Site-Specific Total Phosphorus Criteria for Petenwell Lake, Castle Rock Lake, and Lake Wisconsin

Technical Support Document

May 6, 2019 Draft

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Madison, WI 53703

Summary of findings and recommendations

Wisconsin Administrative Code NR 102.06(7) states that site-specific criteria (SSC) for total phosphorus (TP) may be adopted where site-specific data and analysis using scientifically defensible methods and sound scientific rationale demonstrate a different criterion is protective of the designated use of the specific surface water segment or waterbody. TP SSC were estimated for Petenwell Lake, Castle Rock Lake, and Lake Wisconsin, which are expected to protect the recreation and aquatic life uses of these waters. Analyses described in this document show that the recreational use target (70^{th} percentile chlorophyll *a* < 20 µg/L during July 15 – September 15) is likely the most sensitive use, so the TP SSC were set to meet this target. The SSC are based on empirical estimates of the effects of TP concentration, river discharge, and day of year on chlorophyll *a* concentration. The recommended SSC for Petenwell and Castle Rock are 53 and 55 µg/L TP, respectively, as a summer (June 1 – September 15) mean concentration, which is higher than the existing criteria (40 µg/L TP). The recommended SSC for Lake Wisconsin is 47 µg/L TP, which is lower than the existing criterion (100 µg/L TP). An SSC was evaluated for Lake Du Bay but is not recommended because the relationship between TP and chlorophyll is strongly affected by variable water releases from Big Eau Pleine Reservoir, and the TP concentration that will be reached to meet SSC for the downstream reservoirs is sufficient to meet the chlorophyll target in Lake Du Bay.

Regulatory authority

A site-specific criterion (SSC) is established for an individual waterbody or segment when the statewide criterion is either over- or under-protective to support the designated uses of the waterbody due to site-specific characteristics. The authority for adopting any water quality criteria is established in Wis. Stat. s. 281.15:

> **(1)** The department shall promulgate rules setting standards of water quality to be applicable to the waters of the state, recognizing that different standards may be required for different waters or portions thereof. Water quality standards shall consist of the designated uses of the waters or portions thereof and the water quality criteria for those waters based upon the designated use. Water quality standards shall protect the public interest, which include the protection of the public health and welfare and the present and prospective future use of such waters for public and private water systems, propagation of fish and aquatic life and wildlife, domestic and recreational purposes and agricultural, commercial, industrial and other legitimate uses. In all cases where the potential uses of water are in conflict, water quality standards shall be interpreted to protect the general public interest.

Wisconsin Administrative Code also specifically allows for the development of phosphorus site-specific criteria under Wis. Adm. Code s. NR 102.06(7):

> **NR 102.06 Phosphorus.** (7) SITE-SPECIFIC CRITERIA. A criterion contained within this section may be modified by rule for a specific surface water segment or waterbody. A site-specific criterion may be adopted in place of the generally applicable criteria in this section where site-specific data and analysis using scientifically defensible methods and sound scientific rationale demonstrate a different criterion is protective of the designated use of the specific surface water segment or waterbody.

Applicable designated uses

As specified above in Wis. Stat. s. 281.15 and Wis. Adm. Code s. NR 102.06(7), a site-specific criterion may be set to be protective of the designated use(s) of the waterbody in question. All surface waters are assigned the following four designated uses: Fish and Aquatic Life (hereafter Aquatic Life), Recreation, Wildlife, and Public Health and Welfare. For purposes of this analysis, only aquatic life and recreation are assessed because the state's phosphorus criteria are not applicable to the wildlife or public health and welfare uses.

The aquatic life designated use has the following subcategories: coldwater, warmwater sport fish, warm water forage fish, limited forage fish, and limited aquatic life. Petenwell Lake, Castle Rock Lake, and Lake Wisconsin all have the designated aquatic life use subcategory of "warmwater sport fish". Chapter NR 102.04(3)(b) states: "This subcategory includes surface waters capable of supporting a community of warm water sport fish or serving as a spawning area for warm water sport fish."

The recreation designated use is established under Chapter NR 102.04(5)(a), which states: "All surface waters shall be suitable for supporting recreational use and shall meet the criteria specified in sub. (6). A sanitary survey or evaluation, or both to assure protection from fecal contamination is the chief criterion for determining the suitability of a water for recreational use." See Table 1 for additional criteria that are applicable to the recreation designated use.

Water quality criteria applicable to designated uses

Water quality criteria are developed by the state to support each designated use. Some criteria are divided into subcategories by waterbody type. Table 1 describes the applicable designated uses, metrics and their subcategories, criteria or thresholds, and where those criteria or thresholds are documented (existing code, WisCALM guidance, or proposed code revisions).

Through a separate process, the department is currently proposing several revisions and additions to ch. NR 102, Wis. Adm. Code, which would apply to waterbodies statewide. These include adding both "biocriteria" and "phosphorus response indicators". Biocriteria are metrics indicating the overall health of a waterbody. Phosphorus response indicators are metrics that specifically indicate a response to phosphorus. Both are used to evaluate whether designated uses are being protected. The proposed metrics include the following that are relevant here:

- Chlorophyll *a* criteria for both aquatic life and recreation uses, which are currently in use through Wisconsin's waterbody assessment guidance: Wisconsin Consolidated Assessment and Listing Methodology (WisCALM)
- Aquatic plant criteria to assess both general disturbance responses and phosphorus-specific responses

For the Wisconsin River reservoirs, WDNR used the proposed phosphorus response indicators and biocriteria thresholds to assess the need for an SSC (**Error! Reference source not found.**). Under the proposed rule revisions as applied in this analysis, if any of the thresholds are not attained and a lower phosphorus criterion is needed to attain them, then a more stringent SSC may be appropriate. Alternatively, if data analysis shows that all thresholds will be attained at a higher phosphorus concentration than the currently applicable criterion, then a less stringent SSC may be appropriate. In either case, the SSC value would be set at the phosphorus concentration needed to attain the biological metrics that demonstrate support of the designated uses.

For water quality standards adopted by states, federal regulations, 40 CFR s. 131.11(a), require that, "For waters with multiple use designations, the criteria shall support the most sensitive use." The chlorophyll *a* criterion for aquatic life use in lakes and reservoirs is higher (less sensitive) than the chlorophyll *a* criterion for recreation (Table 1). The phosphorus criterion for aquatic life use in shallow lakes and reservoirs was set equal to the recreational phosphorus criterion because it was shown to be sufficiently protective of sport fisheries.[1] Because the effect of phosphorus on warmwater fish is mainly through its effect on the dominance of algae or rooted plants, and the aquatic life chlorophyll criterion is less sensitive than the recreational one, the aquatic life phosphorus criterion is also less sensitive than the recreational one.

