Lear et al. 2009). Secchi depth (SD) is the most straightforward index to evaluate light penetration in aquatic ecosystems (Smith

2001; Wetzel 2001). Hence it has the longest record of use in optical characterization, and remains the most commonly measured optical attribute (Effler et al. 2008).

Light field of inland waters are typically influenced by optically active substances (OASs) such as phytoplankton (represented by Chlorophyll-a: Chl-a), non-phytoplanktonic suspended solids (NPSS; e.g. mineral particles, dead organisms, decaying organic matter, zooplankton and other microbes) and colored dissolved organic matter (CDOM) that may be carried to the water by rivers from the surrounding land, or re-suspended from the lake bottom or produced in the lake (Reinart et al. 2003). In the last decades, many studies have derived relationships between OASs and SD by using two modeling approaches: a widely used statistical model (Jassby et al. 1999; Armengol et al. 2003; Effler et al. 2002; Zhang et al. 2006; Swan et al. 2007; Obrador & Petrus 2008) and a model based on water optics theory. The latter had a further attempt because many considerations (e.g. delineation of the specific absorption and scattering roles played by each OAS) should be taken into account for its development (Effler et al. 2005; Pierson et al. 2005; Swift et al. 2006; Effler et al. 2008). A comparison between statistical and mechanistic models for SD prediction considering all OAS contributions has not been done so far. In addition, models that quantify all OAS contributions on SD are necessary for appropriate basin ecosystem restoration, and to establish reasonable expectations for related management efforts (Effler el al. 2008).

Statistical approaches based on single OAS, perform poorly in systems where variations in more than one OAS are important in regulating SD dynamics. For instance, Chl-a failed as the best predictor after a reduction of Chl-a concentration could not increase SD levels (Cooke et al. 1993). Later, in many productive inland waters, the suspended inorganic particles have been increasingly suspected to be the most influential substances that regulate light penetration (Davies-Colley et al. 1993; Effler and Perkins 1996; Jassby et al. 1999). More recently, the suspended inorganic particles were implied as the main contributors on SD by some studies using models based on water optics theory (Swift et al. 2006; Effler et al. 2008), but still some uncertainties related to the OAS optical properties remained in order to state them as the most significant substances (e.g. the absorption of the suspended inorganic particles and the variability of the scattering of phytoplankton remained the most understudied). The suspended inorganic particles may have autochthonous (e.g., chemical precipitation; Weidemann et al. 1985) and allochthonous origins (e.g. terrigenous; Nagai et al. 2001).

We undertook this study in two lakes in Japan, Lake Biwa (deep lake with a maximum depth>100 m) and Lake Kasumigaura (shallow lake with a maximum depth<10 m), which offer a broad range of optical conditions within the water bodies due to their diverse morphometries and limnological attributes. In both lakes, a range of optical measurements have been taken occasionally in recent years. However, continuous 11-years and 19-years records of SD and OAS concentrations in Lakes Biwa and Kasumigaura respectively, which provide a quantitative measure of long-term light environment dynamics, are very important for developing robust models with high reliability.

The objectives of this study included (a) understanding the long-term light environment variability in the lake ecosystems by evaluating a statistical and a mechanistic model to predict SD, and (b) quantifying each OAS contribution to SD (i.e. to elucidate the most influential substance that determines the light field in inland waters). As to the first objective, the merits and demerits for each model have been examined and discussed in the present paper, and a spatial and temporal analysis of the model performances has provided some hints about changes in the optical properties during the long-term periods that could improve the models. As to the second, the quantification of each OAS contribution is expected to contribute in a fundamental way to the management of water quality and ecosystem.

Materials and methods

Sites description and monitored data

Lakes Biwa and Kasumigaura are the first and second largest lakes in Japan, respectively (Table 1). Their water quality is a major concern since their waters are used for drinking, industrial, and agricultural purposes. Lake Biwa is geometrically divided into two parts, namely a northern and a southern basin, each with different characteristics. The northern basin is a pelagic zone that accounts for 90% of the total lake area (Belzile et al. 2002) and is therefore the main basin. In this analysis, we focused only on the northern basin (pelagic zone) because it contained a negligible amount of floating and submerged vegetation. In summer, the northern basin is thermally stratified, resulting in thermocline formation. The thermocline usually appears from May to November and has a great impact on material flow in the lake (Monomictic lake: Urabe et al. 1999), and consequently on the growth and the vertical distribution of primary producers. This basin is in mesotropic level.

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Lake Kasumigaura has three basins (two large bays called Takahama-iri and Tsuchiura-iri, and a central basin) and is so shallow and flat that vertical stratification is easily destroyed by a moderately strong wind (>5ms^{-1}: Fukushima and Muraoka 1981). After 1980, aquatic macrophytes disappeared from almost all regions. Lake Kasumigaura is considered to be eutrophic, because of high loads of nutrients and its shallow depth (Fukushima et al. 1996).

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Several factors, such as long periods of observation at numerous stations distributed over the region, and monthly record-keeping offer a unique opportunity to improve our understanding of light field variability in these lakes (Fig. 1). A total of 9 lines are drawn across the northern basin of Lake Biwa at nearly uniform intervals from north to south, and 28 sampling stations are designated, based on 3 fixed points (eastern shore, center of lake, western shore) located on these lines (except for line 17 based on 4 points). In Lake Kasumigaura, 10 sampling stations were located in the bay areas and central basin. In this study, we chose April as the beginning of the year considering the vertical mixing regime and algae blooming outbreak. As the knowledge of the in-situ optical properties is very important for developing the mechanistic model, additional measurements, that include absorption and scattering coefficients, were carried out in 2009 and 2010 for the two lakes. For all measurements (long-term and additional measurements), SD were measured; water samples were collected from the water surface in Lake Biwa and taken using a column sampler (0-2 m depth) in Lake Kasumigaura. For the long-term measurements in Lake Kasumigaura, water samples were immediately filtered onto Whatman GF/F glass fiber filters. The Chl-a was extracted using methanol (10ml) at 3°C for 12 hours in a dark condition, then the extract was centrifugated at 3000 rpm for 10 min and analyzed spectrophotometrically by SCOR-UNESCO (1966). Total suspended solids (TSS) concentrations were measured gravimetrically using pre-combusted Whatman GF/F filters at 450°C for 4 hours. Dissolved organic carbon (DOC) concentrations were measured according to the high-temperature combustion method. Similarly, for all other measurements in the two lakes, the data specifications including measurement methodologies are described in Table 2. The estimation of NPSS concentration using a monthly factor δ (that represents the phytoplanktonic portion in TSS) based on the method of Gons et al. (1992) is explained in Appendix A (Online Resource 1). Representative annual trends of SD and OAS concentrations for the long-term periods are presented in Fig. 3. Regarding the optical measurements, the absorbance of the extracted Chl-a was measured at four wavelengths(λ): 750, 663, 645 and 630 nm using a spectrophotometer (UV-1700, Shimadzu, Tokyo, Japan); and the absorption of CDOM was measured from the filtered water using the same instrument. The absorption of NPSS was obtained after extraction of the pigments from the 0.7 μm Whatman GF/F filter using hot ethanol (80%, 75°C) according to the quantitative filter technique (Mitchell 1990). *In situ* reflectance spectra were collected according to Method 1 of Mueller et al. (2000) for estimating the scattering coefficients based on an inversion of the bio-optical model (Yang et al. 2011).

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Model development

Several assumptions were made as follows. It was supposed that surface waters were well mixed by wind, and that the mixed layer was deeper than the SD. As a result, it was assumed that OAS concentrations were uniform in the layer from the surface to SD.

Statistical model

Multivariate linear regression analyses for the long-term datasets of the two lakes were performed by using SD^{-1} as a response variable and Chl-a ($\mu g l^{-1}$), NPSS ($mg l^{-1}$) and DOC ($mg l^{-1}$) concentrations as explanatory variables. The tested models with all possible combinations of variables (7 models) were evaluated using the Akaike's Information Criterion (AIC) to select the best prediction model.

