Continuous Dissolved Oxygen and Water Temperature Monitoring in Pool 8 Backwaters of the Upper Mississippi River May-September, 2010

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Introduction

The federal/state Long Term Resource Monitoring Program (LTRMP) has been conducting water quality monitoring on Pool 8 of the Upper Mississippi River (UMR) in different aquatic areas since the late 1980s (Johnson and Hagerty, 2008). Most of this work has centered on defining seasonal changes at selected fixed sites or through the quarterly sampling of main channel, side channel, impounded, contiguous backwater and isolated backwater aquatic strata using random sampling. Water samples typically represent grab samples collected near the surface with additional sampling of the bottom waters in deep, low velocity environments. Sample collection times are noon-centered and generally span the hours of 9:00 to 15:00. A complimentary sampling program for fish and aquatic vegetation has provided a wealth of environmental information that has greatly benefited our understanding of factors influencing fish and aquatic life in this navigation pool. Similar monitoring efforts in Pools 4, 13, 26, the open river below the Missouri River, and the La Grange Pool of the Illinois River have provided valuable information for making longitudinal and lateral (across floodplain) evaluations of the aquatic resources of the UMR (Barko et al. 2005; Chick et al. 2005; Houser 2005).

It is well known that dissolved oxygen (DO) and water temperature are critical factors influencing fish and aquatic life. DO is a particularly important water quality criterion necessary to sustain habitat conditions for fish and aquatic life. Most UMR states specify a DO criterion of 5 mg/L for fish and aquatic life use. This criterion is generally attained in flowing channels of the UMR, though there have been excursions below 5 mg/L during the summer months that may be related to respiratory demands of zebra mussel (Sullivan and Endris 1998; Caraco et al. 2000), excessive backwater vegetation (Caraco and Cole 2002) and periods of summer flooding when turbid conditions contribute to increased biochemical oxygen demand and decreased primary production (Houser 2005).

Factors contributing to low DO in shallow aquatic systems are numerous but typically center on excessive aquatic plants, algae blooms, high sediment oxygen demand associated with organic sediments, reduced surface re-aeration due to surface plant coverings, and restricted water exchange with inflows of oxygenated water. The influence of aquatic vegetation is of particular interest since UMR backwaters bordering Wisconsin have extensive beds of submersed aquatic vegetation (SAV), which may support thick growths of filamentous green algae (metaphyton). This algae may form carpet-like mats that cover the water surface over large off-channel areas during the summer months (Sullivan, 2008). In addition, SAV beds may provide quiescent habitat for the development of duckweeds that may also form dense surface coverings in nutrient-rich backwaters and contribute to hypoxic conditions during mid-summer conditions (Sullivan 2008; Giblin et al. 2010). For purposes of this report, these mats of filamentous algae or duckweeds are both generally described as “metaphyton” due to their occurrence at the water’s surface and their dependence on water column nutrients to support their growth.

Studies evaluating factors contributing to metaphyton distribution and growth were implemented in navigation Pool 8 of the UMR in 2009 (Jeff Houser, USGS, personal communication). Those studies were primarily focused on mid-summer conditions and included water quality, plant and sediment chemistry surveys in 10 backwater areas. In 2010, this work was expanded to provide a more comprehensive evaluation of water quality conditions, especially water column nutrients, contributing to temporal changes in metaphyton biomass and composition during the period of May to September. The 2010 study focused on two backwaters that were highly connected to flowing channels and two that were relatively isolated. This design was implemented to further our understandings of hydraulic factors influencing metaphyton/nutrient dynamics in backwaters of Pool 8. One aspect of the 2010 study was to obtain continuous DO and temperature measurements and estimates of metaphyton production during periodic surveys in each of the four backwaters during the study period. An important objective of this work was to evaluate the influence of metaphyton on near surface DO and water temperature and to provide a more comprehensive evaluation of daily DO changes to assess attainment with fish and aquatic life criteria. This report will describe the continuous monitoring results and factors influencing these measurements. A separate report (Giblin et al. in review) will provide information on factors influencing the temporal changes in metaphyton biomass and composition during the 2010 study period.

Methods

Week-long continuous monitoring of dissolved oxygen (DO) and temperature was conducted at approximately monthly intervals in four backwaters of Pool 8 during May-September 2010 (Figure 1). Two of the backwaters were representative of areas with high hydraulic connectivity to flowing channels (Round Lake and Horseshoe) and two areas were reflective of areas with low connectivity (Markle and Beiers Lakes). These backwaters were selected from a group of 10 that were studied in 2009 (Jeff Houser, USGS, personal communication). The actual sampling site for particular backwater was based initially on a random selection of sites 1 to 5 from the 2009 study. In 2010, the sites for continuous monitoring were chosen during the initial sampling event at each backwater in May or early June. Sites were visited sequentially in each backwater and the first site containing metaphyton (filamentous algae or duckweeds), was selected as the sampling location for the remainder of the 2010 study. The only exception was Markle Lake, where the initial sampling site had to be moved during the second visit due to shallow water and the presence of dense emergent vegetation at the initial site. Sampling locations located using a Trimble GeoXM GPS receiver with an established accuracy of +/- 9 m.

Two DO/temperature sondes (D-OptoLogger – Zebra-Tech LTD) were normally deployed for 7-day monitoring intervals during 4 to 5 sampling episodes from May to September (Table 1). The sondes were suspended horizontally about 0.2 m below the water surface in the center of 0.6 m^2 wooden frames constructed using 2.5 x 39 cm wooden boards (Figure 2). The purpose of the frames was to provide measurements of metaphyton biomass and growth during the deployment interval and an assessment of the influence of metaphyton cover on DO concentration and water temperature. Each sonde was secured to the center of a 0.95 cm diameter metal rod that spanned the width near the center of the frame (Figure 2a). Frames were supported by two, 0.55 m long by 7.6 cm PVC diameter pipes with sealed end caps, which provided additional floatation and ensured a portion of the frames remained above the water surface to contain the floating metaphyton during the monitoring period. The frames were secured to a sampling site by placing metal conduits at opposite corners inside the frames and by pushing or driving the conduit supports into the sediment. This allowed the frames to rise or fall freely with changes in stage but allowed little horizontal movement.

DO/temperature sondes were calibrated pre-deployment in the lab using a 2-point calibration procedure (0 and 100 % saturation) following the manufacturers protocol. The sondes were set to log measurements at 15-minute intervals. The loggers were checked for DO calibration drift using the same 2-point calibration method at the end of each deployment period. The maximum DO drift during post- calibration checks was -0.4 mg/L and averaged -0.1 mg/L at 100% saturation. The DO calibration drift at 0% saturation was generally within +/- 0.1 mg/L. Therefore, there were no adjustments made to the recorded DO measurements.

Most of the metaphyton was normally removed from the entire area of one frame (frame 1) during initial deployment using a 0.5 mm mesh soil sieve to provide an initial estimate of metaphyton biomass. A very small quantity of metaphyton was not removed from frame 1 to provide “seed” for a biomass production measurement. The metaphyton present in the second frame (frame 2) was not disturbed during initial deployment. The dominant metaphyton taxa present in each frame was recorded based on visual inspection. Metaphyton biomass was sampled from both frames at the end of deployment interval with frame 1 yielding an estimate of metaphyton production. If substantial metaphyton was present in the frames the area sampled for biomass determination was reduced using a 0.25 m^2 quadrate sampler or soil sieve (0.0314 m^2). Surplus moisture was removed from the metaphyton in the field by spinning the sample on a tethered soil sieve for about 30 revolutions. If filamentous algae was present, the sample was also compressed into a ball by hand to remove additional free-water.

The samples were then placed in plastic bags and stored in a cooler with ice until processed for wet and dry weight analysis in the lab. Metaphyton samples were dried at 80 ^{o}C to determine dry weight. An electronic balance (Ohaus Scout Pro) was used to weigh samples. A 200 gram brass weight standard was used to verify the scale accuracy and was within (+/- 1 gram throughout the study.

Digital pictures were taken of each site and each frame during deployment and retrieval (front cover and Figure 2) to document changes in metaphyton cover. Water quality grab samples of DO, temperature, pH and specific conductance were collected 0.2 m below the surface at the center of each frame and between the frames during deployment and retrieval using a YSI 556 multi-parameter sensor. Additional limnological measurements included water depth, turbidity (Hach 2100P) and visual observations of current velocity. The dominant metaphyton form and qualitative estimates of metaphyton cover were made within a 25-meter radius around the sampling site (Sullivan 2008; Giblin et al. 2010).

Daily Mississippi River flows at Lock and Dam 8 near Genoa, WI were obtained from the US Corps of Engineers (http://www.mvp-wc.usace.army.mil/projects/Lock8.shtml). Daily maximum and average wind speed were obtained at the La Crosse, WI airport from the US Weather Service (http://www.weather.gov/climate/index.php?wfo=arx). Daily solar radiation measurements were obtained from measurements at the Department of Natural Resource's Service Center at La Crosse using an Eppley black and white pyranometer (model 8-48).

Basic statistics, Spearman rank correlations, median tests and Kruskal-Wallis one-way AOV, a non-parametric procedure used to evaluate differences between groupings, were derived using Statistix 8 (Analytical Software, 2003).

Study Sites

Beiers Lake is a 53.9 ha backwater area located east-central portion of Pool 8. The backwater is bordered by marshes and floodplain forest. Inflows into Beiers Lake occur through 3, 1.5 m diameter culverts at the north end of the backwater. These culverts provide little to no flow during normal to low river discharge. A major connection with a flowing channel occurs in the southern end of the backwater (Figure 1). The continuous monitoring site was located at the southeast end of this backwater. Water depths at this site ranged from 0.9 to 2.1 meters during the study period. Submersed aquatic vegetation (mainly coontail and Canadian waterweed) and floating-leaf vegetation (mainly white waterlily) was present at moderate densities. The surface substrate was silt underlain by clay. Water current was not evident at this site except during periods of high winds.

The Horseshoe backwater, also called Horseshoe Island, is a 154 ha area located at the center of the upper impounded area of Pool 8. Man-made islands form the general boundary surrounding the backwater area (Figure 1).These islands are bordered by the main channel to the north and east and a secondary channel (Raft Channel) to the west. A large artificial inflow (cut) provides a substantial source of water directly from the main channel border at the north-central end of the backwater area. This inflow is about 500 cfs during average river flow conditions with flow increasing with greater river discharges (John Hendrickson, USCOE, personal communication). This backwater is relatively shallow and has a silty-sand substrate. The average depth at the continuous monitoring site ranged from about 0.4 to 0.8 m during the study period (Table 1). Water current was normally present at the site, particularly during periods of increased river discharge. Submersed (mainly coontail, Canadian waterweed and Eurasian milfoil), floating-leaf (white waterlily) and emergent (arrowhead) vegetation was common at the site during the study period. Specific conductance was generally higher in this backwater as compared to the three other backwater sites and likely reflects less influence from the Black River, which has relatively low conductivity and tends to flow through the eastern portion of Pool 8.