The next section of this report evaluates the relationship between phosphorus and chlorophyll *a* as they relate to recreational uses. The last section of this report evaluates the relationship between phosphorus and aquatic plant metrics. Based on these analyses, it is unclear whether the

[1] Wisconsin Department of Natural Resources. 2010. Wisconsin Phosphorus Water Quality Standards Criteria: Technical Support Document.

aquatic plant metrics that are applicable to the aquatic life use are more or less sensitive than the recreational chlorophyll *a* criteria in these reservoirs. This uncertainty is mainly due to the lack of aquatic plant data on these specific reservoirs, and on other similar large reservoirs in general. Because the relationship between phosphorus and chlorophyll *a* is much better defined and appears likely to be the most sensitive use, the proposed SSCs are based on this relationship.

Table 1. Designated uses, metrics, and criteria applicable to Petenwell Lake, Castle Rock Lake, and Lake Wisconsin.

Waterbody	**Designated Use***	**Metrics supporting the Designated Use**	**Metric subcategory**	**Applicable criterion or threshold (attains if…)**	**Source of the criterion or threshold**
Petenwell Lake, Castle Rock Lake	Aquatic life: warmwater sport fish	Total Phosphorus	Unstratified	Mean summer TP ≤ 40 µg/L	Ch. NR 102.06(4)(a)
		Chlorophyll *a*	Unstratified	Mean summer chlorophyll *a* ≤ 27 µg/L	WisCALM guidance; Proposed aquatic life criterion in ch. NR 102 revisions
		Aquatic plants – General disturbance (MAC)	Southern drainage lake	Tolerant species ≤ 50%	WisCALM guidance
		Aquatic plants – Phosphorus response (MAC-P)	Southern drainage lake	Phosphorus-sensitive species > 42%	Proposed aquatic life phosphorus response indicator in ch. NR 102 revisions
	Recreation	Total Phosphorus	Unstratified reservoir	Mean summer TP ≤ 40 µg/L	Ch. NR 102.06(4)(a)
		Frequency of moderate algae levels	Unstratified reservoir	70th percentile summer chlorophyll *a* ≤ 20 µg/L	WisCALM guidance; proposed recreation criterion in ch. NR 102 revisions
Lake Wisconsin	Aquatic life: warmwater sport fish	Total Phosphorus	Impounded flowing water	Median growing season TP ≤ 100 µg/L	Ch. NR 102.06(4)(c)
	Recreation	Frequency of moderate algae levels	Impounded flowing water	70th percentile summer chlorophyll *a* ≤ 20 µg/L	WisCALM guidance; proposed recreation criterion in ch. NR 102 revisions

* All surface waters are also assigned wildlife and public health and welfare designated uses, but these are not applicable to this SSC.

Reservoir Descriptions

Petenwell and Castle Rock Lakes are the largest reservoirs on the Wisconsin River, and water quality problems on these reservoirs were the primary motivation for the development of Total Maximum Daily Loads (TMDLs) for total phosphorus (TP) throughout the Wisconsin River Basin. Both reservoirs have a TP criterion of 40 µg/L as a summer (June 1 – September 15) mean concentration because they are classified as shallow (unstratified) drainage lakes. This TP criterion was primarily based on research in Minnesota[2] that showed an increase in algal blooms in shallow lakes when TP exceeds 40 µg/L. Chlorophyll *a* (CHL) concentrations in Petenwell and Castle Rock Lakes are lower than expected given their TP concentrations (Figure 23), so a thorough SSC feasibility analysis was warranted.

Lake Wisconsin is classified as an impounded flowing water because its summer water residence time is less than 14 days, so its TP criterion is equal to the criterion of the inflowing river (100 µg/L). However, the current summer mean TP concentration in Lake Wisconsin is 98 µg/L, and it has frequent and severe algal blooms (mean summer CHL is 48 µg/L), so this criterion is clearly not appropriate.

Lake Du Bay is also classified as an impounded flowing water with a TP criterion of 100 µg/L. The current summer mean TP concentration in Lake Du Bay is 91 µg/L, and it has frequent moderate algal blooms (mean summer CHL is 27 µg/L), so this criterion is also not appropriate.

Overview of Analysis

This analysis is based on four years of biweekly water quality monitoring that was conducted at 3-4 stations per reservoir during the open water seasons of 2010-2013 (Table 2). The first step in the analysis was to plot CHL concentration against several potential drivers of CHL variability, including nutrients, day of year, river discharge, and water temperature (Table 3, Figures 1-4). Next, several statistical models were fit to estimate multiple regression relationships between selected variables and CHL. The best models were then used to estimate daily CHL concentrations during the open water seasons of 2010-2013, and to simulate how those concentrations would change with lower TP loading to the reservoirs.

Table 2. Monitoring stations on Petenwell and Castle Rock Lakes and Lake Wisconsin.

Station ID	Description
10031168	Petenwell - 10.4 miles upstream of dam
10031169	Petenwell - 7.8 miles upstream of dam
10031170	Petenwell - 4.7 miles upstream of dam
10031171	Petenwell - 1.8 miles upstream of dam

[2] Minnesota Pollution Control Agency. 2005. Minnesota Lake Water Quality Assessment Report: Developing Nutrient Criteria", Third Edition.

10031172	Castle Rock - 7.7 miles upstream of dam
10031173	Castle Rock - 3.7 miles upstream of dam
10031174	Castle Rock - 1 mile upstream of dam
10031184	Lake Wisconsin - Between Stoners Bay and Pine Bluff
10031185	Lake Wisconsin - Upper reach of reservoir
10031186	Lake Wisconsin - SW of Weigands Bay
373445	Lake Du Bay – 4.6 miles upstream of dam
10031116	Lake Du Bay – 2.7 miles upstream of dam
503163	Lake Du Bay – 1 mile upstream of dam

Relationships between chlorophyll and other variables

The scatter plots of CHL versus other parameters in Petenwell and Castle Rock Lakes are similar, which indicates that the processes that drive algal growth are similar in the two reservoirs (Figures 1-2). As expected, there is positive correlation between TP, TN, and CHL in these reservoirs. The inorganic forms of both nutrients (PO4, NO3, and NH4) are all negatively correlated with CHL, which makes sense because as algae grow, they convert these forms to organic matter. TKN, which is primarily organic N given the mostly low NH4 concentrations, is strongly positively correlated with CHL. There is a weak positive correlation between DOC and CHL, which indicates that the upper range of DOC concentrations in these reservoirs does not limit light availability for algal growth. The plots of both TEMP and JD indicate that warmer water and/or more solar radiation are associated with higher CHL. There is a weak negative correlation between Q and CHL, although especially in Petenwell, CHL also appears to decrease at the lowest flows. There is a weak positive correlation between DO and CHL, which probably reflects the role of CHL in photosynthesis, which produces oxygen.

The scatter plots of chlorophyll *a* versus other parameters in Lake Wisconsin are mostly like those for Petenwell and Castle Rock Lakes, with a few differences (Figure 3). First, the relationships between CHL and TP and TN are weaker in Lake Wisconsin. Second, CHL reaches higher concentrations earlier in the season (around June 1) and follows less of a seasonal pattern than the other reservoirs. And third, the relationship between CHL and Q is clearer in Lake Wisconsin, and there is no evidence of less CHL at the lowest flows.