Mechanistic model

The equations involved in this model were selected from the best currently available knowledge of water optics. Based on the contrast transmittance theory (Tyler 1968, Preisendorfer 1986), the following Secchi depth relation was developed:

$$\mathrm{SD}^{-1} = \Gamma^{-1} \cdot [\bar{\bar{\mathrm{c}}} + \bar{\bar{\mathrm{K}}}_{\mathrm{d}}] \quad (1)$$

where $\bar{\bar{\mathrm{c}}}$ and $\bar{\bar{\mathrm{K}}}_{\mathrm{d}}$ are depth-averaged (from water surface to SD) beam and diffuse attenuation coefficients, respectively. Both describe spectrally averaged conditions weighted towards the wavelength-dependency of the human eye's photopic response and downwelling irradiance at the water surface (Preisendorfer 1986). The photopic function possesses a maximum around 555nm and is near zero at the two ends of the visible spectrum. Γ is a coupling constant that depends on variations in ambient conditions during measurements (Preisendorfer 1986). In this study, the value of Γ for each specific system was estimated by adjusting its value to give the smallest root mean square error (RMSE) index, when the predicted reciprocals of Secchi depths (SD^{-1}) were compared to the measured SD^{-1}. Beam attenuation coefficient $c(\lambda)$ was expressed as the sum of absorption and scattering coefficients:

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (2)$$

Absorption $a(\lambda)$ and scattering $b(\lambda)$ are inherent optical properties (IOPs) and therefore can be expressed as the sum of contributions by individual components (Mobley, 1994). Since there is no standard method for measuring the mass concentration of CDOM, it is conventionally measured as the absorption coefficient of CDOM at the reference wavelength 440 nm: $a_{CDOM}(440)$ (Babin et al. 2003a).

$$a(\lambda) = a_w(\lambda) + [Chla]\cdot a_{ph}^*(\lambda) + [NPSS]\cdot a_{NPSS}^*(\lambda) + a_{CDOM}(440)\cdot a_{CDOM}^*(\lambda) \quad (3)$$

and

$$b(\lambda) = b_w(\lambda) + [Chla]\cdot b_{ph}^*(\lambda) + [NPSS]\cdot b_{NPSS}^*(\lambda) \quad (4)$$

where the terms in brackets [Chla] and [NPSS] refer to the concentrations of Chl-a ($\mu g l^{-1}$) and NPSS ($mg l^{-1}$), respectively. $a_w(\lambda)$ is the absorption coefficient of pure water (Pope and Fry 1997), and $b_w(\lambda)$ represents the scattering by pure water (Morel 1974). $a_{ph}^*(\lambda)$, $a_{NPSS}^*(\lambda)$, and $a_{CDOM}^*(\lambda)$ are the specific absorption coefficients for phytoplankton, NPSS and CDOM, respectively. $b_{ph}^*(\lambda)$, and $b_{NPSS}^*(\lambda)$ are the specific scattering coefficients for phytoplankton and NPSS, respectively. Similarly to Zhang et al. (2005), we related $a_{CDOM}(440)$ and DOC concentration linearly.

$$a_{CDOM}(440) = a^+(440)\cdot[DOC] + e' \quad (5)$$

where [DOC] represents the concentration of DOC ($mg l^{-1}$). The slope $a^+(440)$ and intercept e' represent the DOC-absorption coefficient and the constant background of uncolored DOC in surface waters, respectively. $a^+(440)$ and e' have been obtained for the additional measurements in the two lakes (Table 3), and their average values in each lake were used to estimate $a_{CDOM}(440)$ for the long-term prediction of SD.

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Diffuse attenuation coefficient $K_d(\lambda)$ was estimated based on the relationship given by Kirk (1984).

$$K_d(\lambda) = \frac{[a(\lambda)^2 + k_\mu \cdot a(\lambda)\cdot b(\lambda)]^{0.5}}{\mu_0} \quad (6)$$

The coefficient k_μ was estimated from the following equation (Bowers et al. 2000)

$$k_\mu = 0.425 \cdot \mu_0 - 0.19 \quad (7)$$

where μ_0 is the cosine of zenith angle of refracted solar photons, calculated from the solar zenith angle (SZA) using Snell's Law with the appropriate index of refraction for water and air. The SZA was calculated from date, time, and latitude using equations given in Kirk (1994b). The values of μ_0 ranged between 0.440-0.708 and 0.738-0.939 for Lakes Biwa and Kasumigaura, respectively.

Estimation of specific inherent optical properties (SIOPs)

$a^*_{ph}(\lambda)$ was obtained by dividing the absorption due to phytoplankton by the Chl-a concentration (Fig. 2). Similarly, $a^*_{NPSS}(\lambda)$ was obtained by dividing the absorption due to non-phytoplanktonic particles by the NPSS concentration. The separation of phytoplankton and NPSS scattering ($b^*_{ph}(\lambda)$ and $b^*_{NPSS}(\lambda)$) was based on the assumption that the contributions of scattering due to phytoplankton cells and NPSS are proportional to the ratios of their masses. A similar assumption but referring to backscattering was considered by Brando and Dekker (2003). As demonstrated in previous studies, $a^*_{CDOM}(\lambda)$ and $a^*_{NPSS}(\lambda)$ together with $b^*_{NPSS}(\lambda)$, could be fitted with an exponential wavelength function as described in Table 4.

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For the long-term prediction of SD, all SIOPs obtained from the additional measurements conducted during 2009 and 2010 in the two lakes were used.

OAS contributions to SD

Long-term averaged OAS concentrations for the two lakes were used to investigate the OAS contributions to SD for both statistical and mechanistic models. First, we calculate the effect of pure water: in the mechanistic models this effect was evaluated by setting other OAS concentrations (Chl-a, NPSS, and DOC) equal to zero, while in the statistical models it was estimated from the intercept. Then, we evaluate the effect of the respective OASs by setting each long-term averaged concentration as the only input to the models. Using both models the obtained contribution of each OAS includes the water effect which needed to be subtracted.

Spatial and temporal patterns of SD prediction performance

A three-factor ANOVA was applied to the ratios of measured vs. predicted SD^{-1} for the long-term monitoring data to evaluate year, month and station effects on the predictive ability of the two models. This procedure revealed how significantly the ratios differed between stations and times.

$$\text{ratio} = \frac{SD^{-1}_{\text{predicted}}}{SD^{-1}_{\text{measured}}} \quad (8)$$

On the other hand, the excellent performance of the mechanistic model in estimating SD for the additional measurements using measured SIOPs, suggested that the assumption of constant SIOPs for the long-term prediction of SD was responsible for the results of lower performance. Then, an analysis of the spatial and temporal patterns of SD prediction using the mechanistic model was meaningful because the variation of the above ratio from the value of 1 could be attributed to the variation of SIOPs. In this way, ANOVA results obtained by this analysis provided perspective about how SIOPs varied spatially and temporally. Additionally, as the correlation coefficients of statistical models depend on the data, we tried to understand how the prediction of SD would be affected by different arrangements of data. In this regard, ANOVA results using the statistical model suggested a specific grouping of the datasets designed to improve the performance of this approach.

Results

Overview of SD and OAS long-term trends

In Lake Biwa, SD annual averages broadly increased from 5 to 6.7 m during the 10 years (1998-2007) and decreased to 6 m in 2008 (Fig. 3a)**.** In contrast, SD annual averages in Lake Kasumigaura was 0.97 m in the late 1980s and then decreased to 0.46 m until 2005, and finally increased reaching 0.64 m in 2007 (Fig. 3e). Regarding the OAS concentrations, Chl-a and NPSS concentrations in Lake Biwa were generally stable for the long-term period with relatively high values in spring and higher and lower values in summer and winter, respectively (Fig. 3b, 3c). In Lake Kasumigaura, there is a moderate peak for Chl-a concentrations in 1995 and 1996 followed by steadily decrease over time to 2005, and finally rise to 77.1 $\mu g l^{-1}$ in 2007 (Fig. 3f). Figure 3g shows an increasing trend of NPSS concentrations until 2005 and decrease after that. DOC concentrations in both lakes (Fig. 3d, 3h) exhibited a tendency to increase gradually, presenting some peaks as in Lake Biwa (in 2000) and in Lake Kasumigaura (in 1990, 1995 and 2002).