Markle Lake is a 84.2 ha backwater located in the east-central portion of Pool 8. The area is bordered by the Burlington-Northern railroad tracks on the eastern side (Figure 1). Floodplain forest and marsh habitat borders the remaining sides. Connectivity with the river is minimal during normal to low river discharge and generally occurs through a shallow narrow channel in the southwest portion of the backwater. The continuous monitoring site was initially located in a relatively shallow area on the southern end of this backwater in mid-May (red x, Figure 1). However, a large bed of emergent vegetation subsequently developed in this area in late May, which required relocating to a new location when the backwater was re-visited in late June. The alternate site was determined randomly and was located in the northern portion of the backwater in an area where floating-leaf (white waterlily) and sparse emergent (arrowhead) was present. The major submersed species included coontail and flatstem pondweed. Water depths at the northern site ranged from 0.4 to 1.1 m during the monitoring period. The sediment at this site was dominated by silt-clay.

Round Lake is a 54.7 ha area located in the upper portion of Pool 8 just below the earthen dike that separates Pool 7 from Pool 8 (Figure 1). The lake is surrounded by marsh and floodplain forest with Interstate highway I-90 dividing the lake into an upper and lower section. The French Island Spillway provides a major source of inflow to Round Lake via a narrow channel at the northern end. This spillway has two notches that deliver a combined flow of 200 cfs during normal to low flow conditions. The continuous monitoring site was located in a small bay in the northwest end of the lake just upstream from I-90. The water depth at this site ranged from about 0.7 to 1.5 m during the monitoring period (Table 1). Even though the area was adjacent to the inflow channel, the site had no noticeable current during the study period likely due to dense beds of aquatic vegetation dominated by white waterlily, coontail, Candian waterweed and Eurasian milfoil. The sediment substrate was silt-clay. This backwater had noticeably lower conductivity than the other three backwater areas and was likely due to a greater influence of the Black River, a major tributary with relatively low specific conductivity, which contributes an important source of water to lower Pool 7 (Lake Onalaska). The Black River tends to flow through the eastern half of Lake Onalaska, but a portion of this inflow can often be detected at the French Island Spillway, especially during periods when this tributary's discharge is high.

Results and Discussion

Hydraulic and Meteorological Conditions

Daily river flows varied substantially during the study period and exceeded 30,000 cfs during most of the period with the exception of several days in early June (Figure 3c). Flows approached or exceeded 60,000 cfs during periods in late May, late June, mid-August and late September. During June through August, the median river flow at Lock and Dam 8 was about 56,000 cfs, which was about 40% higher than normal based on flow duration data for this location (years 1972-2000). The most rapid change in flow occurred in mid-August and resulted in a 0.7 m increase in stage in Markle Lake, the backwater where DO sondes were deployed during this period (Table 1).

Daily average wind speed was quite variable and normally ranged from about 3 to 10 mph and only exceeded 15 mph on September 3rd and 24th (Figure 3d). Periods of moderate wind speed exceeding 10 mph daily average for more than three consecutive days occurred in early July and late September. The average daily wind speed for the June-August period was 6.8 mph which was about 15% lower than a long-term averaged derived for the 1984-2001 period (Paul Hudsepth, National Climatic Data Center, personal communication).

Daily solar radiation exhibited large variation during the study period and ranged from about 100 to 700 langleys/day (Figure 3e). Such changes are typical of radiation measurements due to daily changes in cloud cover and seasonal changes. Maximum radiation occurred in late May to early July and corresponds with summer solstice. The average solar radiation during June-August was 491 langleys/day and nearly identical to the long-term average collected at La Crosse by the Wisconsin Department of Natural Resources from 1988 to 2009.

Seasonal Changes in DO and Water Temperature

Large seasonal changes in average daily DO and water temperature were observed during the May through September period (Figure 3a and 3b). Highest daily average DO was generally found during periods when the water temperature was less than 20 ^{o}C, particularly in May and early June. Backwaters with low hydraulic connectivity to flowing channels (Beiers and Markle Lake) experienced hypoxic (< 2 mg/L) to near anoxic (<0.2 mg/L) conditions during July and August when average daily water temperatures exceeded 25 ^{o}C. In contrast, Horseshoe, the backwater with the highest hydraulic connectivity, had higher DO concentrations throughout the monitoring period with daily averages normally exceeding 5 mg/L. A marked increase in river flow, from about 40,000 to 77,000 cfs, occurred in mid-August during monitoring in Markle Lake (Figure 3c) and resulted in a 0.7 m stage increase at this site as discussed above. However, this influx of water only resulted in a modest increase in daily average DO from about 0.3 to 2 mg/L. This inflow also resulted in noticeable decrease in specific conductance from about 442 to 295 uS/cm and suggests dilution due to an inflow with lower conductance (Table 1). Additional discussion of flow-related impacts on DO measurements are discussed later in this paper.

A closer evaluation of seasonal DO and temperature changes were made by preparing box plots of daily maximum, minimum, average, and diurnal (daily min-daily max) statistics by month and by backwater (Figures 4 and 5) for continuous measurements made in frame 2. Greatest seasonal charges were observed in daily maximum, average and diurnal DO in Markle Lake between May and August. Daily maximum DO ranged from a high of 25.8 to a low of 0.4 mg/L for May and August, respectively (Figure 4a). Part of this response was the result of moderately cooler water temperatures during the onset of monitoring in Markle Lake in May (Figure 5) since DO saturation is higher in colder water. However, photosynthetic activity by a dense subsurface layer of filamentous algae was likely the primary factor contributing to very high DO levels and diurnal flux at the Markle Lake site in May. Metaphyton biomass was about 25 g/m^2 dry weight at this site during this period (Table 2).

The lowest DO concentrations were present in Beiers Lake in July and August with average daily values below 3 mg/L (Figure 4b). Average daily minima during this period were near 0 mg/L (Figure 4c) indicating this backwater experienced anoxic conditions mid-summer. Markle Lake and Round Lake also experienced hypoxic to anoxic conditions during periods in July and August (Figure 4c), but DO levels in these backwaters were generally greater. Surprisingly, no dead fish were observed in any of these three backwaters during July and August, which suggests the fish were able to find refuge in other areas where the DO concentrations were higher. Daily minimum DO in the Horseshoe backwater did not fall below 1.4 mg/L during the July and August monitoring periods and averaged about 3 mg/L. Mid-summer anoxic conditions were likely avoided in the Horseshoe backwater as a result of a greater inflow of oxygenated water from the main channel as discussed previously. Further, this backwater was dominated by filamentous algae (Table 2), which may allow for oxygen input into the water column due to photosynthesis and atmospheric re-aeration when this metaphyton resides below the water surface. (Sullivan 2008; Giblin et al. 2010).

Water warmed very rapidly in May (Figure 3b) and daily maxima values exceeded 30 ^{o}C in Beiers Lake in late May (Figure 5a). Temperatures above 30 ^{o}C are typically observed during July and August. The rapid temperature rise during May was associated with relatively high diurnal temperature flux exceeding 5 ^{o}C (Beiers and Markle Lakes, Figure 5d). Horseshoe backwater also exhibited high diurnal temperature swings in early June and were likely related to lower river flow (Figure 3c) and shallow water conditions at the monitoring site during this period (Table 1).

Water temperatures cooled rapidly in September and likely contributed to improved DO conditions in the backwaters monitored during that period (Figure 3a and 3b).

Spatial Differences in DO and Water Temperature

Daily DO and temperature metrics (avg., min., max. and diurnal) were compiled for each backwater for the June to August period (Table 3). Sampling days with less than a full day of monitoring were excluded from the analysis to avoid missing maximum and minimum values. May and September data were excluded since some backwaters were not monitored during these months and they also represented a period of time when DO and temperature conditions were changing rapidly as discussed previously. A Kruskal-Wallis non-parametric AOV was used to test for significant difference ($p<0.05$) in the DO and temperature metrics among the backwaters monitored. Two results are available for each metric since the analyses included sondes deployed in frames 1 and 2.

Daily DO metrics differed substantially between backwaters. Highest DO concentrations were found in the Horseshoe backwater and lowest levels were present in Beiers Lake. When pairwise comparisons were made, the backwaters were found to be in two or three groupings where the metric averages did not differ significantly from one another (Table 3). Daily average and daily minimum DO revealed Horseshoe grouped with Round Lake and daily maximum and diurnal DO indicated Beiers, Markle and Round Lakes had similar means. These grouping were likely related to hydraulic connectivity and aquatic vegetation similarities, which contributed to similar photosynthetic and respiratory influences within these backwaters. However, Horseshoe backwater had moderately high daily maximum (13 mg/L) and diurnal DO (10 mg/L), which distinguished this backwater from the other three. This response was likely related to a stronger main channel influence and the presence of moderate filamentous algae at this site during July and August rather than duckweeds as discussed previously.

An evaluation of temperature data did not reveal any significant differences between the four backwaters (Table 3). This suggests spatial differences in DO were not related to differences in water temperature. Further, continuous temperature measurements provided little information to discriminate spatial differences in these backwaters during mid-summer periods.

Metaphyton Biomass, Production and DO

Measurements of metaphyton biomass were made during each continuous monitoring survey in the four backwaters (Table 2). Metaphyton biomass during initial frame deployment was often not made due to very low metaphyton content in frame 1. The best representation of typical metaphyton biomass encountered during frame deployments was available from frame 2, which was sampled at the end of each survey. Metaphyton biomass in frame 2 averaged 73.5 and ranged from about 25 to 190 g/m^2 dry wt. (Table 2). The initial biomass measured in frame 1 in Beiers Lake in August was extremely high (430 g dw/m^2) and likely represented a wind-driven accumulation of duckweeds. Highest biomass was associated with *Lemna* sp. and *Spirodela polyrhiza*. The biomass of sites dominated by duckweeds ranged from 29 to 190 g dw/m^2 (frame 2) and are consisted with those reported by Landolt and Kandeler (1987). Sites dominated by filamentous green algae had noticeably lower biomass with most values below 50 g dw/m^2.

