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Water Quality Modeling in the Nam Pong River, Northeast Thailand

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ABSTRACT: Poor water quality which caused massive fish kills in the Nam Pong River in 1999 was associated with low dissolved oxygen (DO). A dynamic water quality model was thus constructed using data collected for 2 years from 1999-2000 to predict whether there was an algal bloom which subsequently died off and caused low DO and fish kills on the same day in 1999. Flow and runoff were calibrated by using lignin and tannin (LT) as a conservative trace. Root mean square error (RMSE) of the flow calibration with LT was comparable with literature values, using salinity as a conservative trace. Results of correlation coefficients (R^2) from the runoff calibration were reasonable (0.64-0.75 for 1999 and 0.62-0.88 for 2000). RMSE values from the model calibration and validation of conventional nutrients were found to be comparable to literature values for steady-state models. The predictive capability for chlorophyll *a* showed that, with the flow calibrated from LT, the bloom was not overestimated. The model predicted the bloom die-off which lowered DO and possibly caused fish kills on the same day in 1999, and suggested that the accuracy of the dynamic model was on a time scale of days, not seasons like most steady-state models.

KEYWORDS: water quality; lignin and tannin; Nam Pong River

INTRODUCTION

The Nam Pong River in the Northeast of Thailand has been polluted from multiple sources, ranging from agricultural runoff to remnants of past untreated effluent's spill for more than a decade. As a result, this river has experienced sporadic fish kills, particularly in the summer. For example, on May 21st, 1993 a large number of dead fish, shellfish and other aquatic fauna were seen floating along this river, as dissolved oxygen (DO) reportedly dropped to 3.1 μmol/L[1]. Another major incident occurred in 1997 when over 500,000 fish in net-pen aquaculture died[2]. Thus, this study using both water quality monitoring and modeling, was initiated to investigate the cause of poor water quality which killed the fish.

In this paper, a dynamic water quality model was developed by using lignin and tannin (LT) as a conservative trace, for estimating the unavailable runoff data and calibrating the flow. LT was proposed as the conservative trace because they are known to be the signature of vascular plants on land[3,4], and their debris makes LT present in the agricultural runoff[5,6,7]. Moreover, LT have long half-lives, from a few days[8] to several months[9,10], owing to their stable aromatic structures.

This paper also demonstrates the use of dynamic modeling to predict the algal bloom on a time scale of days, unlike most steady-state modeling which predicted blooms on a time scale of seasons[11,12]. The results of correlation coefficients (R^2) and root mean square error (RMSE) for the model calibration and validation, which were not as widely available as those of the steady-state models, are reported.

Site Description and Problems

The river reach between the Ubolratana Dam and the Nong Wai Weir (Figure 1a) under this study is in the Nam Pong Watershed, which is a food production base in Southeast Asia, according to the U.N. Food Task Force of the Trilateral Commission[13]. The Nam Pong Watershed is the largest basin in the Northeast of Thailand which provides an important water resource for agriculture, electricity generation, aquaculture, domestic uses, industrial and recreational purposes.

The Ubolratana Dam was constructed in 1964 to generate electricity and prevent flooding of the agricultural land in the Lower Nam Pong Watershed. The Nong Wai Weir was constructed approximately 34 kilometers below the Dam to supply large volumes of water for over 48,000 hectares of agricultural land to expand food production. In 1999 and 2000, within the river reach under study, there were three aquaculture sites, namely Chot (CT), Sua Ten (ST), and Kum Pae/Bua Noi (KP/BN).

Model Establishment

The water quality model was developed from the data monitored between 1999-2000. During these two years, the water samples from 0.5-m depth at locations shown in Figure 1a were collected on a weekly basis. Each sampling trip of approximately 34 kilometers was completed within 6 hours. 5-day biochemical oxygen demand (BOD_5), DO, total Kjedalh nitrogen (TKN), NH_3-N, and NO_3-N were analyzed according to the Standard Methods[14], using the methods of Nessler distillation (NH_3-N), and cadmium reduction (NO_3-N). LT concentrations were determined with the Folin phenol reagent (tungstophosphoric and molybdophosphoric acids) according to the Standard Methods, Method 5550. Water/air temperatures, pH and electrical conductivities were measured *in situ* at every sampling site, using portable meters. Visual descriptions of the sampled water and the number of fish kills from aquaculturalists were recorded.

The Water Quality Simulation Program (WASP) version 6.1 developed by the Environmental Protection Agency of the United States (USEPA) was chosen for