In Lake Du Bay, the relationships between CHL and TP and TN appear bifurcated, with groups of samples with low and high ratio CHL per unit nutrient. While the general relationship between CHL and Q is similar to the other reservoirs (i.e., low CHL at high Q), there are several samples with high CHL at high Q. Upon further evaluation, patterns of CHL in Lake Du Bay appear to be strongly influenced by the timing of water releases from Big Eau Pleine Reservoir, which has a mean summer CHL of 69 µg/L.

Table 3. Water quality and hydrologic parameters

Abbreviation	Name	Units
CHL	Chlorophyll *a*	µg/L
JD	Julian day	day
Q	River discharge[3]	ft^3/s
TEMP	Water temperature	C
DO	Dissolved oxygen	mg/L
DOC	Dissolved organic carbon	mg/L
TN	Total nitrogen	mg/L
DIN	Dissolved inorganic nitrogen	mg/L
TKN	Total Kjeldahl nitrogen	mg/L
NO3	Nitrate + nitrite	mg/L
NH4	Ammonium	mg/L
TP	Total phosphorus	µg/L
PO4	Ortho-phosphate	µg/L

[3] River discharge at the Petenwell Hydro Dam was used for Petenwell and Castle Rock Lakes. River discharge at USGS station ID 05406000 (Wisconsin River at Prairie du Sac) was used for Lake Wisconsin. River discharge at the Du Bay Hydro Dam was used for Lake Du Bay.

Figure 1. Scatter plots of chlorophyll a versus other parameters in Petenwell Lake, 2010-13.

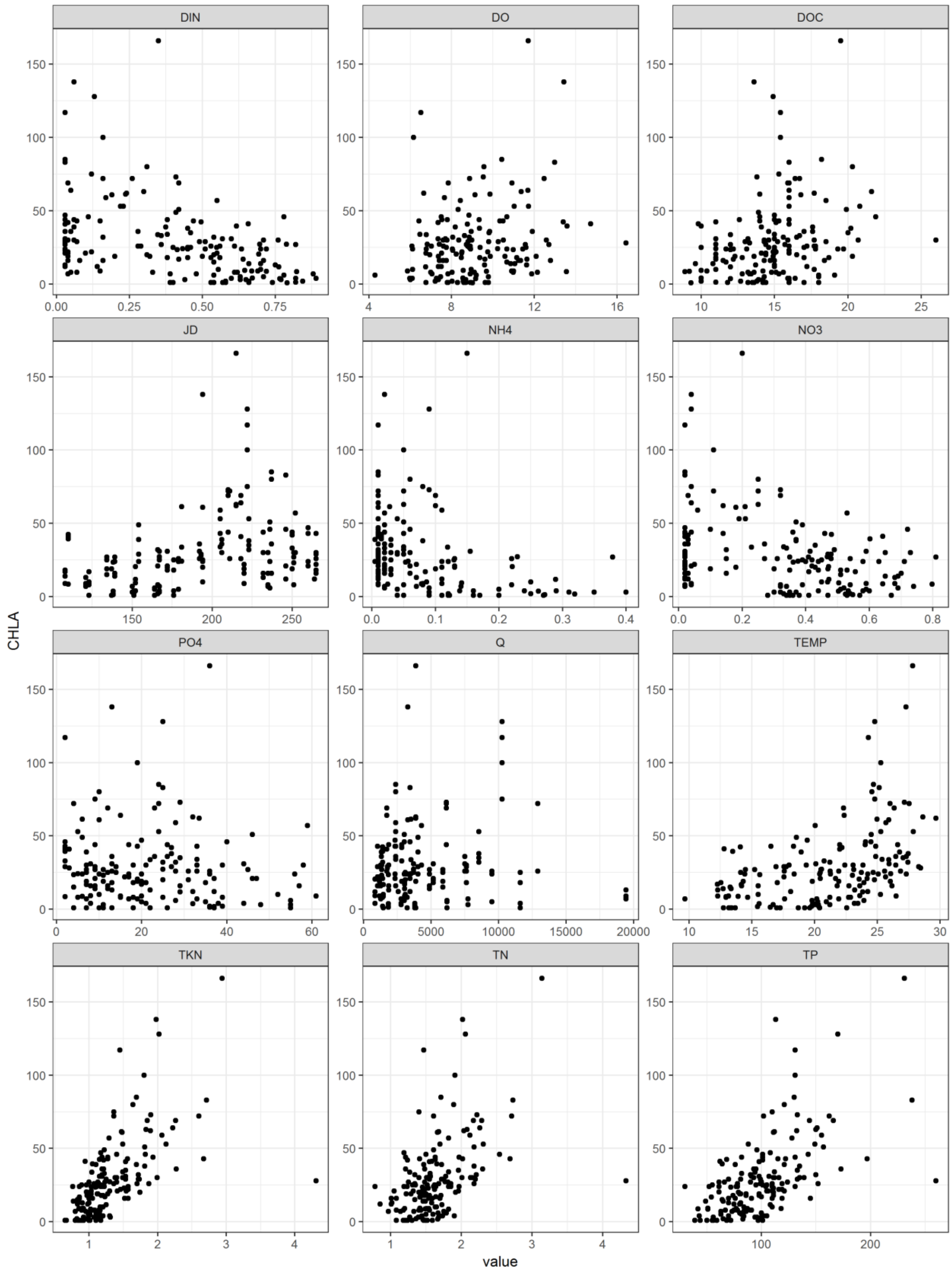


Figure 2. Scatter plots of chlorophyll a versus other parameters in Castle Rock Lake, 2010-13.