Biomass samples from Markle and Beiers Lake were higher than Horseshoe or Round Lake. Highest biomass was associated with members of the *Lemnaceae* family including: *Spriodela polyrhiza*, *Lemna minor*, and *L. trisulca*. It is possible that sampling frames could have collected and trapped metaphyton during periods of high winds or boat waves. However, it was not possible to discern this bias. Further, it was also possible that water currents could have displaced metaphyton at times, especially forms such as *L. trisulca* or filamentous algae, that may have resided below the surface. The metaphyton biomass values found during these surveys were noticeably greater than those measured from Pool 8 in August of 2009 (Houser et al. in prep), which were based on random sampling of 10 backwaters, some of which contained little to no metaphyton due to unfavorable habitat. Plotting the biomass estimates made in 2010 by collection period did not reveal any consistent temporal pattern in the four backwaters (Figure 6a).

Estimates of metaphyton production were available from biomass measurements derived from frame 1 since metaphyton was initially removed from this frame during frame deployment then sampled again at the end of the deployment period (normally 7 days). Metaphyton found in frame 1 at the end of the sampling period was assumed to represent growth though we could not discount the possibility of physically-induced collection due to wind, waves or currents as described above. This was likely a factor during surveys in Markle Lake in June and Beiers Lake in July, when very high production estimates were derived for sites dominated by *Spirodela polyrhiza* since they exceeded the theoretical maximum (20 g/dw/m^2/d) suggested by Landolt and Kandeler (1987). Excluding these two values yielded an average metaphyton production of 2.2 and a range of 0.3 to 8 g dw/m^2/day (Table 2). The highest production was associated with *Spirodela polyrhiza*, which was common in the four backwaters in 2010. Filamentous algae production in Horseshoe and Round Lake during July and August were very similar and averaged 3.3 g dw/m^2/day. Plotting the production measurements by collection period indicated generally higher rates during mid- to late summer (Figure 6b).

Median DO measured during the frame deployments was found to differ significantly ($p<0.05$) by dominant metaphyton type. Highest median DO was 6.1 mg/L in frames where filamentous green algae dominated and then was followed by *Lemna* sp. and *Spirodela polyrhiza*, 4.5 and 3.7 mg/L, respectively. The median DO associated with *Wolffia* sp. was 0.6 mg/L, but this was based on limited data for this taxa (Table 2). These results are consistent with previous work where filamentous algae were found in waters with moderate DO and duckweeds were commonly found in waters with substantially lower DO (Sullivan, 2008).

Influence of Metaphyton on Surface DO and Temperature

The influence of surface metaphyton mats on DO and temperature were evaluated by performing a two-sample median test ($p<0.05$) on measurements in frame 1 and 2 for each of the 18 surveys in the four backwaters (Table 2). We hypothesized that a surface covering of metaphyton would result in lower DO levels due to reduced surface re-aeration and light penetration. Further, attenuation of light energy by surface metaphyton was expected to contribute to lower sub-surface water temperatures.

A significant difference between DO medians between frames was found in 11 of 18 surveys. Of these 11 surveys, 9 revealed lower DO in frame 2 (with metaphtyon) and 2 surveys indicated higher DO in frame 2. For the 9 surveys revealing a lower DO in frame 2, the median DO was 0.6 to 3.2 mg/L lower than frame 1. The two samples exhibiting higher DO with a covering of metaphyton were found in Markle Lake in July and August. The July sample from Markle Lake had moderate sub-surface *L. trisculca* surrounding the DO sonde. It is suspected that since the sensor depth was only at about 0.2 m, sufficient light energy was available for this lemnid to produce oxygen and contribute to higher DO even below a moderate surface layer of *Spirodela polyrhiza*. The reason for the increased DO in frame 2 for the August sample was not established.

Surface metaphyton removal had no significant effect on the continuous DO measurements made in the Horseshoe backwater and marginal influence in Round Lake (Table 2). These backwaters have oxygenated inflows from flowing channels. The Horseshoe backwater in particular had noticeable water current due to flow from the main channel and this likely offset any localized impact associated with differential metaphyton covering between sampling frames. Further, this site was dominated by filamentous algae during July and August which tends to exhibit moderate vertical movements. These algae may contribute to increased subsurface oxygen concentrations during periods when the metaphyton resides below the surface and light is not limiting. The highest diurnal DO during June, July and August was evident in the in the Horseshoe backwater

(Figure 4d), which suggests greater photosynthetic activity at this site. The combination of increased flow and photosynthetic activity in the Horseshoe backwater negated any influence due metaphyton cover.

A comparison of median surface water temperatures measured in frame 1 versus frame 2 did not reveal significant differences during the 18 continuous monitoring surveys (Table 2). The median difference between frames was within +/- 0.1 ^{o}C throughout the study. There were some differences noted between frames when viewing a plot of the raw data, but these generally occurred during brief periods of sunny weather but were normally less than 1.5 ^{o}C. There was no clear pattern of surface (0.2 m) water temperatures being warmer or cooler under metaphyton during these periods so we were unable to conclude that metaphyton played an important role influencing surface water temperatures.

Influence of River Flow, Solar Radiation, Wind Speed on DO and Temperature

The potential influence of river flow, solar radiation and wind speed on continuous DO and water temperature measurements was evaluated by Spearman correlation analysis. Data were restricted to July and August to minimize the influence of seasonal changes in vegetation and water temperatures. Data collected in the Horseshoe backwater was also omitted because this backwater was strongly influenced by river flow as discussed above and there was interest to know how the remaining three backwaters responded to these factors.

Correlation analysis revealed significant but weak positive correlation between daily average DO and river flow. However, this response was only found in frame 2, which contained metaphyton throughout the sonde deployment periods (Table 4). Metaphyton was removed from frame 1 during initial frame deployment and normally resulted in higher DO in this frame as discussed above. The positive DO response due to initial metaphyton removal in frame 1 may have been sufficient to obscure any positive correlation between DO and flow in this frame.

Daily average temperature was negatively correlated with river flow in both frames and suggests that river flow may play a larger role in influencing surface backwater temperatures than differences in metaphyton cover. Increased flow would be expected to yield cooler water as a result of increased backwater depths, colder tributary inflows and increased cloud cover associated with precipitation events.

Daily average temperature in frame 2 indicated a significant negative correlation with daily average wind speed but this response was not found in frame 1. Again, metaphyton cover apparently played some role in this differential response between frames possibly related to influence these metaphyton mats have on near surface thermal storage and mixing processes. This was reflected in daily diurnal temperatures, which exhibited a moderate negative correlation with daily average wind speed in both frames suggesting that wind-induced destratification, mixing and convectional cooling likely dampened daily temperature fluctuations.

DO and temperature measurements were not found to be correlated with daily solar radiation. The lack of correlation with solar radiation was initially surprising. However, solar radiation was positively correlated with average daily wind speed (r=0.402) suggesting clear weather (high pressure) was associated with increased wind speeds during this study. This suggests the heating of water by increased solar radiation may have been offset by wind-induced mixing and cooling processes. DO concentrations may have been similarly affected due to changes in photosynthetic activity, decreased thermal stratification and mixing of bottom waters low in DO with surface waters.

Backwater DO and Fish and Aquatic Life DO Criterion

Wisconsin’s DO criterion for warm water fish and aquatic life is 5 mg/L minimum. Data described previously indicates that this criterion was not achieved in backwaters measured in this study.

This was further evaluated by calculating the percent of DO concentrations falling below 5, 2 and 0.2 mg/L for each backwater by month (Figure 7). Data for both sondes are presented as another means to evaluate the influence of metaphyton differences between the two sampling frames.

DO levels were less than the 5 mg/L criterion in more than 10% of the samples in all but the May sampling of Markle Lake (Figure 7a, frame 1). Attainment of the DO criterion dropped off dramatically during the summer, especially in Round, Markle and Beiers Lakes, with 50 to 100% of the samples falling below 5 mg/L. The severity of low DO was further illustrated by plotting the DO percentiles falling below 2 and 0.2 mg/L (Figure 7b and 7c, respectively). These figures indicate that hypoxic conditions were present in all months but were especially apparent during July and August. Anoxic conditions were primarily restricted to July and August with a minor occurrence at Beiers Lake in May and Markle Lake in June in frame 2.

The influence greater hydraulic connectivity with the main channel can again be seen in DO percentiles plotted for the Horseshoe backwater (Figure 7a and 7b). This backwater had noticeably greater DO as discussed previously. However, even in this backwater DO levels failed to achieve the 5 mg/L DO criterion in about 25 to 55% of the samples during June-September. It should be noted that main channel DO was less than 5 mg/L during mid-summer based on monitoring at Lock and Dam 8 (John Sullivan, unpublished data) and was likely an important factor influencing low DO concentrations in the Horseshoe backwater during this study.

The frequency of non-attainment of Wisconsin's the fish and aquatic life DO criterion (5 mg/L) during July and August was negatively related to an index of hydraulic connectivity that was derived for each backwater (Figure 8). This index reflects the mean water velocity measured in the backwaters based on summer, fall and winter stratified random sampling surveys collected by LTRMP from 1993-2008 (Jim Rogala, USGS, pers. com.). The presence of metaphyton (frame 2) resulted in a slight increase in the frequency of non-attainment, but the response was small and was only noted in Round Lake and Horseshoe. A similar response was not observed in Markle and Beiers Lakes and was likely related to the very low DO encountered in these backwaters during July and August (Table 2). These latter backwaters had hypoxic to anoxic conditions during this period at the monitored sites and the DO changed very little and with a mixed response (-1.6 to 0.7 mg/L) when the metaphyton was removed from the sampling frames (Table 2). This doesn't mean metaphyton were not important in influencing the DO, rather, the severe DO deficit that was encountered at these sites, couldn't be overcome by removing a relatively small area of metaphyton (0.6 m^2). Future continuous DO monitoring in metaphyton-free backwaters with low hydraulic connectivity during July and August should be considered since it would provide another means for evaluating the potential of these shallow vegetated systems to achieve the fish and aquatic life DO criterion.

Summary and Conclusions

Excessive growths of filamentous green algae and duckweeds, generally described here as metaphyton, have been observed in UMR backwaters. Recent studies have focused on the factors contributing to metaphyton distribution and abundance, especially nutrient sources and availability, habitat and hydraulic factors. Hydraulic connectivity is a particularly important factor since it influences nutrient delivery, nutrient processing, water residence time, DO and other factors. The availability of DO is critically important for fish and aquatic life. The focus of past monitoring efforts have largely been based on grab sampling. Excessive metaphyton development, especially thick growths of duckweeds, have been found to have a pronounced negative effect on DO.