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Statistical model

The results of the evaluation of univariate and multivariate linear regressions using AIC indicated that the model including all OAS concentrations as independent variables predicted SD^{-1} better than the others: AIC are -1812 and -9067 for Lake Biwa and Lake Kasumigaura, respectively.

Coefficients of the regression models were highly significant (p<0.0001) except for the DOC coefficient for Lake Kasumigaura (p-value=0.196). In addition, the model performance yielded better results for Lake Biwa (R^2=0.70, RMSE=0.05 m^{-1}) than for Lake Kasumigaura (R^2=0.62, RMSE=0.39 m^{-1}). A comparison between predicted and measured SD^{-1} for long-term datasets indicated a rather large scatter of the results (Fig. 4). The scatter plot of SD^{-1} prediction for Lake Biwa showed generally a straight line with a moderate amount of scatter (Fig. 4a). On the other hand, the plot for Lake Kasumigaura showed a relatively larger scatter, and the predicted SD^{-1} values at low observed SD^{-1} were much more closely to the fitted line than those at high observed SD^{-1} (Fig. 4b).

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Mechanistic model

The coefficients of determination (R^2) for the additional measurements in Lake Biwa (R^2=0.87 for Nov 9-10, 2009; R^2=0.98 for Feb 2-3, 2010) were higher than the ones obtained in Lake Kasumigaura (R^2=0.79 for Sep 1, 2009; R^2=0.84 for Dec 15, 2009). The results for the additional measurements were expected to be the optimal performance that could be achieved by this approach, because these datasets included measured SIOPs at each station.

The mechanistic model for long-term monitoring data showed higher performance for Lake Kasumigaura (R^2=0.56 and RMSE=0.50 m^{-1} using the SIOPs of Sep 1, 2009; R^2=0.59 and RMSE=0.48 m^{-1} using the SIOPs of Dec 15, 2009) than for Lake Biwa (R^2=0.50 and RMSE=0.08 m^{-1} using the SIOPs of Nov 9-10, 2009, and R^2=0.54, RMSE=0.07 m^{-1} using the SIOPs of Feb 2-3, 2010). From these results applying the mechanistic model, only the best performance results in each lake (obtained using the SIOPs of Feb 2-3, 2010 and Dec 15, 2009 for Lakes Biwa and Kasumigaura, respectively) were considered for further analysis of the long-term predicted SD.

The scatter plot of SD^{-1} prediction for Lake Biwa long-term dataset was generally straight, and the points lay fairly close to the 1:1 line (Fig. 5a). The scatter plot for Lake Kasumigaura long-term dataset using the mechanistic model showed a similar shape to the one using the statistical model, evidencing more crowded in the lower part of the plot than in the upper (Fig. 5b).

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The analysis of long-term datasets gave very similar Γ values, namely 9.8 for Lake Biwa and 10.1 for Lake Kasumigaura. In the case of the additional measurements, they differed between lakes, yielding (6.2-6.9) for Lake Biwa and (9.1-9.5) for Lake Kasumigaura. All Γ values are within the neighborhood of reasonable estimate values (Γ:6-10) given by Preisendorfer (1986).

In Lake Biwa, the coefficients related to the water component were similar. The values were 0.040 m^{-1} and 0.055 m^{-1} for the statistical and mechanistic model respectively. As the water component is a constant value, the agreement of this coefficient between the two models is very important to give confidence to the applicability of the statistical models. Otherwise, a correction of the statistically obtained water coefficient is needed. This correction consists of the process of performing correlation analysis between SD^{-1} (excluding the water component) and other OAS concentrations. For instance, this correction was needed to be applied to the Lake Kasumigaura long-term dataset, where the value 0.055 m^{-1} obtained from the mechanistic model was used as a constant (Table 5). The coefficients of the statistical model for Lake Kasumigaura including the above-mentioned correction included showed that all regression model coefficients corresponding to the respective OAS concentrations were highly significant (p<0.0001).

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The quantification of OAS contributions to SD^{-1} for the two lakes and the two models showed NPSS as the most influential factor responsible for SD^{-1} changes (Fig. 6). In Lake Biwa, NPSS accounted for the 34% and 35% of SD^{-1} by using the statistical and mechanistic model, respectively. In Lake Kasumigaura, NPSS contribution was higher than in Lake Biwa, accounting for the 43% and 75% of SD^{-1} with the statistical and mechanistic model, respectively. The correction of the water contribution by using the statistical model for Lake Kasumigaura was included in this figure.

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The ANOVA results in Table 6 showed a significant change in SD^{-1} prediction performance (p<0.05) using the mechanistic model for all temporal and spatial effects (Year, month and station). Results obtained for the single factors highlighted the main influence of the month and year factors compared to the station factor in both lakes, revealing the *monthly* effect as the strongest effects: Lake Biwa (F=95.09), and Lake Kasumigaura (F=69.49). The variation in the ratios of measured vs. predicted SD^{-1} estimated over years, months and stations using the mechanistic model are shown in Fig. 7. In addition, despite the less influential *spatial* effect in both lakes, certain patterns for stations A, B and C of Lake Biwa were noticed (Fig. 7c), where the prediction ratios of all C-stations were closer to unity in comparison to other stations.

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Using the spatially, yearly and monthly grouping of long-term datasets of the two lakes, statistical models were developed. Their coefficients of determination R^2 are shown in Fig. 8. All models were found to be highly significant (p<0.0001). In case of spatial grouping for Lake Biwa, we grouped stations A, B and C based on the ANOVA results showed in Fig. 7c. For Lake Biwa, the yearly arrangement mostly improved the statistical model performances, and the best results were obtained in the year 2003 (R^2=0.82, RMSE=0.04 m^{-1}). For Lake Kasumigaura, the monthly grouping was the one which improved the statistical model performances, and the model of January yielded the best results (R^2=0.84, RMSE=0.25 m^{-1}). Although the spatial grouping of datasets showed the lowest improvement in the statistical model performances of the two lakes (Fig. 8c), a very clear improvement due to the grouping of certain stations was obtained. This involved grouping the eastern shore stations (C-stations) for Lake Biwa, and grouping the stations located in the center of Lake Kasumigaura (stations 7, 8 and 9). In general, this kind of grouping analysis may therefore prove to be helpful for the planning of future monitoring and datasets arrangement e.g. identifying the best approach to obtain and arrange data for the application of SD models across defined transects (yearly/ monthly/station).

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Discussion

Performance of the models

In both lakes, the models built with long-term measurements could explain more than 62% of the observed SD^{-1} variations using the statistical model and more than 50% using the mechanistic one. The RMSE values for the statistical model were lower than the ones for the mechanistic model. The RMSE values together with the R^2 values indicate the stronger predictive ability of the statistical model over the mechanistic one. By examining the scatter plots of the prediction applying the two models to the Lake Kasumigaura long-term dataset (Fig. 4b and Fig. 5b), we found that for low observed SD^{-1}, the predicted values were much more closely to the fitted line than those at high observed values. As a way of predicting SD^{-1} in Lake Kasumigaura, it appears that both models might work quite well for low SD^{-1}, but not efficient for high values.