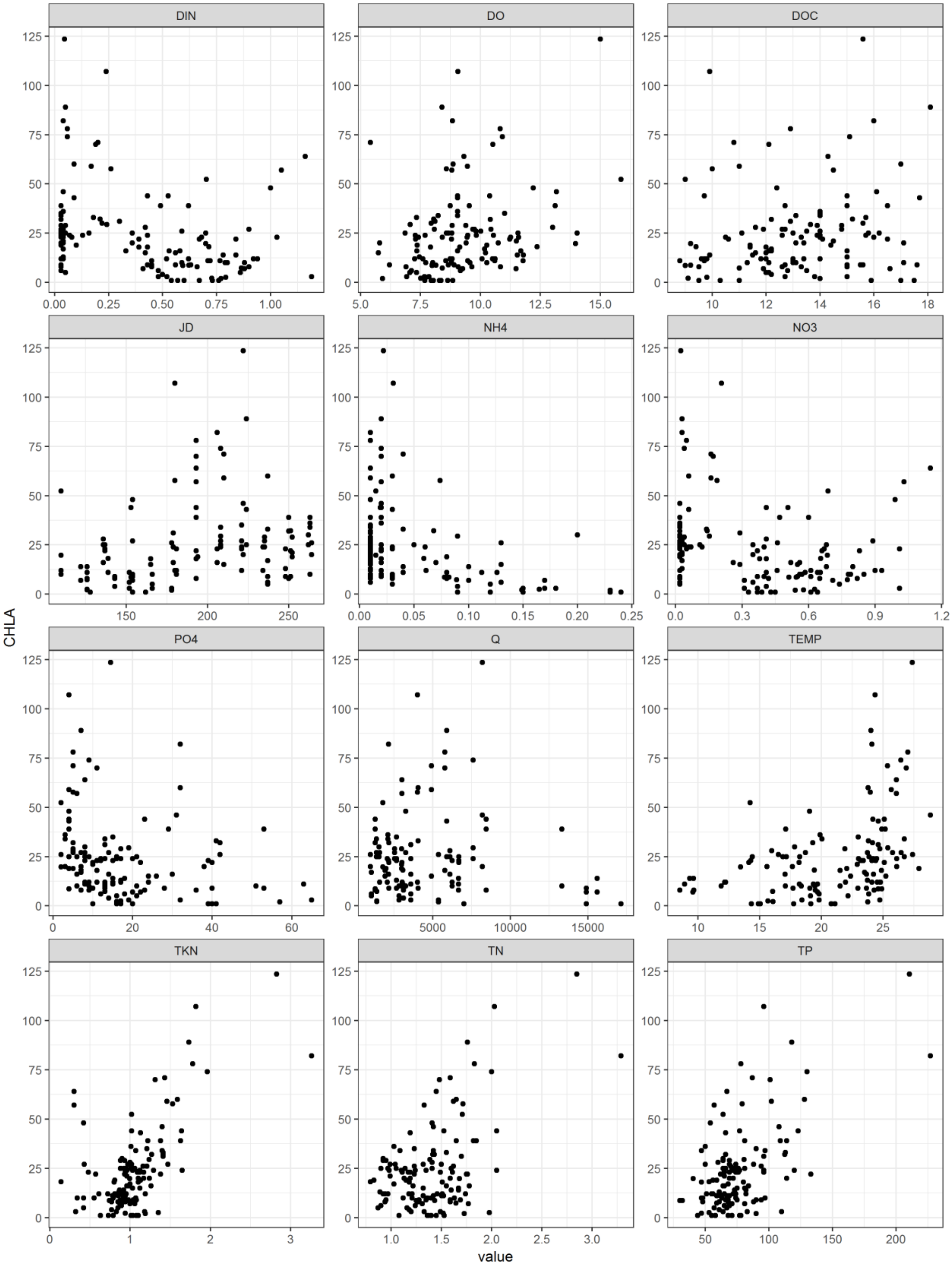


Figure 3. Scatter plots of chlorophyll a versus other parameters in Lake Wisconsin, 2010-13.

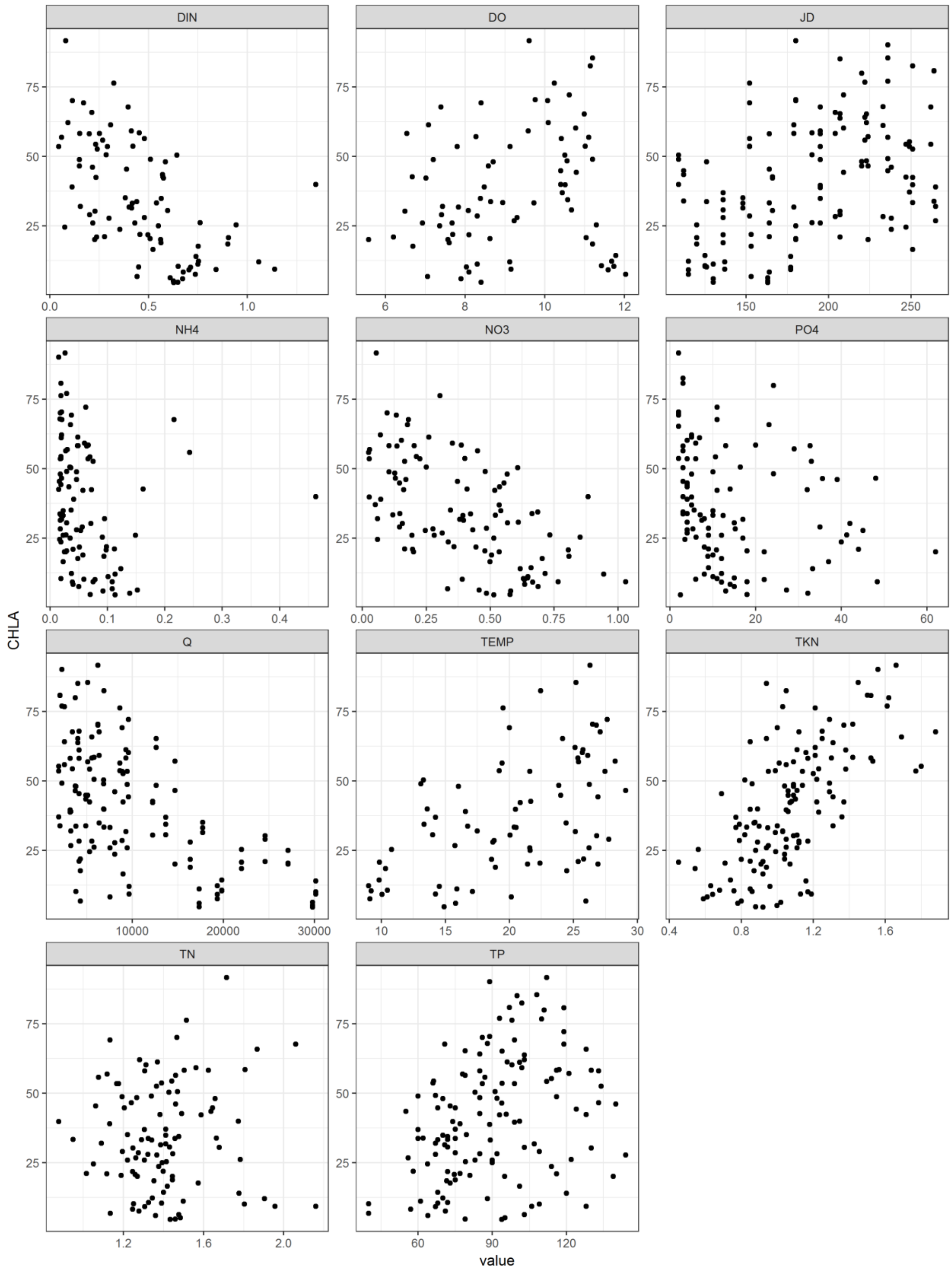
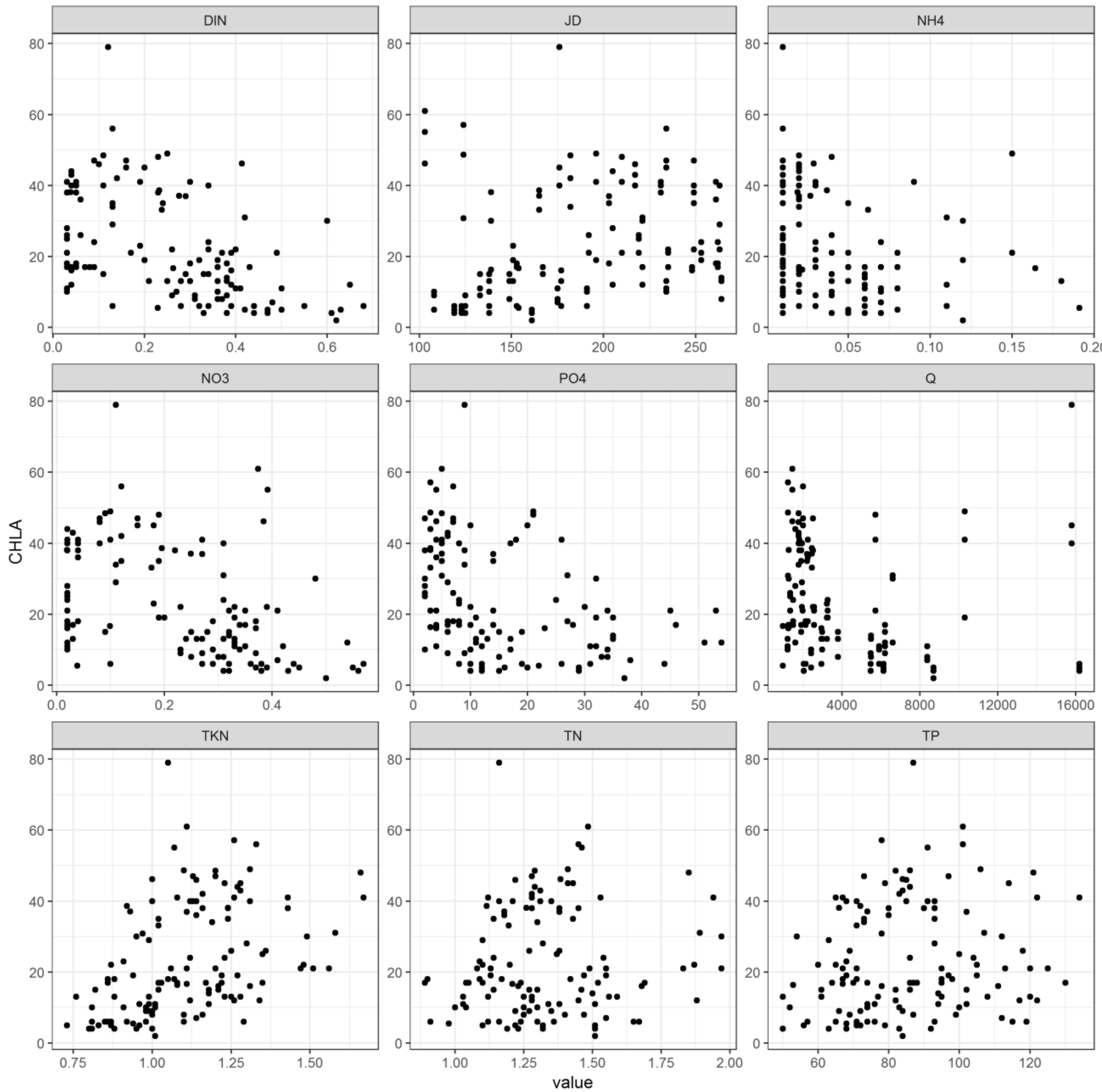