A principal focus of this study was to more closely evaluate the impacts of metaphyton on surface DO and water temperature through the use of continuous DO and temperature equipment and to measure metaphyton production. Metaphyton production is an important measure of nutrient enrichment since these plants rely on water column nutrient concentrations for their growth and development. Understanding factors influencing diurnal changes in DO will improve the ability to define the ability of vegetated backwaters to provide suitable habitat for fish and aquatic life.

Week-long continuous monitoring of surficial DO and water temperature was conducted at approximately monthly intervals in four backwaters of Pool 8 from May to September 2010. Two backwaters were reflective of high connectivity to the river and flowing channels and two were indicative of low connectivity areas. DO/temperature sondes were deployed in the center of two small wooden sampling frames in areas that contained metaphyton. The sampling frames allowed measurements of metaphyton biomass and production during the week-long deployment periods.

River flows exhibited moderate to large seasonal variation during the study period and ranged from about 30,000 to 80,000 cfs. Median river flow at Lock and Dam 8 for June through August was about 55,000 cfs, which was about 40% higher than normal for this period. River flow changes contributed to small to moderate fluctuations in water depths ranging from about -0.5 to 0.7 m during sonde deployments in the monitored backwaters. These flow fluctuations provided additional information for evaluating DO/temperature response to temporal changes in hydraulic connectivity.

DO and water temperature exhibited large seasonal changes from May through September. Average daily DO ranged from near 0 to 15 mg/L. Highest values were associated with cooler water in May and in the Horseshoe backwater area, which received oxygenated infow directly from the main channel. Lowest values were found in the Markle and Beiers lakes during July and August when daily average temperatures exceeded 25 ^{o}C. These backwaters have very little connection with flowing channels during normal flows, dense beds of aquatic vegetation, high sediment oxygen demand and reduced surface re-aeration due to dense metaphyton mats, which contribute to hypoxic to anoxic conditions during mid-summer. A rapid rise in river flow from about 40,000 to 77,000 cfs during mid-August only resulted in a small increase in DO in Markle Lake indicating increased connectivity with oxygenated inflows, but hypoxic conditions still persisted. Surprisingly, no dead fish were encountered during periods of near anoxia in Markle and Beiers lakes suggesting fish were able to find refuge in areas with higher DO.

June through August DO concentrations revealed significant differences between backwaters that were likely influenced by hydraulic connectivity and metaphyton form and abundance. Backwaters with higher connectivity to flowing channels, Horseshoe and Round Lake, generally responded similarly with respect to daily average and daily minimum DO and had metaphyton normally dominated by filamentous green algae. Markle and Beiers lakes are more isolated, have substantially lower hydraulic connectivity with flowing channels and had greater metaphyton biomass dominated by duckweeds, resulting in noticeably lower DO. The Horseshoe backwater exhibited substantially greater daily maximum and diurnal DO, about 13 and 10 mg/L, respectively, than the other three backwaters. This backwater was more directly influenced by the main channel and the mid-summer metaphyton community was dominated by filamentous algae rather than the duckweeds.

Water temperature metrics (daily average, minimum, maximum, diurnal) were generally similar across the four backwaters during June through August. This suggests water temperature was not an important factor influencing spatial differences in DO and provided little information for characterizing thermal differences in the backwaters studied.

Metaphyton biomass averaged 73.5 and ranged from about 25 to 190 g/m^2 dry wt based on measurements in frame 2. Biomass was generally greater in Markle and Beiers Lake than Horseshoe or Round Lake. Highest biomass was associated with members of the *Lemnaceae* family. There was no consistent temporal pattern in biomass among the four backwaters. Some biomass measurements were likely influenced by wind or wave-driven accumulations so data reported here should be used with caution.

Metaphyton production averaged 2.2 and ranged from about 0.3 to 8 g dw /m^2/day after excluding values that likely reflected wind or wave-driven accumulations. Highest production was associated with *Spirodela polyrihiza*. Production averaged 3.3 g/ dw/m^2/day where metaphyton was dominated by filamentous green algae. In general, metaphyton production was highest during mid- to late summer in the four monitored backwaters.

Median DO derived from continuous measurements was found to differ significantly by dominant metaphyton type. Metaphyton dominated by filamentous green algae had the highest daily median DO (6.1 mg/L), followed by *Lemna* sp., *Spirodela polyrhiza*, and *Wolffia.* Backwaters where metaphyton was dominated by duckweeds had substantially lower DO with hypoxic conditions common during July and August. These responses likely reflect differences in the fate of oxygen produced by algae versus duckweeds and the effects these plant mats have on atmospheric re-aeration of water. Filamentous algae release oxygen directly to water, especially when it is present below the surface. In contrast, most of the duckweeds, with the exception of *L. trisulca*, would release oxygen to the atmosphere and dense surface mats of these plants limit atmospheric re-aeration.

Square wooden sampling frames were deployed to test the influence of metaphyton removal on surface (0.2 m) DO and temperature measurements. A significant difference in median DO was found in 11 of 18 surveys with 9 showing a lower DO (0.6 to 3.2 mg/L) in frames where metaphyton was not removed. In one situation where median DO increased in the frame containing metaphyton, the sonde was surrounded by *L. trisculca,* which likely contributed to a localized increase in DO. Metaphyton removal from sampling frames deployed in the Horseshoe backwaters did not have any significant effect on median DO. This backwater had substantially greater water exchange with the main channel and this oxygen inflow was sufficient to off-set the influence of differential metaphyton cover between the two sampling frames.

There was no evidence of water temperatures being significantly warmer or cooler under metaphyton so we can't conclude that metaphyton played a significant factor influencing surface temperatures measured in this study. Some temperature differences were noted between frames, but these generally occurred during short periods of sunny weather but were normally less than 1.5 ^{o}C and the response to the metaphyton treatment was variable.

Changes in river flow, wind speed and solar radiation were likely important factors influencing continuous DO and water temperature measurements based on data collected mid-summer (July-August). Daily solar radiation was significantly correlated to daily average wind speed suggesting solar heating of water could have been off-set by wind-induced mixing and evaporative cooling. In general, river flow appeared to have a greater influence on DO and wind speed had a stronger influence on water temperature.

Wisconsin's 5.0 mg/L DO criterion for fish and aquatic life was not attained in backwaters monitored during the summer of 2010, especially during July-August. Low DO in backwater areas of the UMR is likely strongly related to the respiratory demands associated with dense beds of aquatic vegetation, increased sediment oxygen demand and decreased surface re-aeration in shallow backwater areas that receive little oxygenated inflows from flowing channels. The presence of these hypoxic to anoxic conditions in backwaters may not necessarily represent a human-caused impairment since such conditions can occur naturally in shallow vegetated systems. However, it is likely that nutrient enrichment of these backwater areas have exacerbated these problems as a result of the increased development of metaphyton, especially duckweeds.

There is need for additional continuous DO measurements in UMR backwaters or similar systems that are not heavily enriched with nutrients as reflected in excessive metaphtyon biomass. Such monitoring, in conjunction with fish and macroinvertebrate sampling, may yield more accurate information for establishing appropriate chemical and biological criteria for defining fish and aquatic life use and would serve as an important reference for comparative purposes.

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Table 1. Grab sample water quality measurements collected during the start and end of continuous water quality measurements in Pool 8 backwaters. Measurements were taken 0.2 m below the surface between sampling frames 1 and 2.

Backwater	Period	Depth m			DO mg/L		Temp. °C		Specific Cond. uS/cm		pH		Turbidity NTU	
		Start	End	Change	Start	End	Start	End	Start	End	Start	End	Start	End
Beiers Lake	May 25-June 1	0.87	0.69	-0.18	3.0	8.5	26.3	24.1	467	419	7.65	8.48	11.0	4.5
	June 25-July 2	1.40	2.07	0.67	10.3	2.8	26.1	23.1	381	396	7.95	6.93	8.2	2.3
	July 23-July 30	1.46	1.34	-0.12	4.5	2.4	26.7	25.0	436	374	7.35	7.24	2.4	5.8
	Aug 20-Aug 27	1.65	1.28	-0.37	0.9	2.3	25.7	22.2	321	363	6.93	6.95	10.8	4.9
	Sept 17-Sept 24	1.07	1.52	0.45	3.6	5.2	17.8	18.2	360	310	7.50	7.30	7.0	21.0
	Avg:	**1.29**	**1.38**	**0.09**	**4.5**	**4.2**	**24.5**	**22.5**	**393**	**372**	**7.48**	**7.38**	**7.9**	**7.7**
Horseshoe	June 3-June 10	0.38	0.40	0.02	11.5	8.2	22.9	20.9	489	505	8.55	7.77	5.3	5.7
	July 2-July 9	0.84	0.72	-0.12	11.1	11.0	24.9	26.5	515	541	8.21	8.38	3.6	2.9
	July 30-Aug 6	0.56	0.46	-0.10	15.2	6.6	26.5	24.8	474	483	8.74	7.83	2.7	2.2
	Aug 27-Sept 3	0.52	0.40	-0.12	11.4	6.9	25.9	20.8	362	377	8.49	7.52	2.1	4.3
	Avg:	**0.58**	**0.50**	**-0.08**	**12.3**	**8.2**	**25.1**	**23.25**	**460**	**477**	**8.50**	**7.88**	**3.4**	**3.8**
Markle Lake	May 14-May 21	0.27	0.46	0.19	22.9	7.5	18.4	19.0	342	420	9.35	8.25	7.4	8.6
	June 18-June 25	0.67	0.91	0.24	7.7	3.5	23.8	23.8	386	465	8.28	7.27	4.5	2.4
	July 16-July 23	0.84	0.88	0.04	7.0	0.5	28.0	24.1	393	292	7.81	7.08	1.9	2.2
	Aug 13-Aug 20	0.37	1.11	0.74	1.2	2.6	26.8	24.6	442	295	7.19	7.14	6.3	6.3
	Sept 10-Sept 17	0.39	0.43	0.04	6.1	5.6	19.5	16.8	430	441	7.32	7.60	4.3	6.0
	Avg:	**0.51**	**0.76**	**0.25**	**9.0**	**3.9**	**23.3**	**21.7**	**399**	**383**	**7.99**	**7.47**	**4.9**	**5.1**
Round Lake	June 11-June 17	0.72	1.01	0.29	10.0	9.3	22.6	26.4	436	254	8.21	8.23	3.9	3.3
	July 9-July 16	1.52	1.36	-0.16	11.2	4.4	28.4	25.1	332	374	8.38	7.43	5.9	4.0
	Aug 6-Aug 13	0.88	1.11	0.23	3.7	3.5	25.3	26.8	173	253	7.05	7.27	5.5	3.6
	Sept 3-Sept 10	0.88	0.86	-0.02	1.7	6.0	20.1	16.9	270	234	7.43	6.36	6.5	6.8
	Avg:	**1.00**	**1.09**	**0.09**	**6.7**	**5.8**	**24.1**	**23.8**	**303**	**279**	**7.77**	**7.32**	**5.5**	**4.4**

Table 2. Median DO and temperature measurements by backwater area, month, and sampling frame for the 2010 metaphyton study in Pool 8. Significant differences ($p<0.05$) in medians (two-sample median test) between sampling frames (F1 & F2) are shown in bold. Metaphyton (Meta) biomass and estimated production measurements are based on a single measurement for each backwater by month. Dominant metaphyton (DomMeta) type during initial frame deployment (F1) and end of monitoring period (F1b, F2) are for biomass and production measurements.