Compared to previous studies, our statistical model gave better predictions than those by Effler et al. (2008), which correlated SD vs Chl-a of 40 years data in Lake Onondaga, obtaining a performance of R^2=0.43. Our mechanistic model was also found to give slightly better performance than previous studies. For example, using an additive semi-analytical model, Swift et al. (2006) obtained R^2=0.49 for data of 4 years in Lake Tahoe. The loss of accuracy (2-20%) encountered in the results of both lakes for the additional measurements using the mechanistic model may be attributable to measurement errors caused by imperfect weather conditions, unstable illumination during measurements, instrument calibration problems, measurements errors in OAS concentrations, etc. Moreover, the mechanistic model for long-term monitoring datasets did not yield performance comparable to that for the additional measurement datasets, where the decreases in performance of about 30% for long-term monitoring datasets could be attributed to the seasonal change in OAS vertical profiles, the change in SIOPs, etc. In addition, testing of the mechanistic model using SIOPs values at the additional measurements has shown that the model works well when SIOPs values from all sampling stations were averaged to one value, with a small loss of accuracy of 3% (R^2=0.95 for Feb. 2-3, 2010) and 1 % (R^2=0.83 for Dec. 15, 2009) for Lake Biwa and Lake Kasumigaura, respectively.

With regard to the applicability of the two models, both were found to be very useful for estimating the OAS contributions on the light field. The mechanistic model can explain better the respective optical factors determining the light field, but the statistical model has merits in regard to simplifying in model development, which is the main reason for its wide use. It was also found that the grouping of data improved statistical performance of the models although caution should be taken when using statistical models for analysis of OAS contributions to SD because the coefficient related to water may need to be corrected as in Lake Kasumigaura. The large number obtained for the water coefficient in Lake Kasumigaura (represented as the intercept in the statistical model) may be attributable to the large values of SD^{-1} in this lake. A comparison of the water coefficients between the two models could be used as a validation step for the statistical model. In this respect, we suggest the combination of the two models in order to get the most reliable results for SD prediction and OAS contributions to SD. The water coefficient in Lake Biwa (0.040 m^{-1} and 0.055 m^{-1} for the statistical and mechanistic model respectively) are also comparable to those obtained using statistical models by Obrador and Petrus (2008) and Armengol et al. (2003), which were 0.040 m^{-1} and 0.034 m^{-1} respectively. Furthermore, the model coefficients obtained statistically by Peng and Effler (2005) for the Finger Lakes in New York (Chl-a coefficient: 0.014 and Tr coefficient: 0.04) had a good agreement with the following statistical model coefficients in Table 5: Chl-a coefficient for Lake Biwa (0.0137) and the Tr coefficient for Lake Kasumigaura (0.04).

A simple statistical SD model (considering all OAS concentrations) could be the one including TSS instead of NPSS as one of its independent variables, which some previous papers have proposed (e.g. Armengol et al. 2003; Zhang et al. 2006; Devlin et al. 2008). However a comparison of the performance of the model using TSS instead of NPSS with our model applied to the long term-period showed that the model including TSS presented a loss of accuracy of 5% (R^2=0.65) and 34% (R^2=0.28) for Lake Biwa and Lake Kasumigaura, respectively. These results reflect the importance of the separation of NPSS from TSS, especially for Lake Kasumigaura. In the past, the estimation of NPSS concentrations has been limited by analytical shortcomings and quite complicated procedures. For example, Swift et al. (2006) evaluated a limited number of samples (30 samples) using individual particle analysis technique of scanning electron microscope interfaced with X-ray image analysis to produce a seasonally-varying estimate of the suspended inorganic particles. Effler et al. (2008) applied the same technique but only to 6 samples. In this regard, the way we estimate NPSS concentrations using the phytoplanktonic portion in TSS (δ) obtained from a long-term analysis has the advantage of being simple and rather accurate. Given the importance of NPSS estimation, we tested the model performance applying a single δ value (yearly average), and results showed a loss of accuracy of about 6 % in both lakes, indicating the importance of monthly change in δ values on SD prediction.

OAS contributions to SD

NPSS has been identified to be the most influential component that governs the light environment in the two lakes. Our result coincides with Swift et al. (2006), in which a semi-analytical model was developed to predict SD in very clear waters (SD in the range of 15-40 m); they also concluded that the suspended inorganic particles dominated the light environment for most of the year. In addition, Effler et al. (2008) showed that the suspended inorganic particles played a critical role in influencing important features of the lake's optical regime. It is worth noting that Lake Biwa and Lake Kasumigaura differed in the second most important contributor to SD. At Biwa it was DOC while in Kasumigaura it was Chl-a.

The high values of NPSS in Lake Biwa were probably caused by input of terrigenous particles through river water, which was due to snow melting in spring, rainfall in early summer, and typhoons in autumn (Nagai et al. 2001). In addition, re-suspension of sediments was the source of NPSS in winter due to internal waves caused by winds (Murase et al. 2005). In Lake Biwa DOC co-varied with SD^{-1} (Fig. 3d). This correlation suggests the importance of this substance on controlling water clarity.

Despite the eutrophic nutrient status of Lake Kasumigaura, the high concentration of NPSS seemed to restrict the light availability (Fig. 3e). Therefore, PSS in Lake Kasumigaura was inversely related to NPSS from 1997 to 2007 ($PSS=-0.4655 \cdot NPSS + 21.71$, $p<0.0001$). The higher NPSS and lower PSS result principally from strong re-suspension of bottom sediment possibly attributed to water turbulence. Regarding DOC in Lake Kasumigaura, the unclear influence reflected in its annual trend (Fig. 3h) confirmed the low contribution on SD obtained by the mechanistic model.

Limitations of the mechanistic approach

It is a difficult task to measure SIOPs, and at present this difficulty is considered to be an important shortcoming for developing the mechanistic model. From the ANOVA results, it was possible to get some idea about how SIOPs may have changed spatially and temporally, so we might expect the *seasonal* variability in SIOPs to be the most important cause for the loss of accuracy in modeling, and conversely the *spatial* effect to be the less influential. Hence further study of the long-term variability of optical properties should be included in the ongoing research effort to estimate SIOPs in inland waters (e.g. Campbell et al. 2010; Ambarwulan et al. 2010). On the other hand, the loss of accuracy in modeling SD was higher in summer months, specifically in August-September in Lake Biwa (Fig. 7b) and July-August in Lake Kasumigaura (Fig. 7e), which may be the result of increasing Chl-a and NPSS concentrations. In Lake Kasumigaura, additional scatter was found in spring months, specifically in April and June (Fig. 7e), which could be explained by blooming of diatoms (e.g. *Cyclotella*). These two analyses suggest the possibility of considering both temporal SIOPs characteristics and seasonal change in OAS concentrations in the long-term SD prediction models.

To test the assumption of vertically uniform OAS concentrations, we tried using the measurements of diffuse attenuation coefficient K_d in both lakes at the additional measurement campaigns. K_d values were determined from radiometric measurements (irradiances) located above the surface and at various depths using a Satlantic hyperspectral radiometer with a StorX data logger system. These limited data of the vertical changes gave us an idea on what may occur vertically. For example, 25 stations in Lake Kasumigaura presented a small vertical change that could be easily ignored (K_d=2.8±0.42); but for 3 stations in Lake Biwa, the vertical change appeared important to be considered (K_d=0.27±0.12). This analysis revealed that the OAS concentrations estimated from surface water samples in Lake Biwa were underestimated. These underestimated OAS concentrations could be counted as uncertainties for the model inputs that would lead to an overestimation of SD values, and hence affect further analysis of each OAS influence on SD. At present, the limited data are insufficient to draw conclusions regarding how greatly the vertical profiles of OASs influence the SD prediction in Lake Biwa, but these shortcomings in measurements could be overcome through future monitoring that considers the vertical profiles in time and space.

Management implications for increasing SD

Management actions derived from this study focus on NPSS reduction to result in substantial increases in SD. For instance, water purification by means of vegetation (aquatic macrophytes) may reduce sediment re-suspension significantly (Vermaat et al. 2000). Thus through their effects on re-suspension, macrophytes should also affect the release of phosphorus from the sediment (Horppila and Nurminen 2003), regulating phytoplankton biomass. In order to reduce pollutant loadings from their catchment areas, inflow from watersheds should be managed. For example, pre-sedimentation ponds attached to the lake (NAIKO) are believed to retain allochthonous suspended inorganic particles, lowering the amount of their entry to the lake (Nakamura et al. 2000).