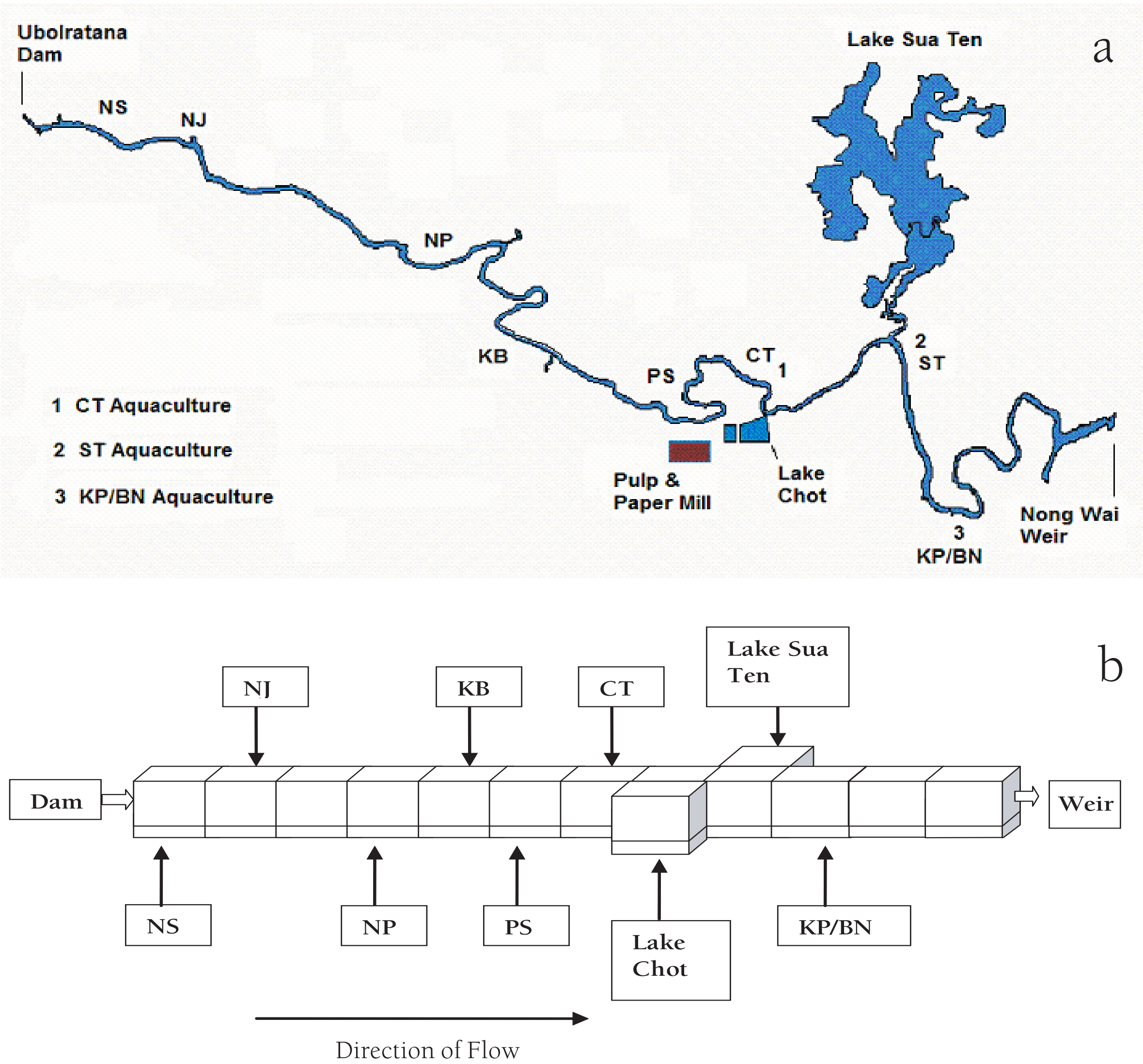

Fig 1. (a) Study Site; (b) Segmentation of the river.

constructing the model in this study. WASP is a general framework for modeling contaminant fate and transport in surface waters. Both non-point loading and point source loadings within a watershed can be studied with this model[12].

The equations solved by WASP are based on the conservation of mass. In this approach, the river can be conceptually represented as a series of small segments or cells. Water travels from an upstream cell to a downstream cell and resides in each cell with complete mixing for a detention time. The one-dimensional mass transport equation is:

$$\frac{\partial C}{\partial t} = -\frac{1}{A}\frac{\partial (QC)}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(EA\frac{\partial C}{\partial x}\right) + S_d + S_k \quad (1)$$

where x = distance, A = cross-sectional area, C = concentration of the water quality constituent, t = time, Q = river flow rate, E = diffusion coefficient, S_d = distributed loading rate (point and non-point sources), and S_k = total kinetic transformation rate. For modeling of phytoplankton,

$$S_k = (G_p - D_p - k_s)P_j \quad (2)$$

where G_p = growth rate constant, D_p = death plus respiration rate constant, k_s = settling rate constant, P_j = phytoplankton population, and j = segment number.

The model of the Nam Pong River was then constructed by dividing the river reach between the Ubolratana Dam and the Nong Wai Weir into 12 segments (Figure 1b) using the cross-sectional data from the Electricity-Generating Authority of Thailand (EGAT). The model was calibrated at 8 sampling sites, denoted as NS, NJ, NP, KB, PS, CT, ST and KP/BN. LT and conventional nutrient data from the Dam were used as the boundary concentrations for the river. The Dam's water release data, from which flows were derived, were acquired from EGAT. The total runoff data for the whole reach between the Dam and the Nong Wai Weir were provided by the Department of Royal Irrigation (RID).

The model was established by first calibrating the flow with LT to ensure that the model could predict its downstream concentrations accurately as a function of space (segment) and time. Chemical and physical transformations of LT were assumed to be negligible in the river during the flow calibration. The volume for each segment was adjusted, starting from the first segment, until the best fit between the predicted and observed LT at each sampling site on February 1st and 22nd, 1999 was obtained.