Figure 4. Scatter plots of chlorophyll a versus other parameters in Lake Du Bay, 2010-13.



Modeling methods

While scatter plots can suggest which variables might be driving CHL production, statistical models can characterize the effect of one variable while controlling for others and can characterize interactions among variables. Generalized Additive Models (GAMs) fit with the mgcv package in R were selected for this analysis because they allow simple specification of complex interactive non-linear relationships. The *te* function was used in the *gam* formulae to fit tensor product smooth functions between the predictor and response variables. This can be thought of as a surface in n (predictor) dimensional space where the value of the surface is estimated CHL concentration and the complexity of the surface is balanced against the fit to the data. There are 128-167 CHL observations per reservoir, so the number of variables in each model was limited to three, given that several degrees of freedom are used by non-linear and interactive effects. Initially, separate models were developed for Petenwell and Castle Rock, but these models were very similar, so a single model was developed for both of these reservoirs. Rather than test all possible combinations of variables, candidate models were constructed to compare plausible hypotheses about the drivers of CHL variability. All models included TP, and additional variables included TN, Q, and either JD or TEMP.

Model structure

The best model for Petenwell/Castle Rock, as assessed by Generalized Cross Validation score, included TP, Q, and JD (Model #1, Table 4). The relationships between these variables and CHL are best visualized through bivariate contour plots, which show estimated CHL across ranges of two variables, while holding the other variable constant at its median value. The contours were augmented with shading to help visualize the transition from low (blue) to high (green) CHL. In Petenwell/Castle Rock, CHL increases with TP and peaks at low to moderate Q (Figure 5). CHL is lower during April-June for a given TP than in late summer (Figure 6). Model #6 was used assess the potential influence of TN on CHL. The contour plot of TP and TN clearly shows that TN has almost no influence on CHL after controlling for the effect of TP (Figure 8).

The best model for Lake Wisconsin included TP and Q (Model #2, Table 5). Model #1 had a slightly lower GCV score, but the contour plots indicated some predictions outside of the range of observations that did not make sense, including negative correlations between CHL and TP at high Q and low JD (April-May). Based on Model #2, CHL increases with TP, especially at low Q (Figure 9). There is no evidence of a drop in CHL at very low Q, as seen with Petenwell/Castle Rock. Based on Model #3, there is no evidence that TN affects CHL after controlling for the effect of TP (Figure 10).

All the models evaluated for Lake Du Bay fit the data poorly and were not consistent with any plausible hypotheses about the drivers of CHL variability. It appears that many of the high CHL concentrations in Lake Du Bay are produced by episodic water releases from Big Eau Pleine Reservoir, which are not synchronized with the mainstem river flow. This situation makes it difficult to characterize the *in situ* TP:CHL relationship in Lake Du Bay, which would be the basis for a site-specific TP criterion. Based on the allocation process described in the TMDL, the summer mean TP concentration in Lake Du Bay would be 45 µg/L when all upstream allocations are met. Since Du Bay's TP:CHL ratio is very similar to those in Petenwell and Castle Rock

(Figure 23), and because TP concentrations of 53-55 µg/L should meet the same CHL target in those reservoirs, it is assumed that the TP concentration that will be reached to meet SSC for the downstream reservoirs is sufficient to meet the CHL target in Lake Du Bay. Therefore, no further analysis was conducted on Lake Du Bay, and no SSC is recommended.

Table 4. Candidate models for Petenwell/Castle Rock Lakes. Model formula conventions are specific to the gam function in the R package mgcv. GCV is the Generalized Cross Validation score (lower is better).