Conclusions

Two types of predictive models relating SD with OASs were compared in this study and they did capture SD variability quite well. In addition, the two models provided valuable information of how the water components affected water transparency. By developing the mechanistic model, each OAS contribution on SD can be understood and investigated in greater detail than would be possible with the statistical model. The mechanistic model provided insights into the control of factors that influence decisions regarding where and how the reduction of OASs should be allocated for maximal effect.

We have found that NPSS is the most important OAS in controlling the light penetration in Lakes Biwa and Kasumigaura. For instance, the extent of light penetration would be negligibly influenced by reduction of nutrients in the two lakes, where reduction of NPSS may be a more appropriate management strategy to achieve increases on SD. Additionally, this study supports other studies about the importance of suspended inorganic particles as the main contributors on SD in inland waters suggesting that further studies would be worthwhile to characterize the different sources of the suspended inorganic particles and to account for the different mechanisms occurring within the water such as mixing events, wave action, re-distribution of sediments, and so on.

There is still room for improvement of mechanistic models, which at present are not generally applied in practice because of optical measurement constraints and complexity. In addition, between temporal and spatial characteristics on SIOPs, we conclude that temporal characteristics on SIOPs will be needed in order to optimize the mechanistic model. On the other hand, when the statistical approach is used, we strongly recommend enhancing its performance by arranging the datasets into groups and for its application the coefficient related to water should be confirmed to be reasonable. A validation step and a correction process related to the water coefficient were suggested for the statistical model. Finally, with regard to the applicability of the models, we have concluded that the combination of the two models could lead to the most reliable results available at present to predict SD and the various contributions of OASs to SD.

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Table legends

Table 1 Characteristics of investigated lakes ([a]Urabe et al. 1999; [b]Havens et al. 2001; [c]Kagami et al. 2006; [d]Goto et al. 2008; [e]Oyama et al. 2009)

Table 2 Monitored data and their measurement methods

Table 3 $a^{+}(440)$ and e' for the additional measurements

Table 4 SIOPs fitting equations

Table 5 Model coefficients related to the respective OAS concentrations and values of evaluation indices for the long-term monitoring data using the statistical approach in the two lakes. The coefficients include 95% confidence intervals [in brackets] and *p*-values ([NS]: non- significant, *p<0.01, **p<0.0001).

Table 6 ANOVA results for yearly, monthly and station effects on the mechanistic estimation of SD^{-1}. *p*-values (**p<0.0001)

Table 1 Characteristics of investigated lakes ([a]Urabe et al. 1999; [b]Havens et al. 2001; [c]Kagami et al. 2006; [d]Goto et al. 2008; [e]Oyama et al. 2009)

Characteristics	Unit	Lake Biwa northern basin			Lake Kasumigaura		
Description		mesotrophic, monomictic [a]			eutrophic, polymictic[e]		
Dominating phytoplankton species		Spring: diatoms[d] Summer: green algae , blue-green algae[c] Autumn: green algae, blue-green algae[c] Winter: diatoms[d]			Spring: diatoms[e] Summer: blue-green algae[e] Autumn: diatoms[e] Winter: diatoms[e]		
Surface area	km^2	616 [a]			171[e]		
Mean depth	m	45.5 [a]			4.0[e]		
Mean total nitrate	μgl^{-1}	300[c]			1095[b]		
Mean total phosphorous	μgl^{-1}	1[c]			75[b]		
Residence time	year	5 [a]			0.6[e]		
		Mean	Min	Max	Mean	Min	Max
SD	m	5.73	0.9	13.2	0.64	0.15	3.8
Chl-a concentration	μgl^{-1}	3.5	0.2	69	63.9	1	352
TSS concentration	mgl^{-1}	1.5	0.6	42	23.5	1.4	118.3
DOC concentration	mgl^{-1}	1.26	0.8	2.1	3.17	1.2	7.7

Table 2 Monitored data and their measurement methods

Measurement			Lake Biwa northern basin	Lake Kasumigaura
Long-term	Database		Lake Biwa Environmental Research Institute (LBERI)	National Institute for Environmental Studies (NIES)
	Homepage		http://www.lberi.jp	http://db.cger.nies.go.jp/gem/inter/GEMS/database/kasumi/index.html
	Period		Apr 1998-Mar 2008	Apr 1988-Mar 2007
	Temporal resolution		monthly	Monthly
	Number of points		28 stations	10 stations
	Measurement Method	Chl-a	ethanol (5ml) extraction (4°C 10 h) and analyzed spectrophotometrically by Nusch (1980)	methanol (10ml) extraction (3°C 12 h) , centrifugated (3000 rpm 10 min) and analyzed spectrophotometrically by SCOR-UNESCO (1966)
		TSS	pre-combusted GF/F filters	pre-combusted (450°C 4 h) Whatman GF/F filters
		DOC	High-temperature combustion method	High temperature combustion method
Additional	Laboratory		University of Tsukuba	
	Date		Nov 9-10, 2009; Feb 2-3, 2010	Sep 1, 2009; Dec 15, 2009
	Spatial resolution		11stations (10B, 11B, 12B, 13A , 13C, 15B, 16B, 17A, 17B and 17C' in Fig.1)	25 stations (8 points in Takahamairi, 8 points in Tsuchiurairi and 9 points in the central basin)
	Measurement Method	Chl-a	measured by methanol (100%) extraction method (4°C 24 h), centrifugated (3000 rpm 5min) and analyzed spectrophotometrically by SCOR-UNESCO (1966)	
		TSS	measured gravimetrically with Whatman GF/F filters after drying (110°C 2h)	
		DOC	measured by high-temperature combustion method with Shimadzu TOC-V CSH	

Table 3 $a^{+}(440)$ and e' for the additional measurements

Lake	[DOC] (mg l^{-1})	$a^{+}(440)$ (lmg^{-1} m^{-1})	e' (m^{-1})
Biwa	1.3 - 1.7	0.08 - 0.18	0.01 - 0.19
Kasumigaura	3.7 - 5.4	0.22 - 0.55	0.05 - 0.87

Table 4 SIOPs fitting equations

Equation	Reference	Fitting factor	Lake Biwa		Lake Kasumigaura	
			Nov 9-10, 2009	Feb 2-3, 2010	Sep 1, 2009	Dec 15, 2009
$\mathbf{a^*_{CDOM}(\lambda) = \exp[-S_{CDOM}(\lambda - 440)]}$	Gege (2004)	S_{CDOM}	0.007	0.008	0.008	0.009
$\mathbf{a^*_{NPSS}(\lambda) = a^*_{NPSS}(440) \cdot \exp[-S_{NPSS}(\lambda - 440)]}$	Giardino et al. (2007)	S_{NPSS}	0.004	0.002	0.006	0.007
		$a^*_{NPSS}(440)$	0.264	0.164	0.129	0.286
$\mathbf{b^*_{NPSS}(\lambda) = b^*_{NPSS}(660) \cdot \left[\frac{\lambda}{660}\right]^{-n}}$	Reinart et al. (2004)	$b^*_{NPSS}(660)$	0.546	0.661	0.419	0.393
		n	0.711	0.538	0.864	0.704

S: Slope parameter of absorption curve

Table 5 Model coefficients related to the respective OAS concentrations and values of evaluation indices for the long-term monitoring data using the statistical approach in the two lakes. The coefficients include 95% confidence intervals [in brackets] and *p*-values ([NS]: non- significant, *p<0.01, **p<0.0001).

Lake	**Chl-a coeff. (ug^{-1}lm^{-1})**	**NPSS coeff. (mg^{-1}lm^{-1})**	**DOC coeff. (mg^{-1}lm^{-1})**	**Water (m^{-1})**	R^2	**RMSE (m^{-1})**
Biwa (*N*= 3696)	0.0137** [0.013, 0.015]	0.100** [0.097, 0.102]	0.031** [0.022, 0.039]	0.040** [0.026, 0.047]	0.70	0.05
Kasumigaura (*N*= 2280)	0.0080** [0.0074, 0.0087]	0.040** [0.038, 0.042]	0.010[NS] [-0.01, 0.03]	0.680* [0.59, 0.75]	0.62	0.39
	0.0086**	0.043**	0.170**	0.055	0.60	0.41

N: number of measurements; underlined values correspond to the ones after correction of the water coefficient (see the text).