After the Dam flow was calibrated for the spatial and temporal accuracy, the rest of the LT data in each year were calibrated to estimate the runoff for each segment. A range of runoff was assigned to each segment and test runs were conducted until the best fit between the predicted and observed LT data was achieved at all sampling sites. The sum of the daily runoff assigned to each segment must be equal to the total daily runoff, provided by RID. The runoff for 1999 and 2000 were calibrated using the LT data of 1999 and 2000, respectively. They were calibrated separately because the rainfall for each year was independent of one another.

The model with the calibrated flow and runoff was ready for the calibration of the non-conservative nutrients of CBOD, DO, NH_3-N, and NO_3-N. The nutrients from the 1999 and 2000 data were used for the calibration and validation, respectively. Runoff CBOD, NH_3-N, and NO_3-N from agricultural land in Thailand, were 121, 22.9 and 0.71 μmol/L, respectively[15]. Runoff PO_4-P measurement was conducted during the mild fish kills and found to be 64.8 μmol/L in the paddy field, and 162 μmol/L near the sugar cane field, using the vanadomolybdophosphoric acid method in accordance with the Standard Methods. Runoff LT was found to be 3.2 μmol phenol/L for a dry year in 1999 and 1.1 μmol phenol/L for a wet year in 2000.

A preliminary calibration of the model with a full set of the 1999 data using the deoxygenation rate within a range of literature values[16], demonstrated that the predicted CBOD on May 3rd, 1999 were inconsistent with the observed CBOD in all segments. As the bloom was suspected, particularly on or near this date, high density of live algae could alter the observed CBOD; data from April 21st-June 15th, 1999 were thus omitted during the model calibration.

Results and Discussion

During the 1999 and 2000 monitoring studies, fish kills occurred on May 10th, 1999, the same day that low DO of 9.4-34.4 mmol/L was found in the river. A week before the fish kills, on May 3rd, 1999, high CBOD and DO were detected at all sampling sites in the river. The possibility of an algal bloom on this day was raised because high CBOD and DO could be due to the contribution of live algae and algal photosynthesis, respectively. Modeling was thus used to study whether there was the bloom on May 3rd, 1999.

Calibration of Flow and Runoff

The spatial and temporal accuracy of the model's prediction could be determined by examining the R^2 and RMSE values from the flow calibration. The LT data from the Dam on February 1st and 22nd, 1999 were selected as the boundary concentrations, as there was no or very small amount of runoff on these two days. The selection of the data from February 1st and 22nd, 1999 for the calibration was appropriate for the purpose of the model, and in accordance with USEPA,[17] since a hydrodynamic model was not used; the purpose of this model was to predict the bloom during low flows (2.3-5.8 m^3/s) from April 27th-June 17th, 1999, and the flows (24.4 and 34.4 m^3/s) on these two dates were considerably low, compared to the rest of the year, e.g. 198 m^3/s on July 8th, 1999.

The R^2 and RMSE values are 0.72 (Figure 2a) and 1.17 mmol phenol/L (Figure 2b), respectively, for the whole river segment. When the RMSE of this model was compared with those of other models using salinity in stead of LT[15,17], the RMSE in this model was within their ranges, suggesting that the model's prediction of the conservative trace achieved an acceptable spatial and temporal accuracy.

For the runoff calibration with LT at all sampling sites in 1999 and 2000, the results are shown in Figure 3. The R^2 and RMSE values for all segments in 1999 and 2000 are reported in Table 1. R^2 values of the runoff calibration for both 1999 and 2000 were reasonable for all segments, except for ST and KP/BN. The lower R^2 values for ST and KP/BN could have been due to the unavailable LT data inside Lake Sua Ten.

Although the calibration results of the flow and runoff showed reasonable R^2 values and RMSE values within the literature values[17], they were also tested whether they met the purpose of modeling, which was to study the bloom. Therefore, the flow and runoff from both calibrated and uncalibrated models were compared during the model application to study their difference in the prediction of the bloom.

Model Calibration and Validation

CBOD, DO, NH_3-N, and NO_3-N were calibrated and validated at all segments against observed data. Figures 4 and 5 show examples of the nutrient calibration and validation in segments CT and ST, respectively. The calibrated model coefficients were nitrification rate (0.09 day^{-1}), denitrification rate (0.16 day^{-1}), organic-nitrogen mineralization rate (0.075 day^{-1}), and CBOD deoxygenation rate (0.08 day^{-1}). These values were within the literature values suggested by Wool et al., 2003. The results of R^2 from the multiple regression analysis and RMSE of nutrient calibration and validation in each segment are summarized in Table 1.

This model used three criteria recommended by USEPA[17] for determining the goodness of fit. Firstly, the predicted and observed data of nutrients showed similar profiles. Secondly, the average RMSEs in this model were comparable to those in other models even though they were steady-state models[15,17,18,19,20]. Finally, the dissolved oxygen RMSEs were within the literature values of diurnal variability in the eutrophic waterbody[18,19]. R^2 values for all nutrients were lower in segments ST and KP/BN because of unavailable data inside Lake Sua Ten and possible algal involvement in nutrient uptake and degradation. Under dynamic conditions, the model's predictions "curve-fit" well with observed values, indicating that its predictive capability of conventional nutrients was reliable.