			Dissolved Oxygen mg/L				Temperature °C				Meta. Biomass g DW/m^2		Meta. Production	F1	F1b	F2
Backwater	**Month**	**N**	**F1**	**F2**	**Diff**	**p**	**F1**	**F2**	**Diff**	**p**	**F1**	**F2**	**g dw/m^2/day**	**DomMeta**	**DomMeta**	**DomMeta**
Markle Lake	May	659	11.3	9.5	1.8	**0.000**	19.9	19.9	0.0	0.876	23.7	25.2	0.40	Fil. Algae	Fil. Algae	Fil. Algae
Markle Lake	June	669	5.1	3.7	1.4	**0.000**	24.2	24.2	0.0	0.804	ns	150.4	45.7[a]	ns	Spirodela	Spirodela
Markle Lake	July	659	1.3	1.7	-0.4	**0.000**	25.9	26.0	-0.1	0.160	3.3	144.7	0.96	Spirodela	Spirodela	L. trisulca
Markle Lake	Aug	649	0.6	2.2	-1.6	**0.000**	25.3	25.2	0.1	0.483	ns	56.8	1.76	ns	Wolffia	Spirodela
Markle Lake	Sept	662	4.3	3.5	0.8	**0.000**	19.4	19.4	0.0	1.000	58.8	41.2	1.91	L. minor	L. minor	L.minor
Beiers Lake	May	633	6.0	2.8	3.2	**0.000**	26.2	26.1	0.1	0.843	8.5	70.2	1.03	Spirodela	Spirodela	Spirodela
Beiers Lake	June	577	5.5	5.0	0.5	**0.008**	25.0	25.0	0.0	0.767	ns	28.8	0.53	ns	L. minor	L. minor
Beiers Lake	July	793	0.9	0.2	0.7	**0.000**	26.6	26.6	0.0	0.667	ns	77.0	20.6[a]	ns	Spirodela	Spirodela
Beiers Lake	Aug	657	0.0	0.0	0.0	-	25.3	25.3	0.0	0.334	429.7	102.8	5.31	L. minor	L. minor	Spirodela
Beiers Lake	Sept	633	4.7	4.3	0.4	**0.000**	18.1	18.0	0.1	0.867	155.0	190.0	2.40	L. minor	L. minor	L. minor
Horseshoe	June	666	8.1	8.1	0.0	0.826	22.3	22.3	0.0	0.868	17.0	43.5	1.12	Spirodela	Spirodela	Spirodela
Horseshoe	July	797	6.5	6.6	-0.1	0.960	25.1	25.1	0.0	0.757	ns	30.5	3.39	ns	Fil. Algae	Fil. Algae
Horseshoe	Aug	946	5.7	5.4	0.3	0.299	25.8	25.8	0.0	0.558	ns	43.8	3.14	ns	Fil. Algae	Fil. Algae
Horseshoe	Sept	230	4.8	4.5	0.3	0.483	23.9	23.9	0.0	0.921	ns	49.7	0.86	ns	Spirodela	Spirodela
Round Lake	June	679	7.6	7.5	0.1	0.683	21.7	21.7	0.0	0.634	ns	39.6	0.29	ns	Spirodela	Spirodela
Round Lake	July	654	4.8	4.2	0.6	**0.023**	26.7	26.6	0.1	0.451	17.2	52.0	3.43	Fil. Algae	Fil. Algae	Fil. Algae
Round Lake	Aug	664	2.3	1.7	0.6	**0.000**	27.1	27.1	0.0	0.632	14.2	98.0	8.17	Spirodela	Spirodela	Spirodela
Round Lake	Sept	648	5.1	5.1	0.0	0.889	18.0	17.9	0.1	0.912	95.6	79.6	0.90	L.minor	L.minor	L. minor

[a]Metaphyton production estimate likely baiased high due to wind or wave blown accumulation.
Diff - Difference in DO and Temperature between Frame 1 and Frame 2.
F1- Frame 1 Metaphyton biomass sample removed from frame at the start of the monitoring period.
F1b - Frame 1 Metaphyton biomass sampled removed from frame at the end of the monitoring period.
F2 - Frame 2 Metaphyton biomass sample in Frame 2 at the end of the monitoring period.
ns - no sample or not measured.

Table 3. Average daily dissolved oxygen (DO) and temperature metrics by backwater area for the June to August period. A Kruska-Wallis (K-W) AOV was used to test for significant differences between backwater areas. Significant differences at $p < 0.05$ indicated in bold. Groups identified with similar letters do not differ significantly from one another.

		Beiers Lk.		Horseshoe		Markle Lk.		Round Lk.		K-W
Variable	**Frame[1]**	**N**	**Avg.**	**N**	**Avg.**	**N**	**Avg.**	**N**	**Avg.**	**p**
Daily Avg. DO mg/L	1	18	2.0 **c**	22	7.5 **a**	18	2.7 **bc**	17	5.0 **ab**	**0.000**
	2	18	1.8 **c**	22	7.5 **a**	18	2.8 **bc**	17	4.5 **ab**	**0.000**
Daily Min. DO mg/L	1	18	0.6 **b**	22	3.2 **a**	18	0.9 **b**	17	3.0 **a**	**0.000**
	2	18	0.6 **c**	22	3.1 **a**	18	1.3 **bc**	17	2.7 **ab**	**0.000**
Daily Max. DO mg/L	1	18	4.1 **b**	22	13.3 **a**	18	5.2 **b**	17	7.7 **b**	**0.000**
	2	18	3.5 **b**	22	13.1 **a**	18	4.9 **b**	17	6.6 **b**	**0.000**
Daily Dirunal DO mg/L	1	18	3.5 **b**	22	10.1 **a**	18	4.3 **b**	17	4.7 **b**	**0.000**
	2	18	2.9 **b**	22	10.0 **a**	18	3.6 **b**	17	3.8 **b**	**0.000**
Daily Avg. Temp. ^{o}C	1	18	26.1	22	24.9	18	25.3	17	25.6	0.144
	2	18	26.0	22	24.9	18	25.4	17	25.5	0.245
Daily Min. Temp. ^{o}C	1	18	24.4	22	23.2	18	24.0	17	24.1	0.246
	2	18	24.4	22	23.2	18	24.0	17	24.1	0.223
Daily Max. Temp. ^{o}C	1	18	28.4	22	27.3	18	27.2	17	27.6	0.377
	2	18	28.2	22	27.5	18	27.4	17	27.4	0.631
Daily Diurnal Temp. ^{o}C	1	18	4.0	22	4.2	18	3.2	17	3.6	0.488
	2	18	3.8	22	4.3	18	3.4	17	3.3	0.441

[1]Frame 1 - Metaphyton removed from the sampling frame at the start of the monitoring period.
Frame 2 - Metaphyton not removed from the sampling frame at the start of the monitoring period.

Table 4. Spearman rank correlations of daily river flow, daily solar radiation and wind speed verus dissolved oxygen (DO) and water temperature variables measured in Beiers, Markle and Round Lakes during July-August 2010. Correlations significant at $p<0.05$ indicated in bold.

Variable	Frame	Daily Flow	Daily Solar Radiation	Daily Average Wind Speed
Daily Avg. DO	1	-0.064	0.167	0.019
	2	**0.374**	0.125	-0.152
Daily Diurnal DO	1	0.036	0.209	-0.090
	2	0.283	0.144	-0.108
Daily Avg. Temp.	1	**-0.367**	0.026	-0.282
	2	**-0.374**	0.011	**-0.341**
Daily Diurnal Temp.	1	-0.192	-0.131	**-0.378**
	2	-0.104	-0.172	**-0.543**