Table 6 ANOVA results for yearly, monthly and station effects on the mechanistic estimation of SD^{-1}. *p*-values (***p*<0.0001)

	Lake Biwa					Lake Kasumigaura				
	SS	***df***	***MS***	***F***	***p-value***	***SS***	***df***	***MS***	***F***	***p*-value**
Year	24.64	10	2.46	72.07	**	19.54	18	1.09	52.22	**
Month	35.76	11	3.25	95.09	**	15.89	11	1.44	69.49	**
Station	53.23	26	2.05	59.88	**	6.95	9	0.77	37.14	**
Year * Month	51.85	110	0.47	13.79	**	44.21	198	0.22	10.74	**
Year * Station	14.73	260	0.06	1.66	**	5.36	162	0.03	1.59	**
Month * Station	17.95	286	0.06	1.84	**	4.90	99	0.05	2.38	**
Error	97.78	2860	0.03			37.05	1782	0.02		
Total	295.94	3563				133.90	2279			

SS: Sum of squares; *df*: Degrees of freedom; *MS*: Mean of squares; and *F*: Test statistic value

Figure legends

Fig. 1 Locations of two lakes and long-term sampling stations (closed circles).

Fig. 2 Phytoplanktonic SIOPs in Lakes Biwa and Kasumigaura: (a) specific absorption coeff. a*ph (λ); and (b) specific scattering coeff. b*ph (λ).

Fig. 3 Time series of annual conditions of SD and OAS concentrations in Lake Biwa (a,b,c,d) and Lake Kasumigaura (e,f,g,h). Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show minimum and maximum values, and open circles indicate mean values.

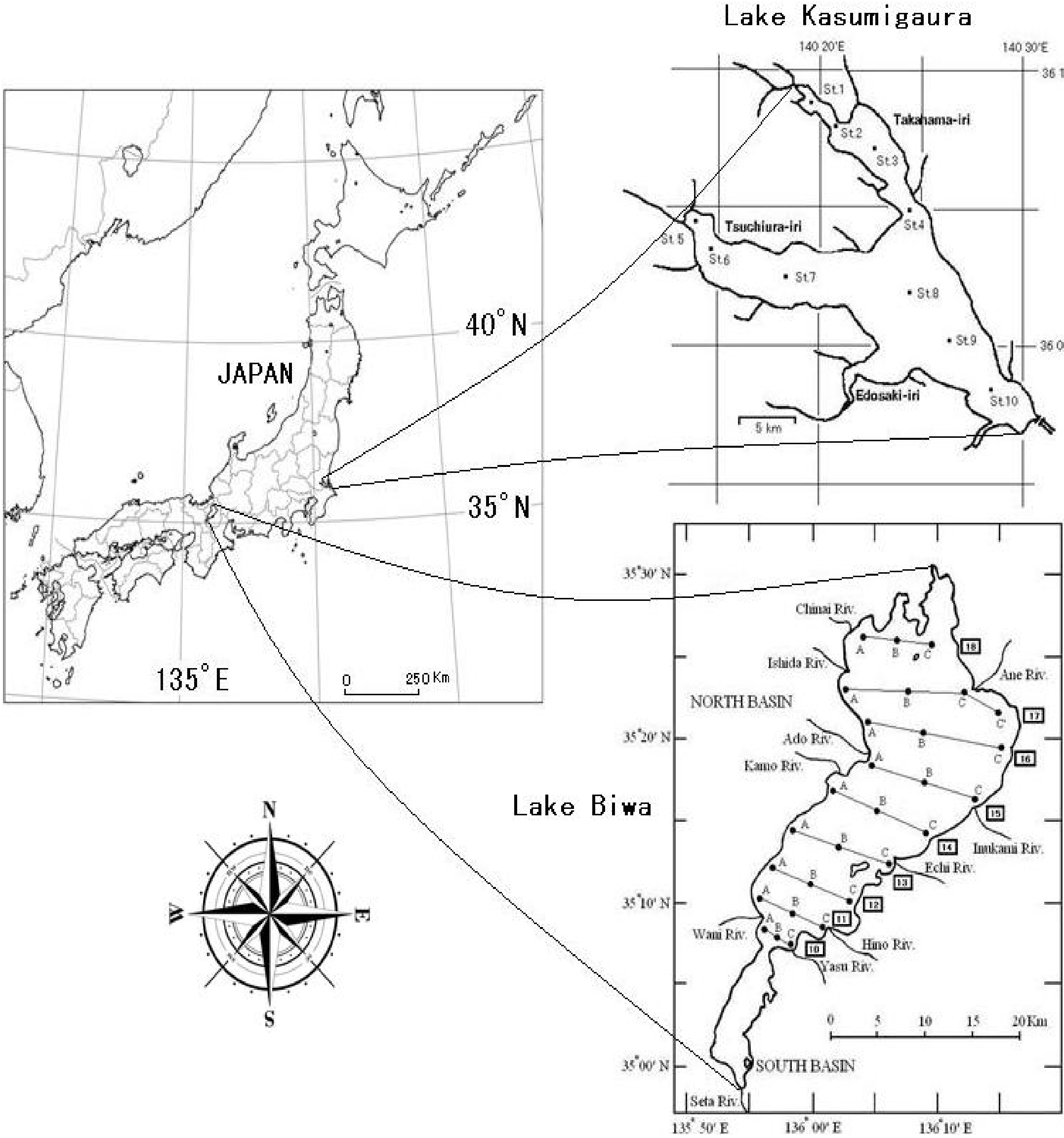
Fig. 4 Statistical model performance (measured vs. predicted reciprocal of SD) for the long-term dataset. Solid lines represent linear regression curves and dotted line denotes 1:1 prediction line.

Fig. 5 Mechanistic model performance (measured vs. predicted reciprocal of SD) for long-term dataset. Solid lines represent linear regression curves and dotted line denotes 1:1 prediction line.

Fig. 6 OAS contributions on SD^{-1} values (a) Lake Biwa and (b) Lake Kasumigaura

Fig. 7 Mean (±Standard deviation) of the ratios of measured vs. predicted SD^{-1} estimated over years, months and stations using the mechanistic model for Lake Biwa (a,b,c) and Lake Kasumigaura (d,e,f), respectively.

Fig. 8 Coefficient of determination R^2 of statistical models using temporal and spatial grouping of long-term datasets. The open circles correspond to Lake Biwa, and the closed circles to Lake Kasumigaura. The dashed and solid lines are the R^2 values using whole datasets of Lakes Biwa and Kasumigaura, respectively.



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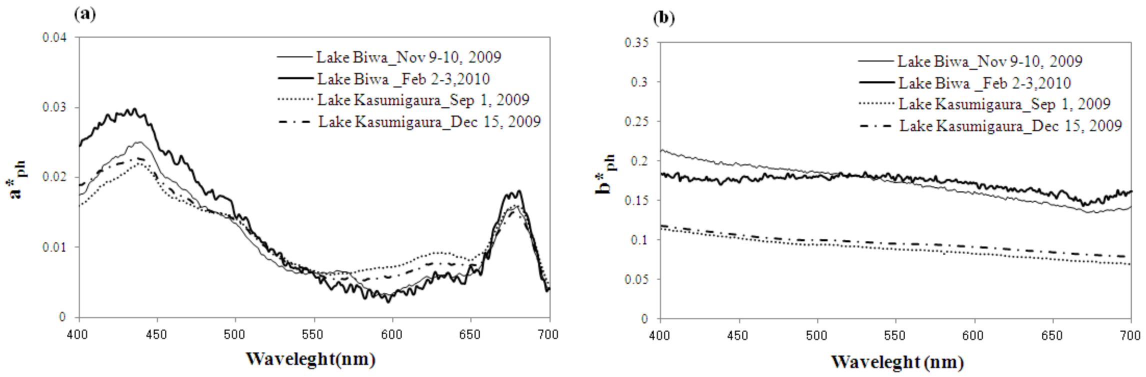