Model Application

The calibration-validation model could be used to investigate whether a bloom existed and its subsequent die-off was the cause of low DO and fish kills. Although chlorophyll *a* (denoted as *Chl a*) was not monitored in 1999 and 2000, it could be simulated under literature constants and coefficients of phytoplankton, as described by Park and Lee[21] because the results of *Chl a* simulation were to be compared on the basis of their relative magnitudes. Since there were low DO and fish kills in 1999 and almost no fish kill in 2000, the simulations of *Chl a* should show a peak of *Chl a* in 1999 and no or very small peak of *Chl a* in 2000 - if the algal die-off was the cause of low DO. The relative *Chl a* simulation shows the presence of two *Chl a* peaks in all segments in 1999 (Figure 6). No *Chl a* peak was observed in the simulation of relative *Chl a* in 2000, which confirmed the fact that there was almost no fish kill in 2000.

The model prediction of the bloom and its die-off was accurate on a time scale of days, using DO on May

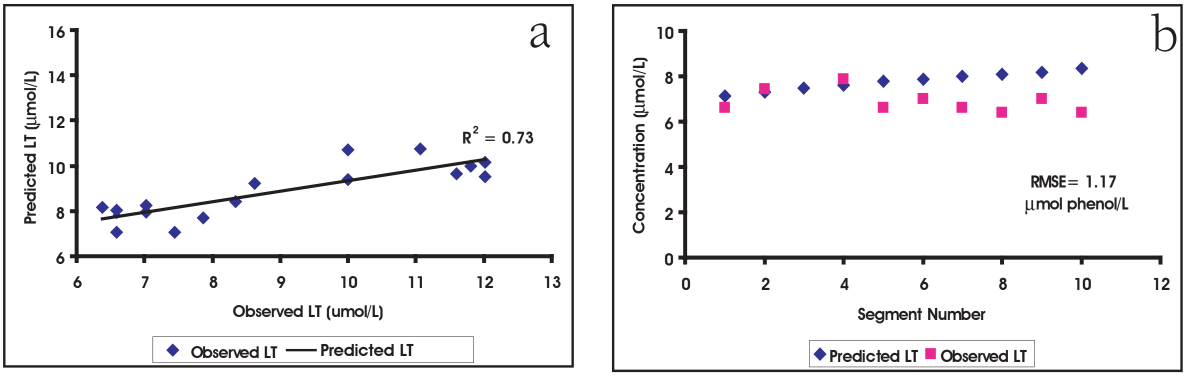

Fig 2. (a) Regression between observed and predicted LT on February 1st and 22nd, 1999; (b) Comparison between predicted and observed LT at each segment, using LT on 2/22/99.

Table 1. R^2 and RMSE (mmol phenol/L) values from runoff calibration using 1999 and 2000 LT data, and R^2 and RMSE (mmol/L) values from calibration and validation of nutrients using 1999 and 2000 data for all segments.

Segment	Runoff Calibration (1999 LT data)		CBOD Calibration		DO Calibration		NH_3-N Calibration		NO_3-N Calibration	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
NS	0.75	1.32	0.63	27.5	0.86	20.3	0.65	4.3	0.65	3.6
NJ	0.75	1.32	0.7	21.6	0.72	22.8	0.63	3.6	0.71	2.9
NP	0.70	1.43	0.65	25.6	0.74	22.8	0.80	4.3	0.77	2.1
KB	0.69	1.43	0.72	20.6	0.77	25	0.62	4.3	0.63	3.6
PS	0.73	1.38	0.72	20.6	0.68	25.9	0.63	4.3	0.70	2.9
CT	0.80	1.29	0.69	21.6	0.60	33.1	0.63	4.3	0.71	2.9
ST	0.75	1.32	0.49	24.7	0.65	26.9	0.66	4.3	0.66	3.6
KP/BN	0.64	1.52	0.37	27.5	0.55	32.5	0.64	4.3	0.51	4.3
RMSE for River		1.38		23.8		26.2		4.3		2.9

Segment	Runoff Calibration (2000 LT data)		CBOD Calibration		DO Calibration		NH_3-N Calibration		NO_3-N Calibration	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
NS	0.88	0.25	0.60	13.80.44	0.94	RMSE	R^2	RMSE	R^2	RMSE
NJ	0.84	0.32	0.64	10.90.35	0.87	10.9	0.83	0.36	0.94	0.28
NP	0.88	0.25	0.64	10.90.35	0.83	15.3	0.76	0.71	0.91	0.28
KB	0.83	0.32	0.62	13.40.43	0.78	16.6	0.66	0.5	0.70	0.93
PS	0.85	0.32	0.56	5.60.18	0.78	19.4	0.64	0.71	0.66	1.07
CT	0.83	0.35	0.58	13.70.44	0.68	19.4	0.66	0.5	0.70	0.93
ST	0.62	0.36	0.40	14.70.47	0.61	22.8	0.60	0.57	0.82	0.43
KP/BN	0.64	0.36	0.44	19.10.61	0.63	27.2	0.53	0.64	0.66	0.93
RMSE for River		0.32		12.80.41		26.9	0.51	0.64	0.58	0.64