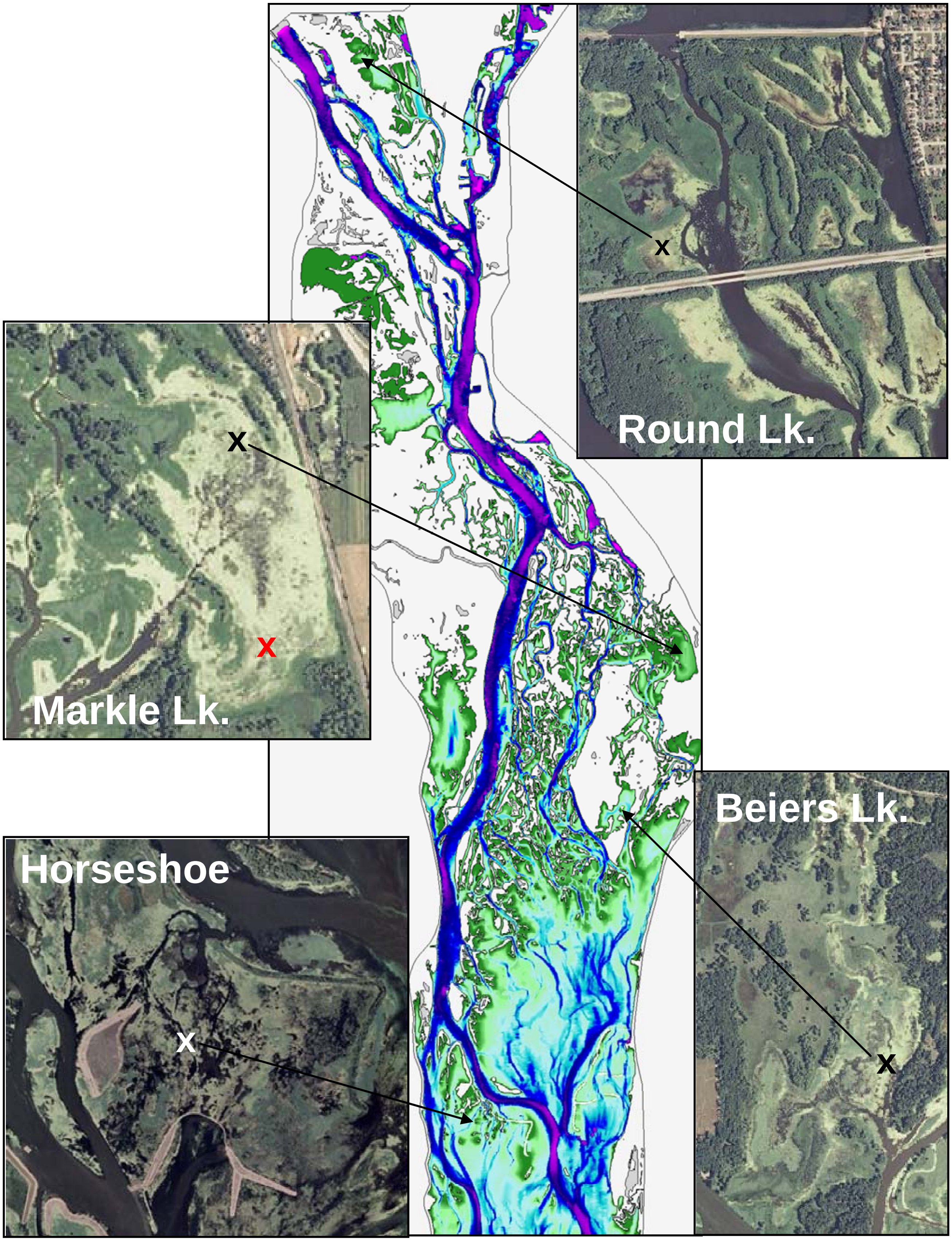

Figure 1. Map and aerial photos of four backwater study areas of navigation Pool 8 in the Upper Mississippi River. A bold “x” denotes the continuous monitoring site location used in this study. Based map from obtained from the USGS Upper Midwest Environmental Sciences Center web site.

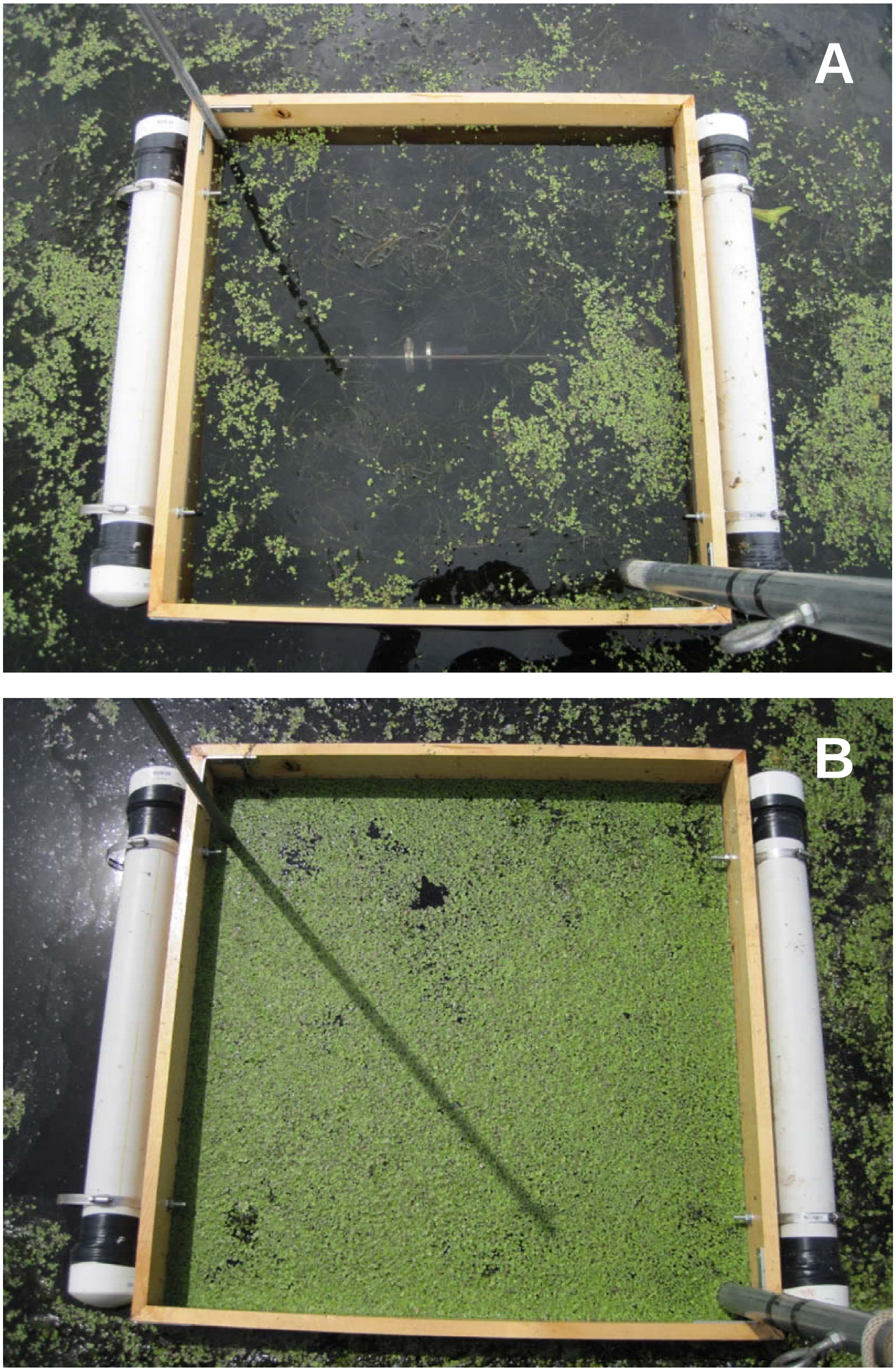

Figure 2 A. Metaphyton sampling frame 2 in Round Lake June 11, 2010. A D-Opto DO/temperature sensor can be seen mounted on an underwater support bar. B. Same frame and location on June 17, 2010. Metaphyton dominated by *Spirodela polyrhiza*.

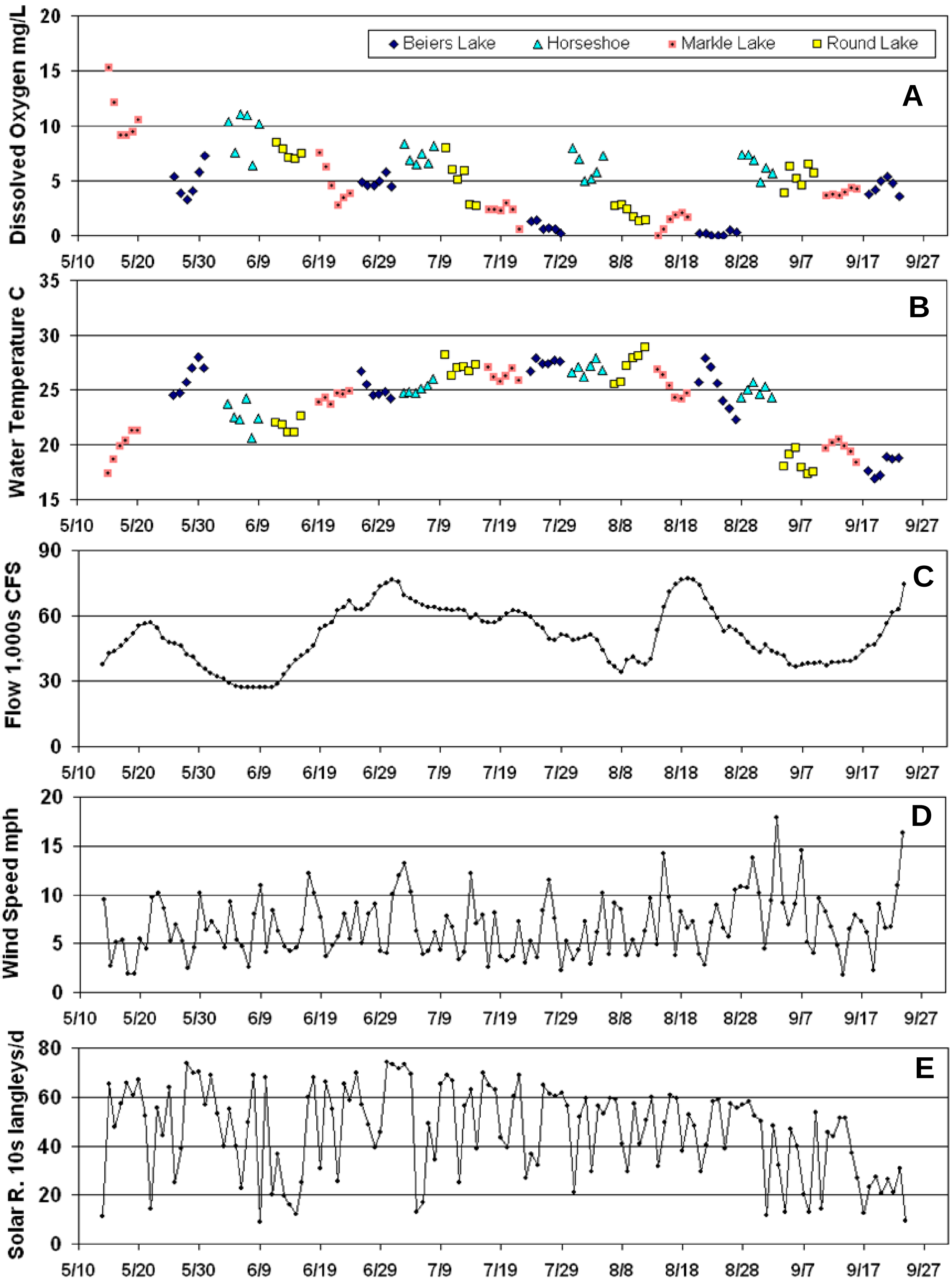

Figure 3. Average daily dissolved oxygen (A) and water temperature (B) measured in four backwaters of Pool 8 during May-October 2010. Daily river flow (C) at Lock and Dam 8 reported by the US Corps of Engineers. Average daily wind speed (D) reported by the National Weather Service for the La Crosse Airport. Daily solar radiation (E) measured by the Wisconsin DNR at the La Crosse Service Center.