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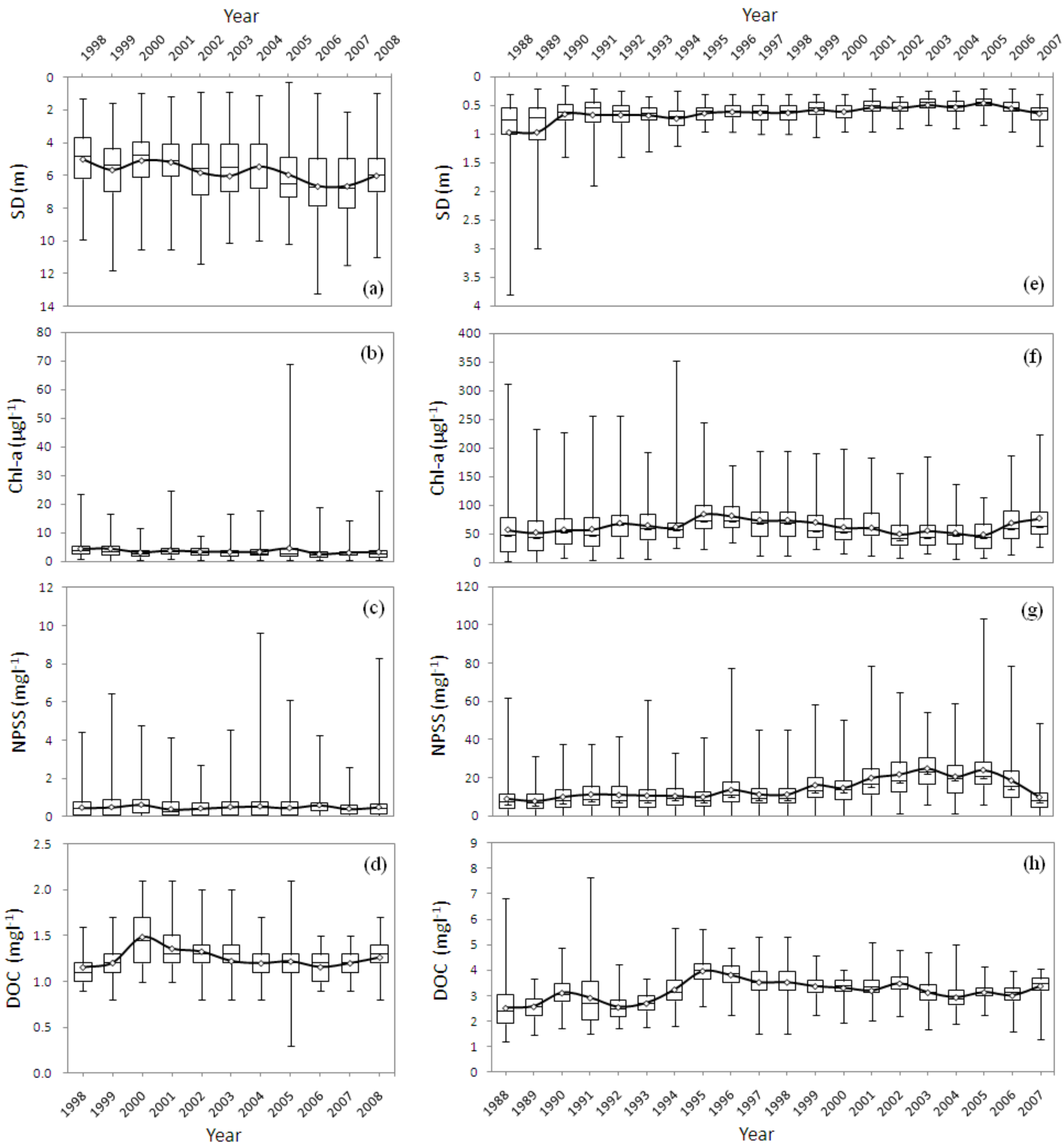

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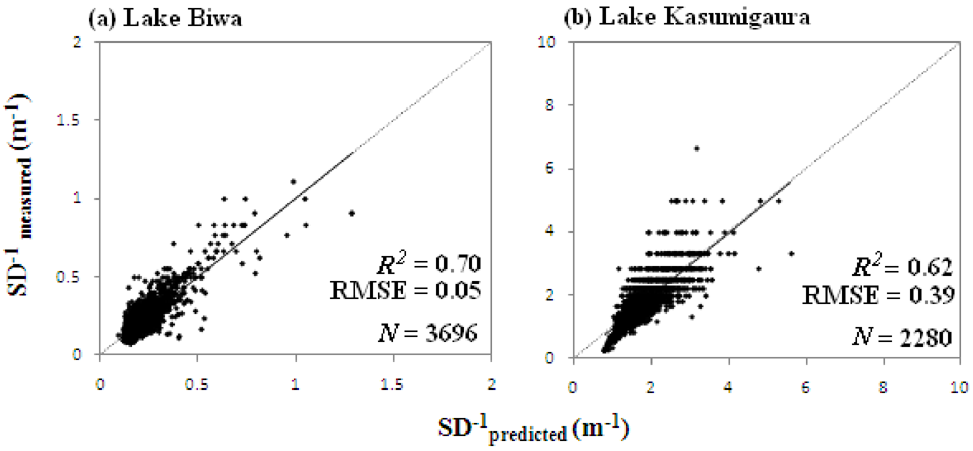


Fig. 4 Statistical model performance (measured vs. predicted reciprocal of SD) for the long-term dataset. Solid lines represent linear regression curves and dotted line denotes 1:1 prediction line.

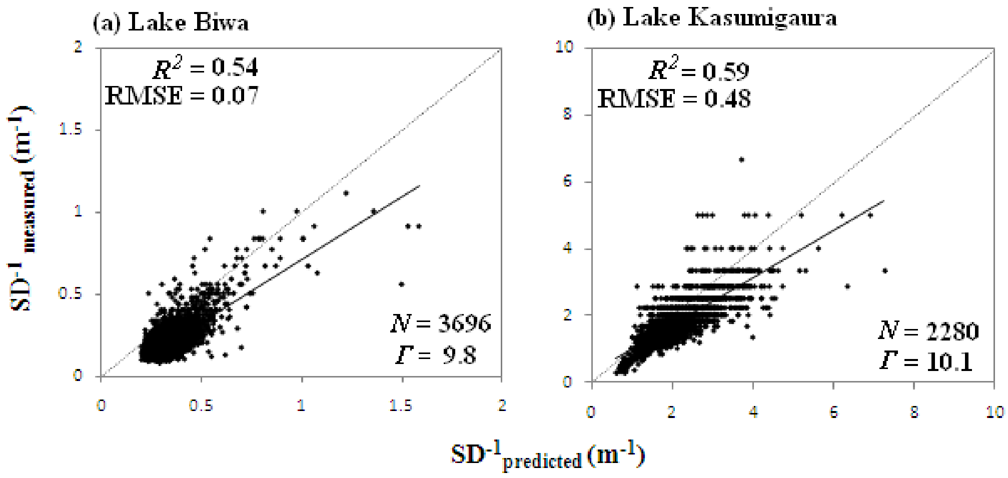
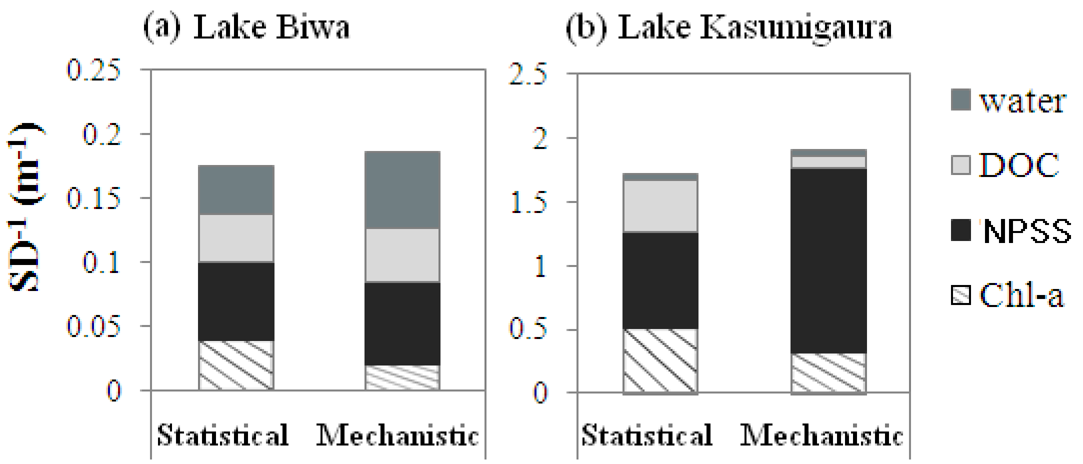


Fig. 5 Mechanistic model performance (measured vs. predicted reciprocal of SD) for long-term dataset. Solid lines represent linear regression curves and dotted line denotes 1:1 prediction line.