3rd and 10th, 1999 as the reference points. The presence of the bloom as illustrated in Figure 6, which peaked from May 1st-4th, 1999 confirms high CBOD and DO on May 3rd, 1999. And, as the bloom died off, both *Chl a* and CBOD decreased on May 10th, 1999; the predicted DO also decreased to the observed value. The bloom could have died off for two reasons, namely cellular respiration and low light extinction caused by continuous heavy rainfall from May 4th-15th, 1999 (e.g., 85.8 mm of rain on May 4th at the Khon Kaen meteorological station). The die-off caused low DO on May 10th, 1999. If high DO on May 3rd, and low DO on May 10th at the CT aquaculture were used to determine *Chl a*, there should have been approximately 353 mmol C/L of algae on May 3rd (Figure 7), and 399 mmol C/L on May 1st, 1999. The second bloom on June 3rd, 1999 (Figure 6) did not cause fish kills because it was flushed out of the river with high Dam flows starting from June 18th, 1999 before it died off. Had the second bloom died off in the river, it might have also killed the fish.

The most realistic scenario that could have happened in 1999 was that there could have been a bloom in the reservoir since April 19th, 1999, as seen by high CBOD and DO from the contribution of live algae and algal photosynthesis. When the bloom entered the river from April 19th-May 3rd,1999, it proliferated with ample supply of runoff nutrients and high summer temperatures. Combined with existing algae in the river and additional algae from the runoff, the total size of the bloom became even larger.

The model's predictive capability on chlorophyll *a* was tested by exposing the model to possible but least likely conditions which could cause the bloom, i.e., lower temperatures in the river, and lower nutrients from the reservoir, on days when the water was not sampled. Under those conditions, the bloom was still predicted because it was mainly caused by low Dam flows and runoff nutrients. The impact of the low flow on the bloom and fish kills was in agreement with other studies[12,22,23] .

When the models with calibrated and uncalibrated flows were compared, the simulation results of the relative *Chl a* at the CT aquaculture are shown in Figure 6. The size of the bloom in the uncalibrated model designated as "Before calibration" is larger than the calibrated model designated as "After calibration," suggesting that the calibrated model could not overestimate the bloom. The size of the bloom in the