Model #	Formula	GCV
1	log(CHLA) ~ te(log(TP), log(Q), JD)	0.722
2	log(CHLA) ~ te(log(TP), log(Q), TEMP)	0.783
3	log(CHLA) ~ te(log(TP), JD)	0.798
4	log(CHLA) ~ te(log(TP), TEMP)	0.850
5	log(CHLA) ~ te(log(TP), Q)	0.878
6	log(CHLA) ~ te(log(TP), log(TN), log(Q), k=3.5)	0.882
7	log(CHLA) ~ s(log(TP))	0.967

Table 5. Candidate models for Lake Wisconsin. Model formula conventions are specific to the gam function in the R package mgcv. GCV is the Generalized Cross Validation score (lower is better).

Model #	Formula	GCV
1	log(CHLA) ~ te(log(TP), log(Q), JD, k=3)	0.223
2	log(CHLA) ~ te(log(TP), log(Q), k=4)	0.239
3	log(CHLA) ~ te(log(TP), log(TN), log(Q), k=4)	0.254
4	log(CHLA) ~ te(log(TP), TEMP)	0.315
5	log(CHLA) ~ te(log(TP), JD)	0.392
6	log(CHLA) ~ s(log(TP))	0.453

Figure 5. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and Q (cfs) in Petenwell/Castle Rock Lakes from Model #1 (Table 4). Circles are observations (diameter proportional to log(CHL) concentration).

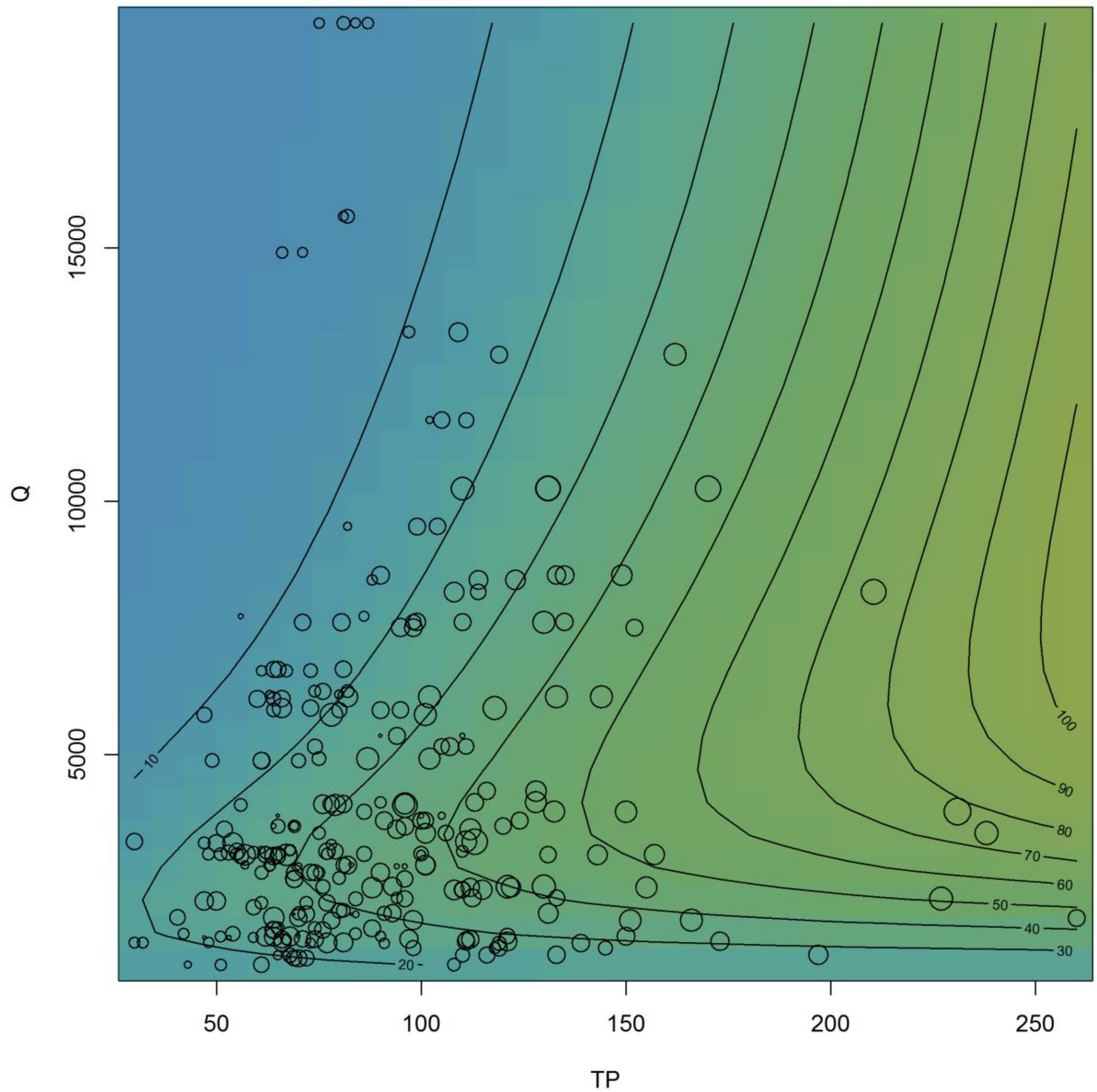


Figure 6. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and JD in Petenwell/Castle Rock Lakes from Model #1 (Table 4). Circles are observations (diameter proportional to log(CHL) concentration).