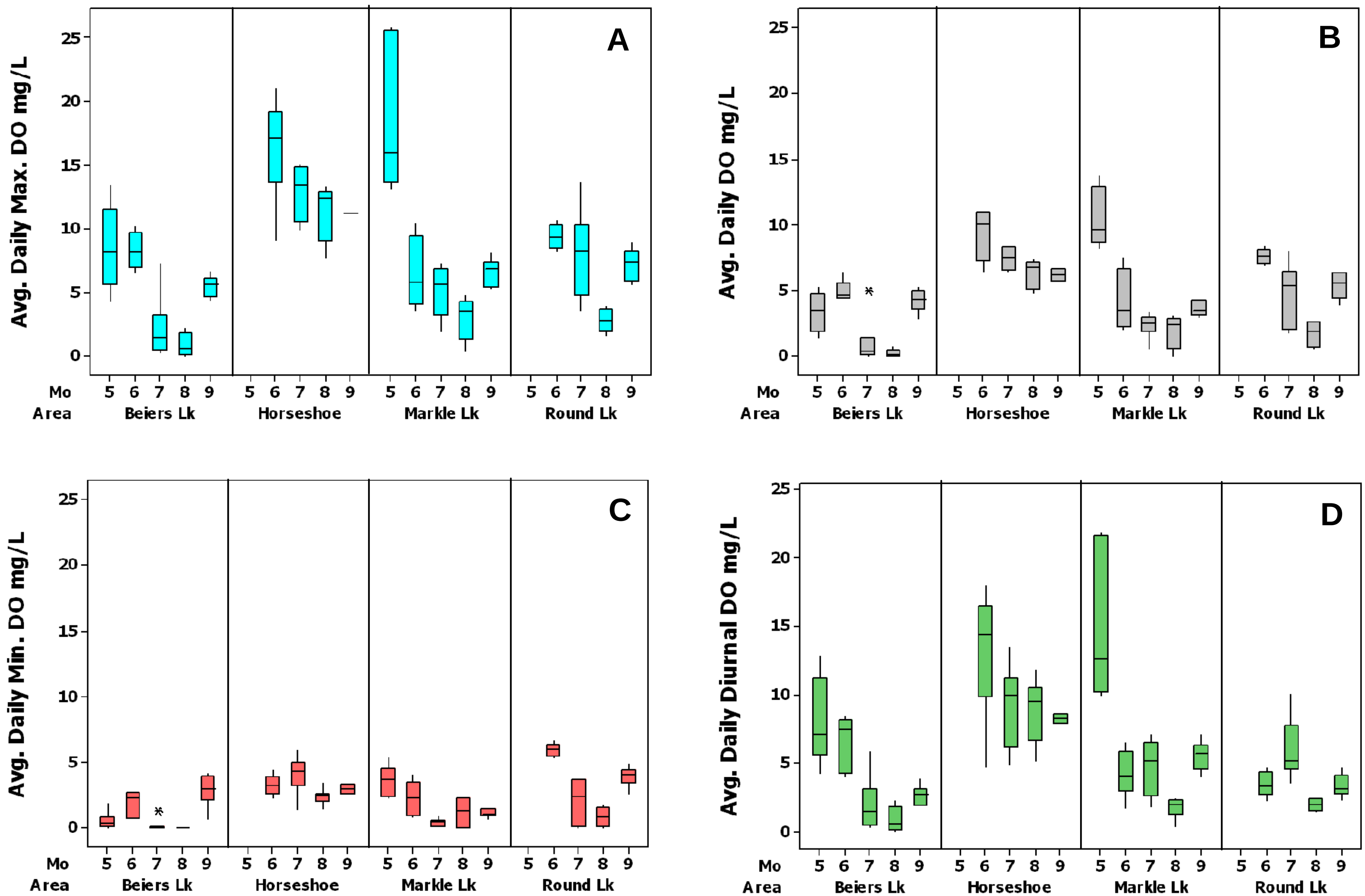

Figure 4. Box plots of average daily maximum dissolved oxygen (DO) (A), average daily DO (B), average daily minimum DO (C) and average daily diurnal DO (D) measured in four backwater areas of Pool 8 during May-September in 2010. Data are for frame 2 (metaphyton not removed).

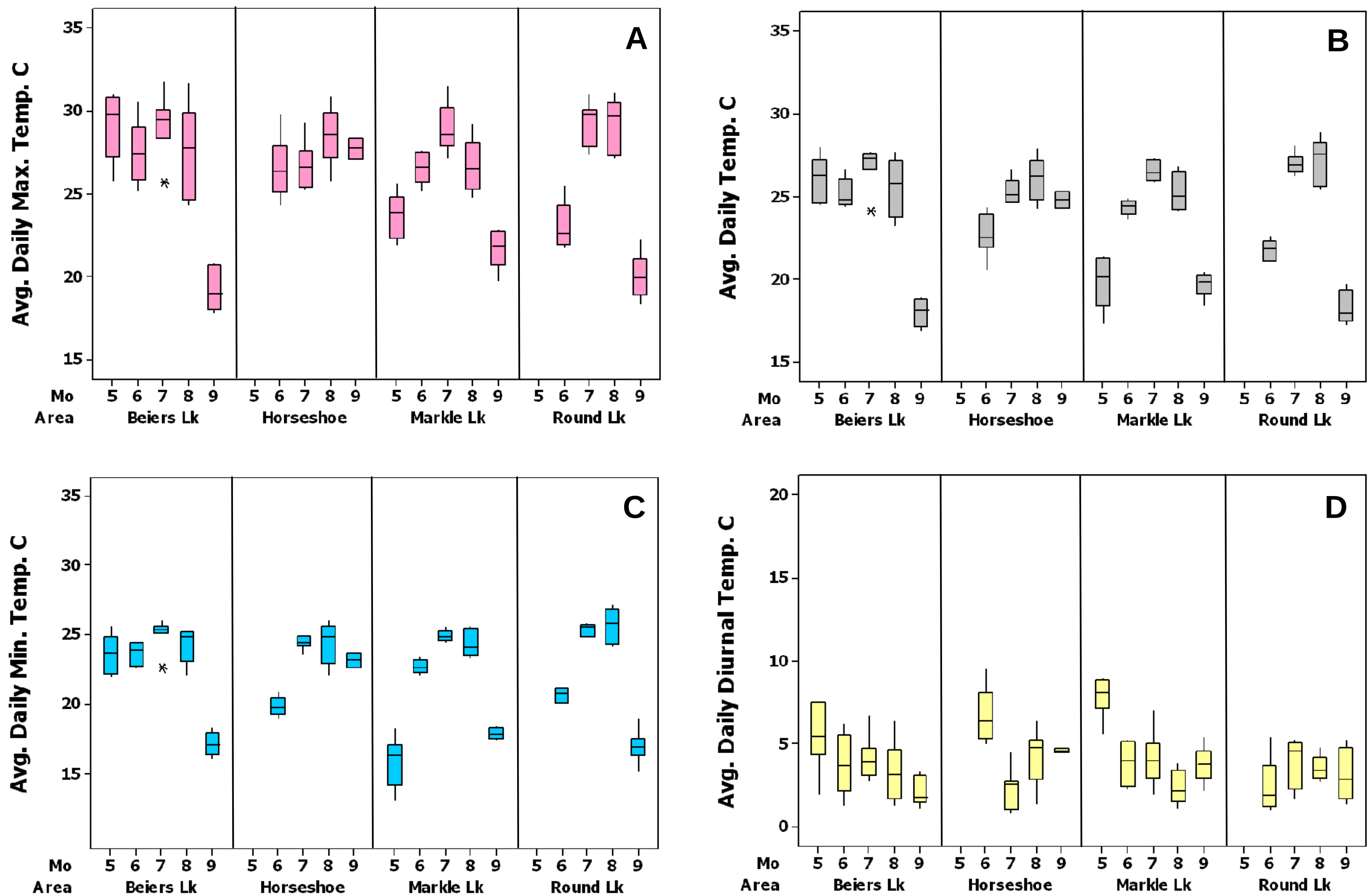

Figure 5. Box plots of average daily maximum water temperature (A), average daily water temperature (B), average daily minimum water temperature (C) and average daily diurnal water temperature (D) measured in four backwater areas of Pool 8 during May-September in 2010. Data are for frame 2 (metaphyton not removed).