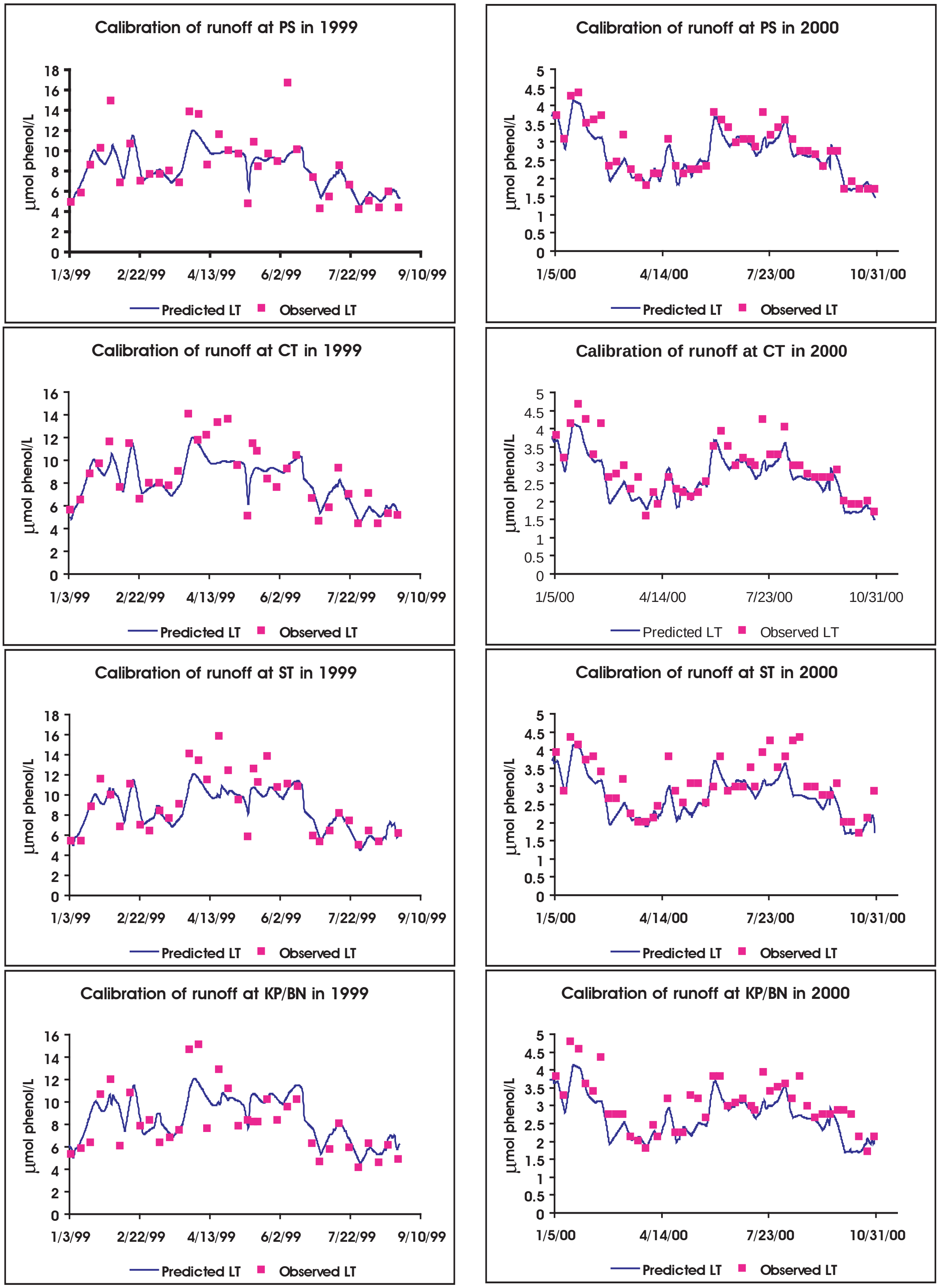

Fig 3. Model calibration of runoff using LT as a conservative trace at 4 segments (PS, CT, ST and KP/BN) in 1999 and 2000 (line: predicted LT, dot: observed LT).

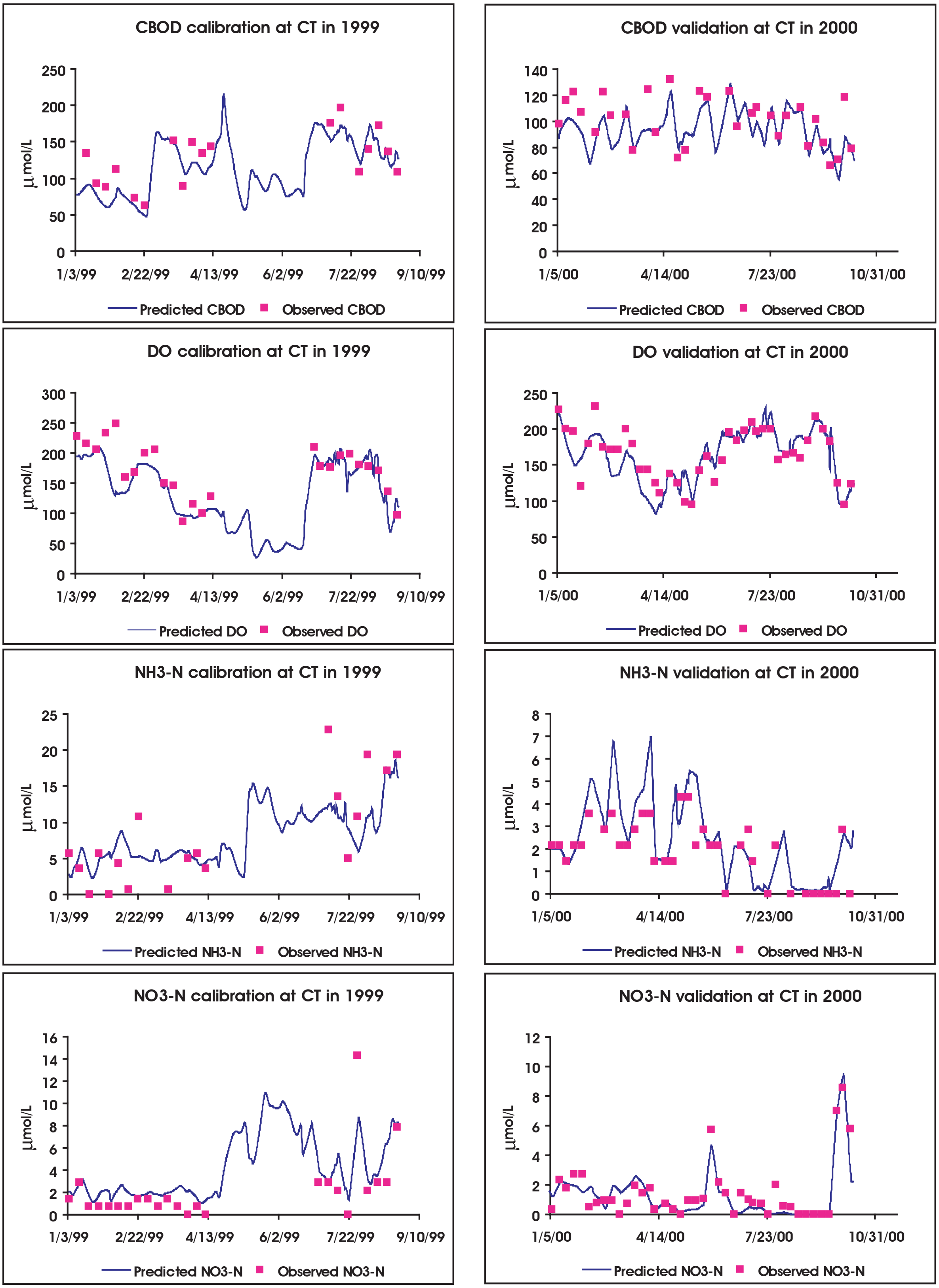

Fig 4. Calibration and validation of conventional nutrients (CBOD, DO, NH_3-N, NO_3-N) at segment CT using the 1999 and 2000 data (line: predicted nutrient, dot: observed nutrient).