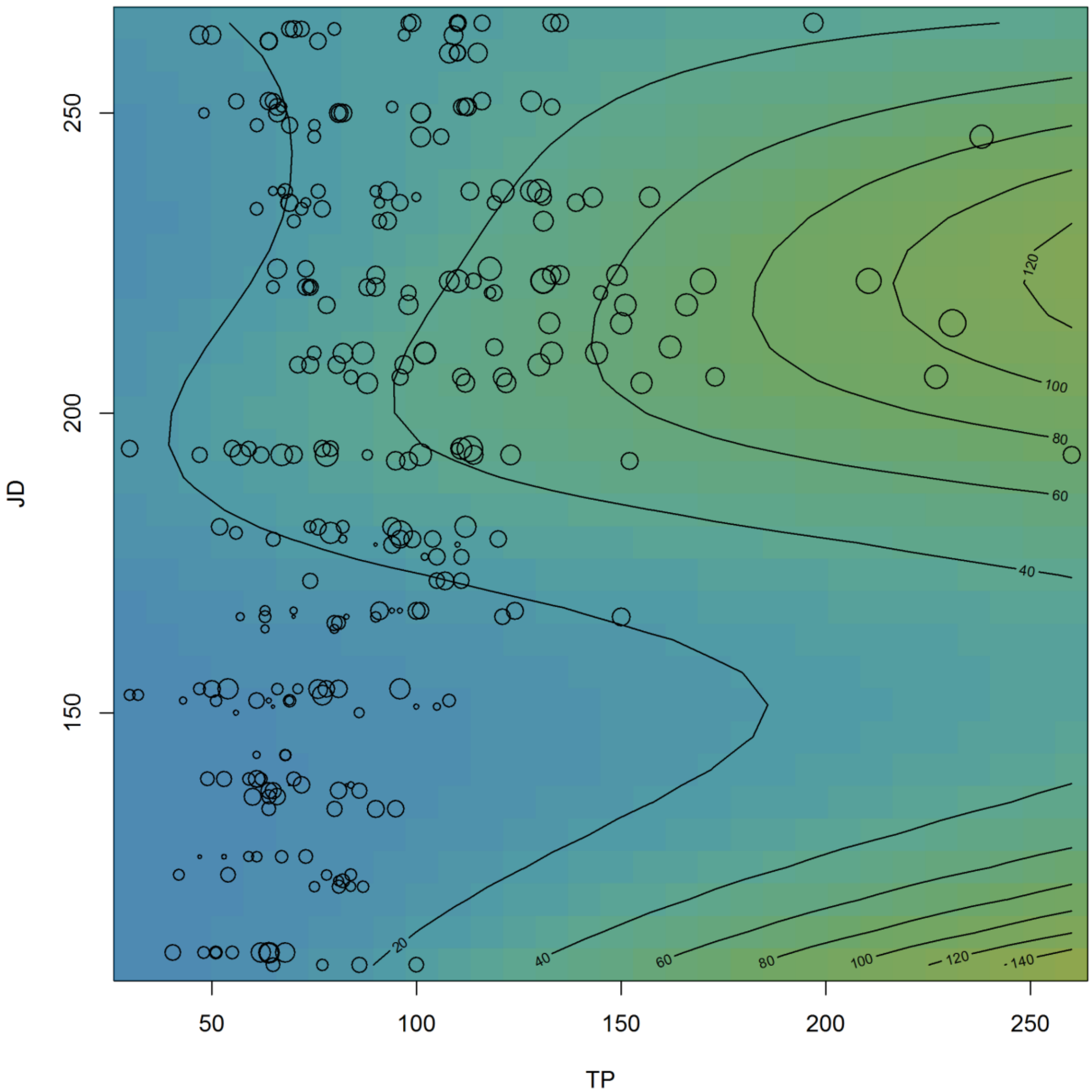


Figure 7. Contour plot of estimated CHL concentration (µg/L) as a function of Q (cfs) and JD in Petenwell/Castle Rock Lakes from Model #1 (Table 4). Circles are observations (diameter proportional to log(CHL) concentration).

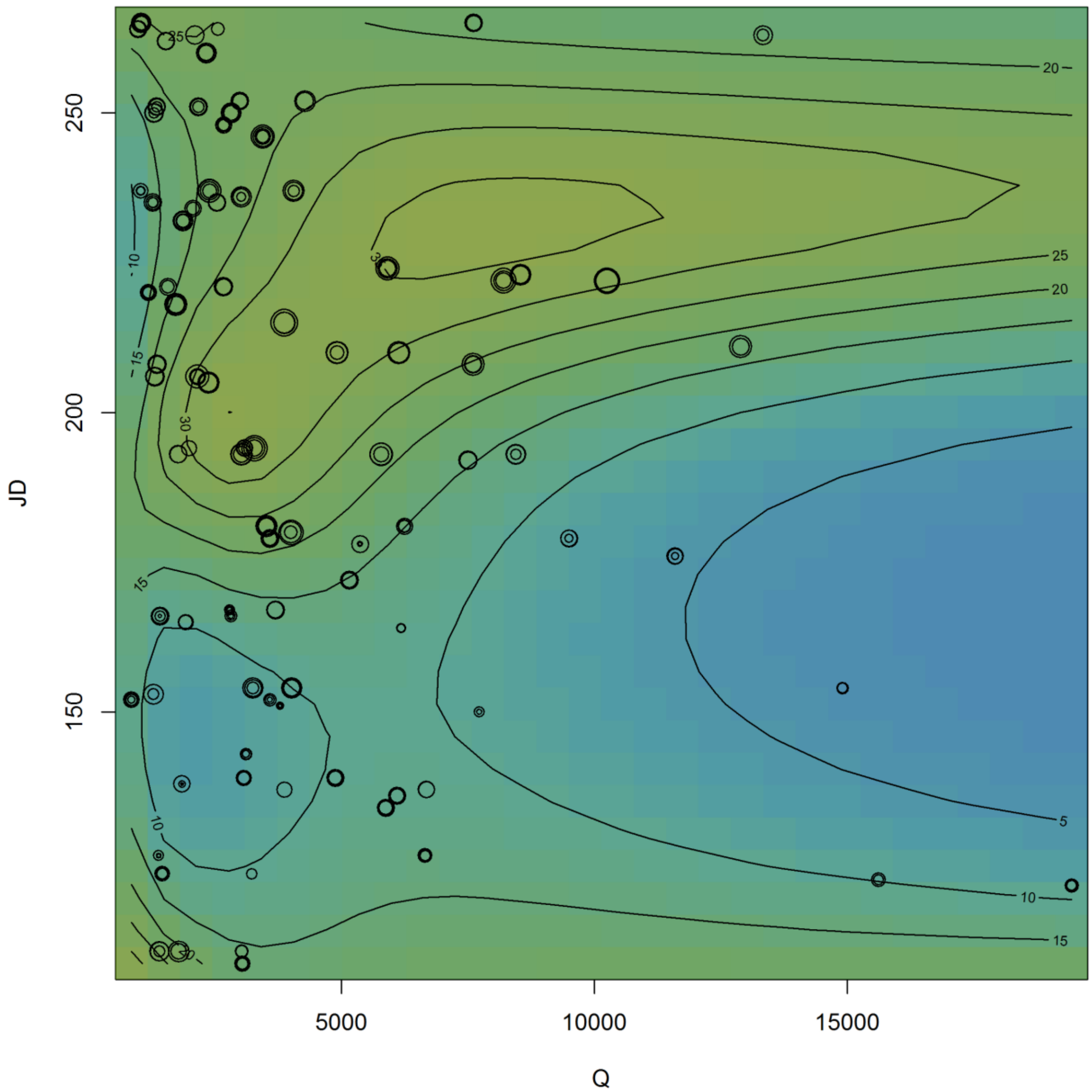


Figure 8. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and TN (mg/L) in Petenwell/Castle Rock Lakes from Model #6 (Table 4). Circles are observations (diameter proportional to log(CHL) concentration).