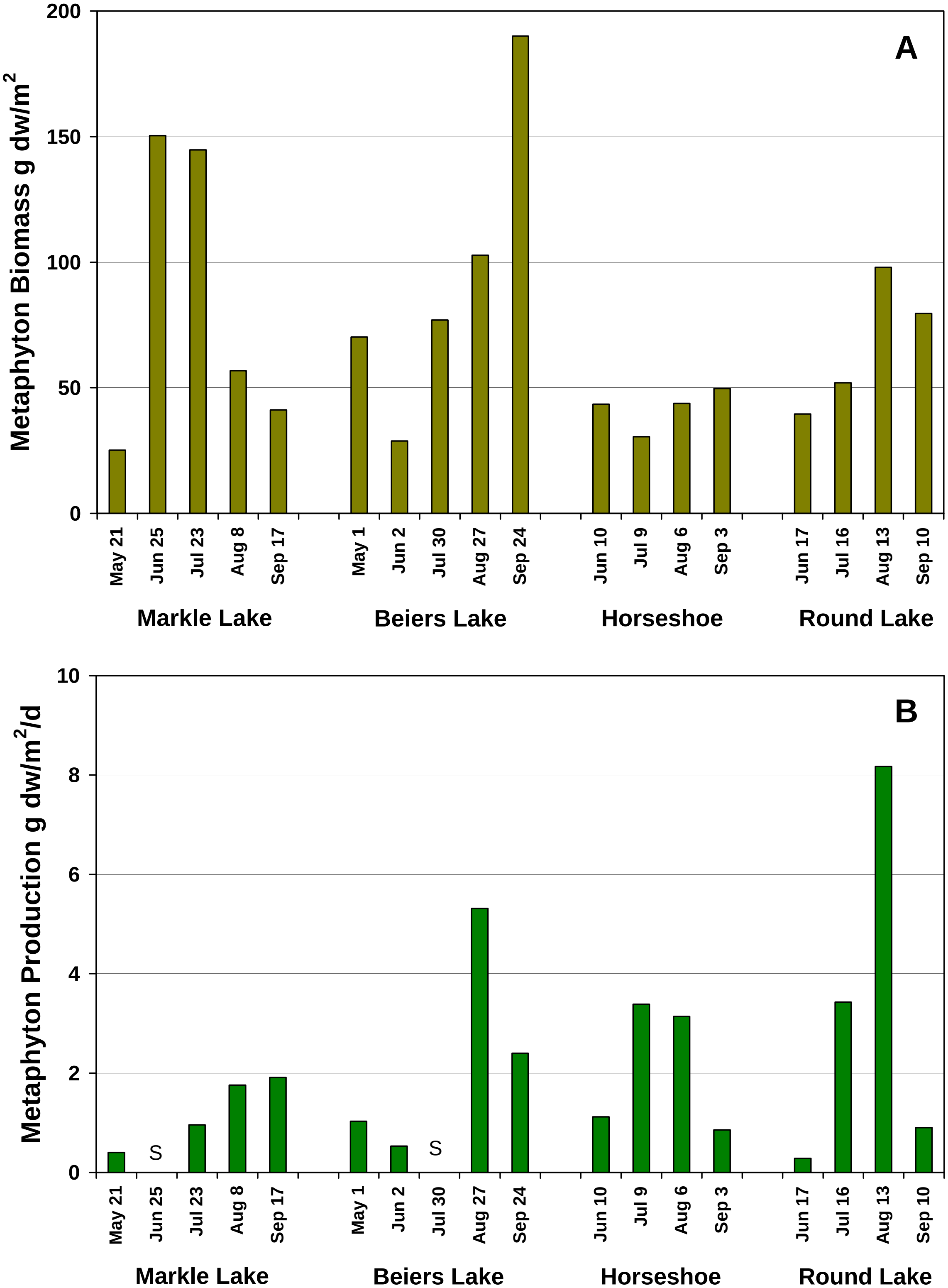

Figure 6. Metaphyton biomass measured in frame 2 (A) and metaphyton production (B) measured in frame 1 in four backwaters of Pool 8 during May to September 2010. The indicated date is for the end of the week-long monitoring period. Production marked with "S" reflects suspect data and are not included.

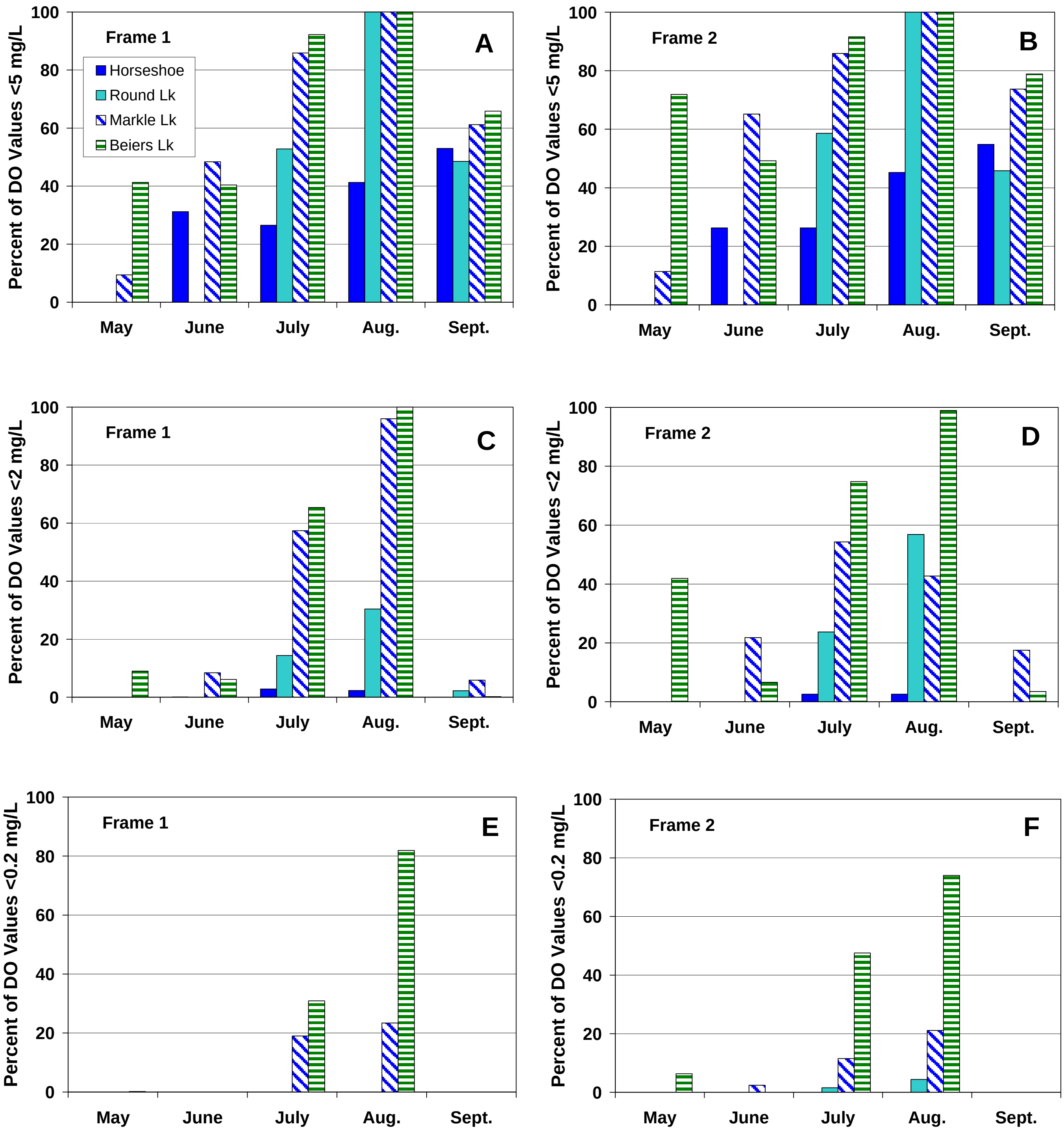

Figure 7. Percent of dissolved oxygen (D0) values less than 5 mg/L measured in frame 1 (A) and frame 2 (B); percent of DO values less than 2 mg/L measured in frame 1 (C) and frame 2 (D); percent of DO values less than 0.2 mg/L measured in frame 1 (E) and frame 2 (F) in four backwaters of Pool 8 during May-September in 2010.

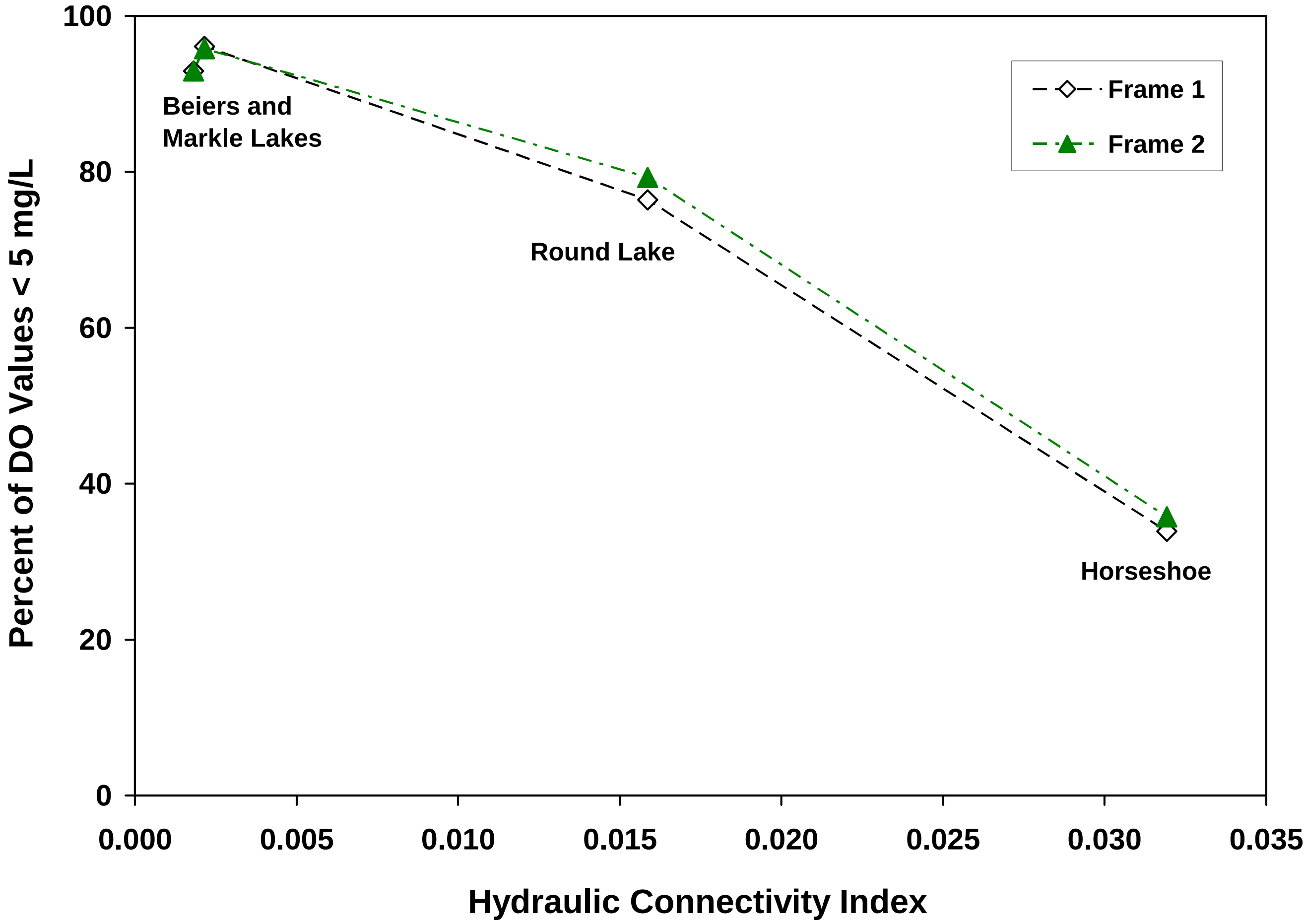

Figure 8. Non-attainment frequency of Wisconsin's dissolved oxygen (DO) criterion versus an index of hydraulic connectivity for four backwaters monitored in Pool 8 during July and August, 2010. The hydraulic connectivity index was derived from mean backwater velocity measurements during summer, fall and winter conditions (Jim Rogala, USGS, pers. com.)