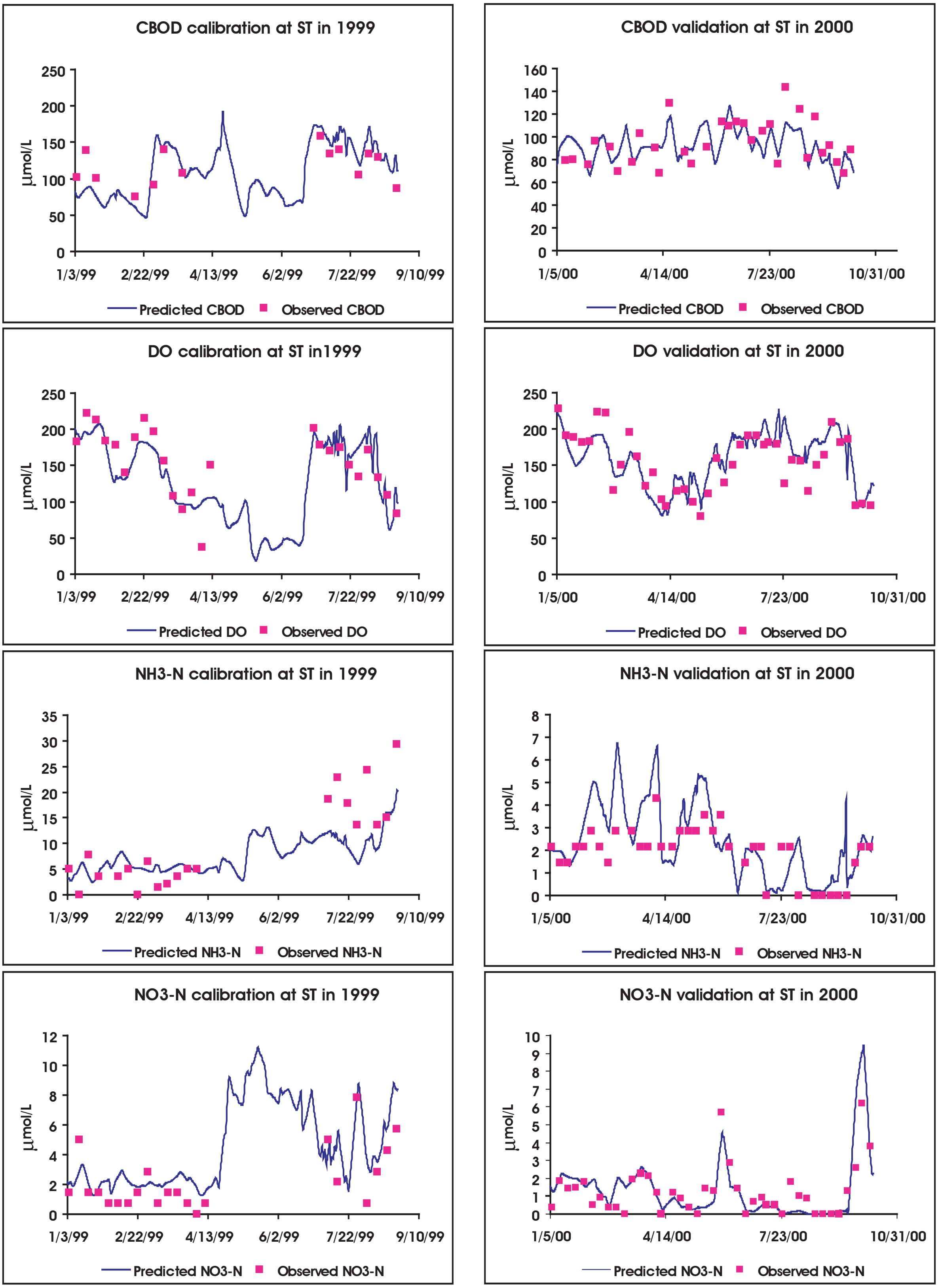

Fig 5. Calibration and validation of conventional nutrients (CBOD, DO, NH_3-N, NO_3-N) at segment ST using the 1999 and 2000 data (line: predicted nutrient, dot: observed nutrient).

uncalibrated model was larger because the larger volumes of the uncalibrated model allowed a longer residence time for the algae to proliferate within the river segment. The uncalibrated model also predicted that the second bloom was substantially larger than the first bloom because longer segments allowed algae to multiply more with larger amount of runoff from mid-May to mid-June for the bloom in June.

When the calibrated and uncalibrated runoff in 1999 were simulated, the bloom was still predicted but at different sizes, depending on how much runoff was added upstream or downstream relative to the CT aquaculture. If more runoff was added to the upstream segments to the CT aquaculture, the predicted size of the bloom at the CT aquaculture would be larger. As the worst-case scenario, if there was no runoff above the CT aquaculture at all, the runoff which was provided by RID, must be added to downstream segments, and the bloom would have occurred near the end of the river, resulting in fish kills at only the last aquaculture site of KP/BN. The worst case, however, was unlikely for two reasons. First of all, fish kills were reported at all aquaculture sites, not just at the KP/BN aquaculture. Secondly, the CT aquaculture was situated almost in the middle of the river segment under study, and there must have been some runoff coming from the upper watershed to provide nutrients for the bloom at the CT aquaculture. From April 26th- May 10th, 1999, when the critical bloom was studied, the runoff of 39% of the total daily runoff, assigned to segments above the CT aquaculture, reflected the smaller bloom at the CT aquaculture, as seen by lower CBOD at the CT aquaculture (194 mmol/L on May 3rd) than at the ST (244 mmol/L on May 3rd) or KP/BN (231 mmol/L on May 3rd) aquacultures. Since the R^2 values of the runoff calibration from the first segment to the ST segment in 1999 were already high and the proportion of the runoff during the critical period reflected the relative size of the bloom, only a slight error in the runoff was expected and should not significantly reduce the predictive capability of the model for the bloom.