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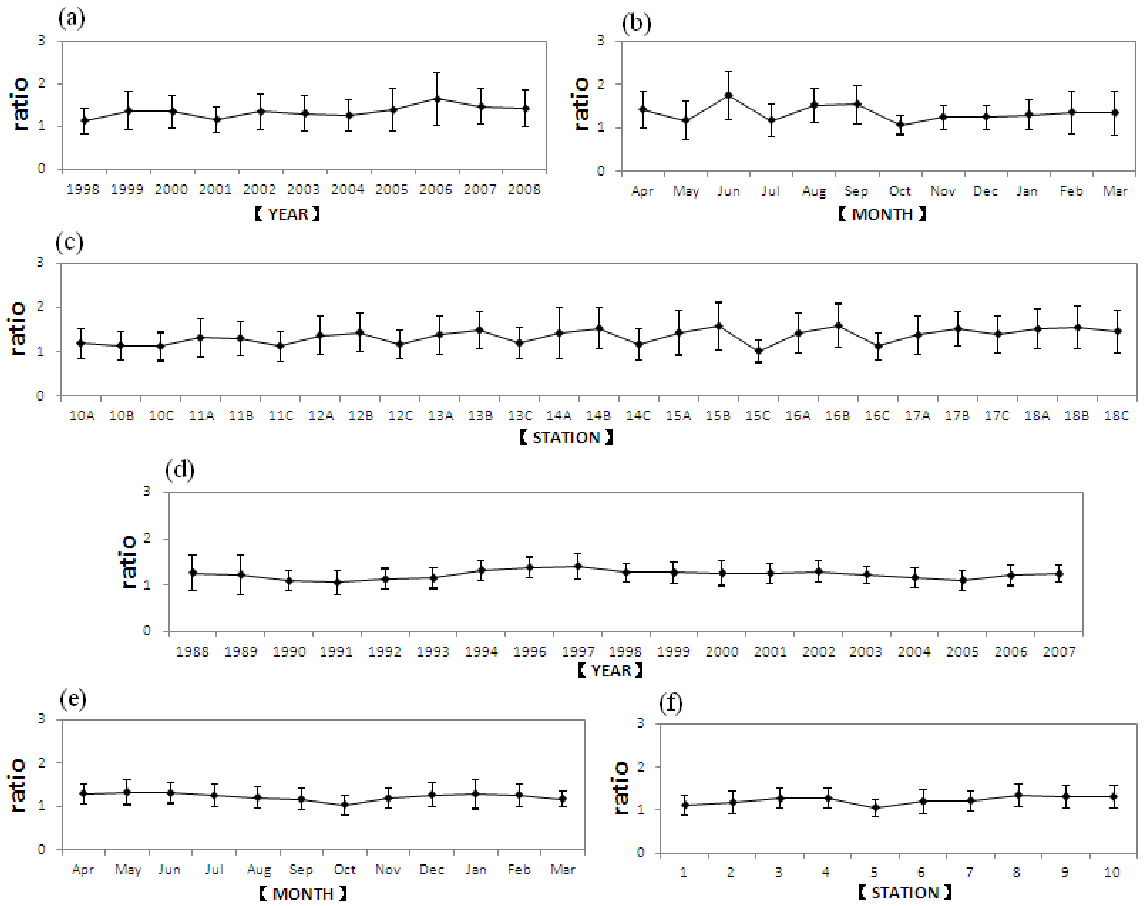

Fig. 7 Mean (±Standard deviation) of the ratios of measured vs. predicted SD^{-1} estimated over years, months and stations using the mechanistic model for Lake Biwa (a,b,c) and Lake Kasumigaura (d,e,f), respectively.

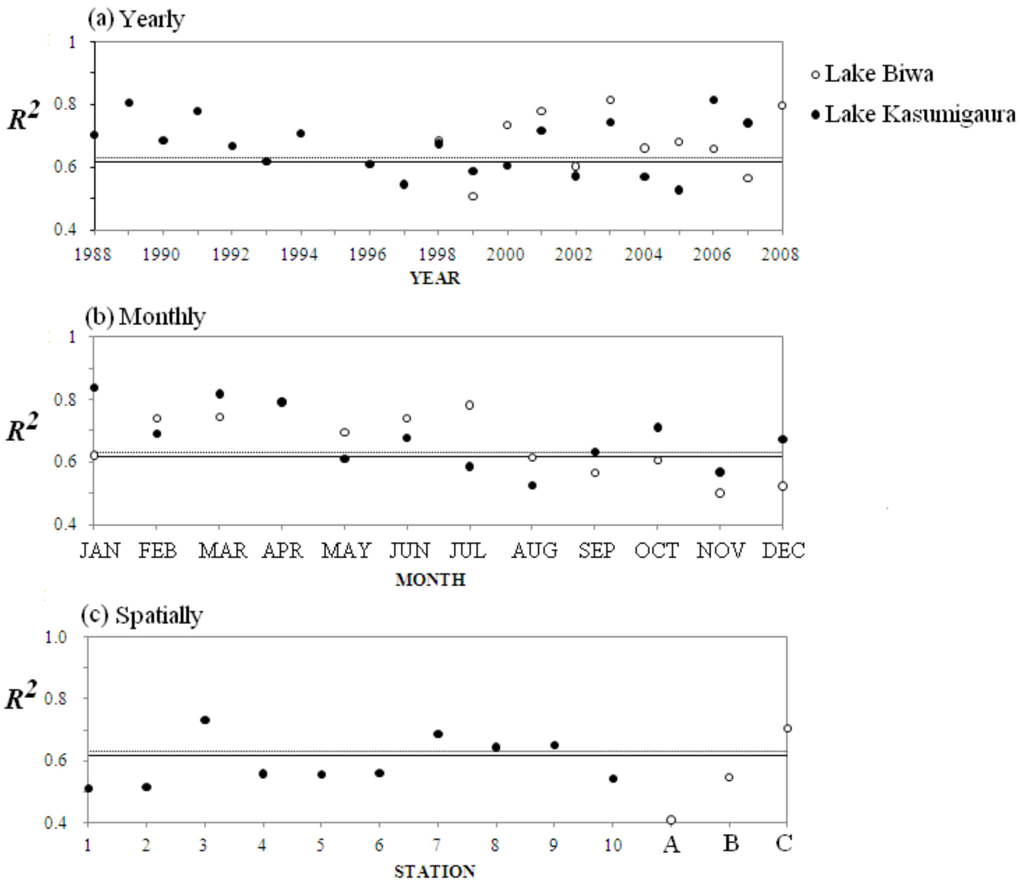

Fig. 8 Coefficient of determination R^2 of statistical models using temporal and spatial grouping of long-term datasets. The open circles correspond to Lake Biwa, and the closed circles to Lake Kasumigaura. The dashed and solid lines are the R^2 values using whole datasets of Lakes Biwa and Kasumigaura, respectively.