Conclusion

The dynamic model was constructed after the water quality had been monitored between 1999-2000. The RMSE of the flow using LT was within the literature values using salinity, suggesting that LT can be used for the flow calibration. The selection of the LT data, from the low-flow period, was crucial to the success of the flow calibration for studying the bloom because, as mentioned, low flows significantly affected the bloom. In addition to low flows, there should be no or very small amount of runoff when LT was used for the flow calibration because LT was also present in the runoff. The runoff calibration using LT yielded reasonably high R^2 values, particularly for the year 2000.

LT could potentially replace the traditional use of synthetic dyes or salinity for runoff and flow calibration because LT is applicable with freshwater river where salinity is not available. Unlike synthetic dyes, LT does not interfere with the normal use of river water because it is naturally-occurring. Furthermore, information on the watershed was not necessary as the runoff could be calibrated.

The results of the model calibration and validation of conventional nutrients showed good fit between the predicted and observed values, suggesting its "generality" for future prediction. Better results of calibration and validation than those reported in Table

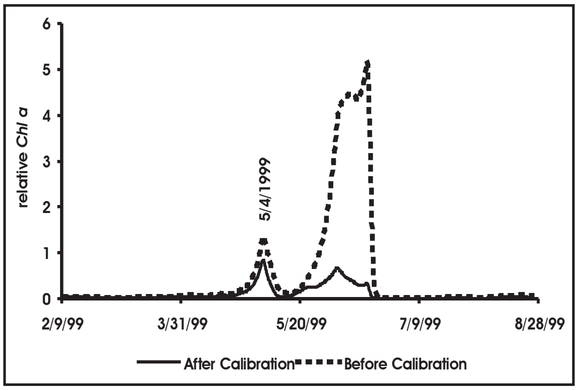

Fig 6. Comparison of relative *Chl a* before and after the calibration of the mass transport at the CT aquaculture in 1999 (line: before calibration, dot: after calibration). Notice that the relative *Chl a* after the calibration is smaller than before the calibration; therefore, the calibrated model could not overestimate *Chl a*.

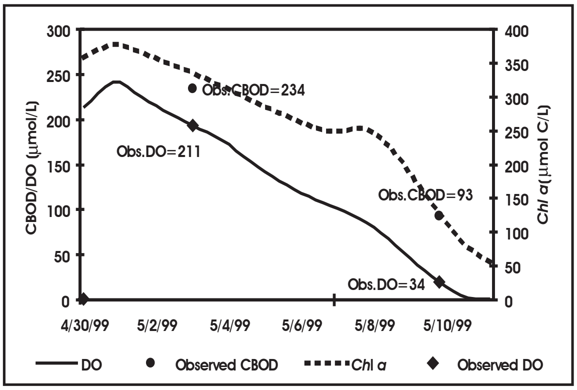

Fig 7. Simulation of DO (mmol/L) and *Chl a* (mmol C/L) with observed CBOD and DO on May 3rd and 10th, 1999. Notice that all *Chl a*, CBOD, and DO are high on May 3rd, and low on May 10th, 1999. The units of *Chl a* and CBOD are on different scales.

1 might be difficult to achieve because a dynamic model with undulating change could not be expected to predict the "generality" as well as the steady-state model with constant change.

From the dynamic modeling, there could have been approximately 353 mmol C/L of *Chl a* at the CT aquaculture on May 3rd, 1999, which died off and caused low DO on May 10th, 1999. The *Chl a* simulation demonstrated that the algal die-off, low DO and fish kills occurred on the same day, suggesting that the model was accurate on a scale of days.

Management Recommendations

This study showed that the algal die-off after the bloom was the cause of low DO and possibly fish kills; it was thus recommended that low DO and eutrophication be controlled first. The sensitivity analysis showed that the Dam flow significantly affected both DO and *Chl a*. Scenario simulations with the 1999 data were thus applied to determine the minimum flow to control *Chl a*.

When the simulated *Chl a* was 0.21 mmol C/L in 1999, there was no low DO and fish kill; and if this value was set as the management target of *Chl a* during scenario simulations, the daily water release from the Dam must be increased by 500% of that during the fish-kill period in 1999. If, however, the daily water release was set at a minimum of 11.57 m^3/s, the highest efficiency of algal reduction per water release was achieved, but *Chl a* would not be reduced to the management target. The minimum daily water release of 11.57 m^3/s was initially recommended for trial based on its efficiency. From 2001-2004 when the minimum daily water release was tried, there had been no fish kills greater than 1% in the summer. The 1% fish kill might have been due to small blooms which could not be flushed out of the river with the minimum daily water release from the Dam.

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