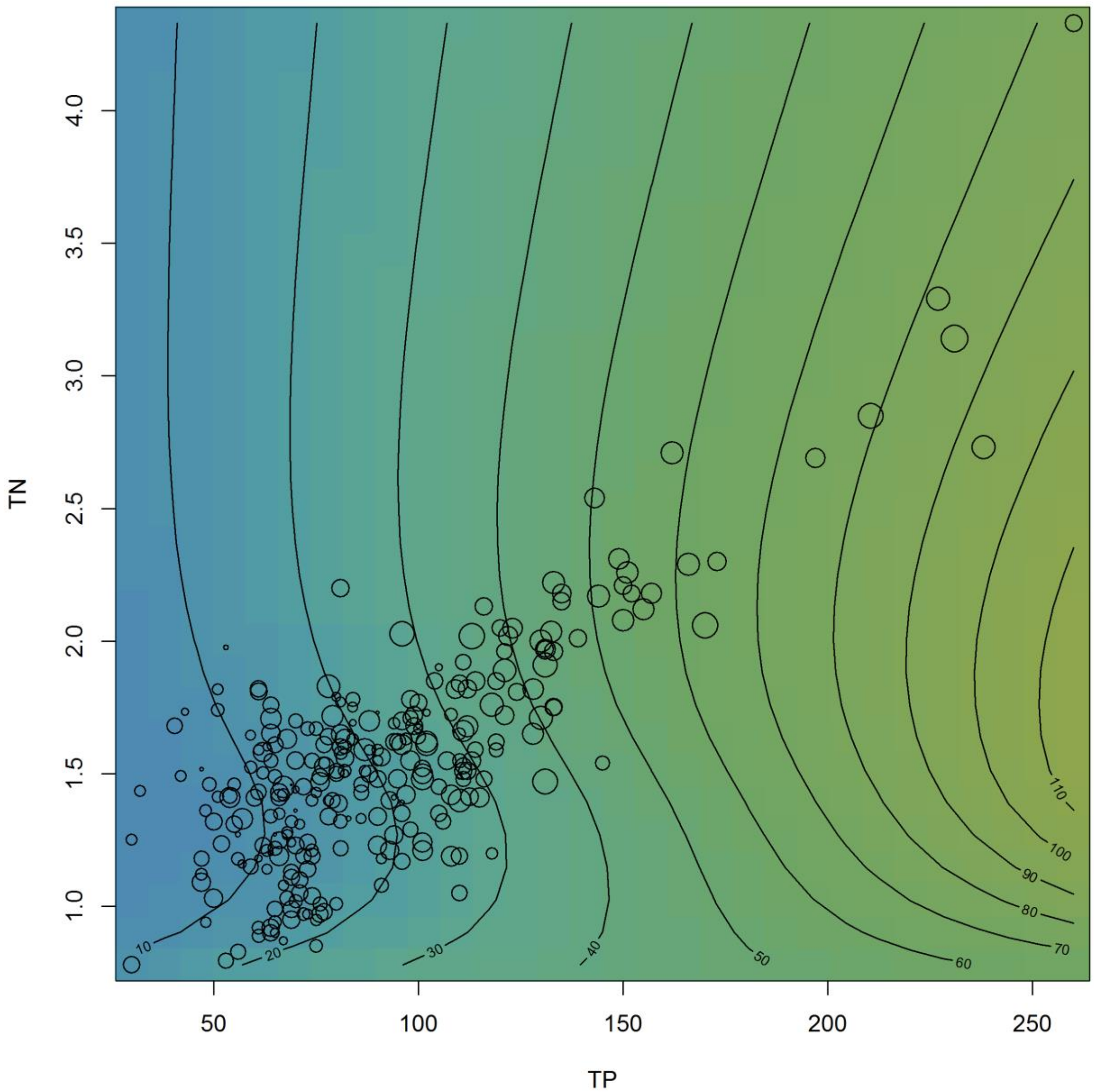


Figure 9. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and Q (cfs) in Lake Wisconsin from Model #2 (Table 5). Circles are observations (diameter proportional to log(CHL) concentration).

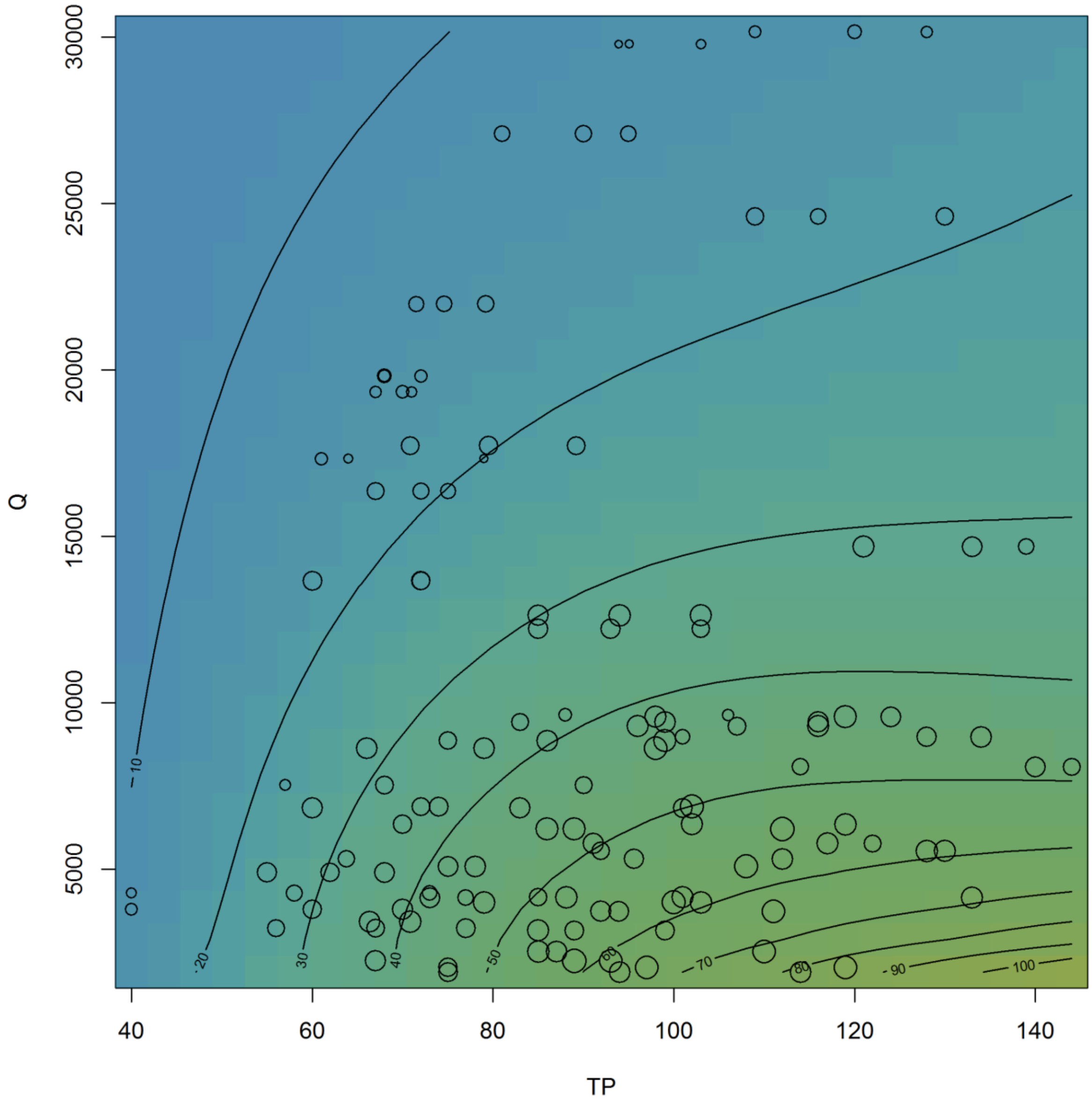
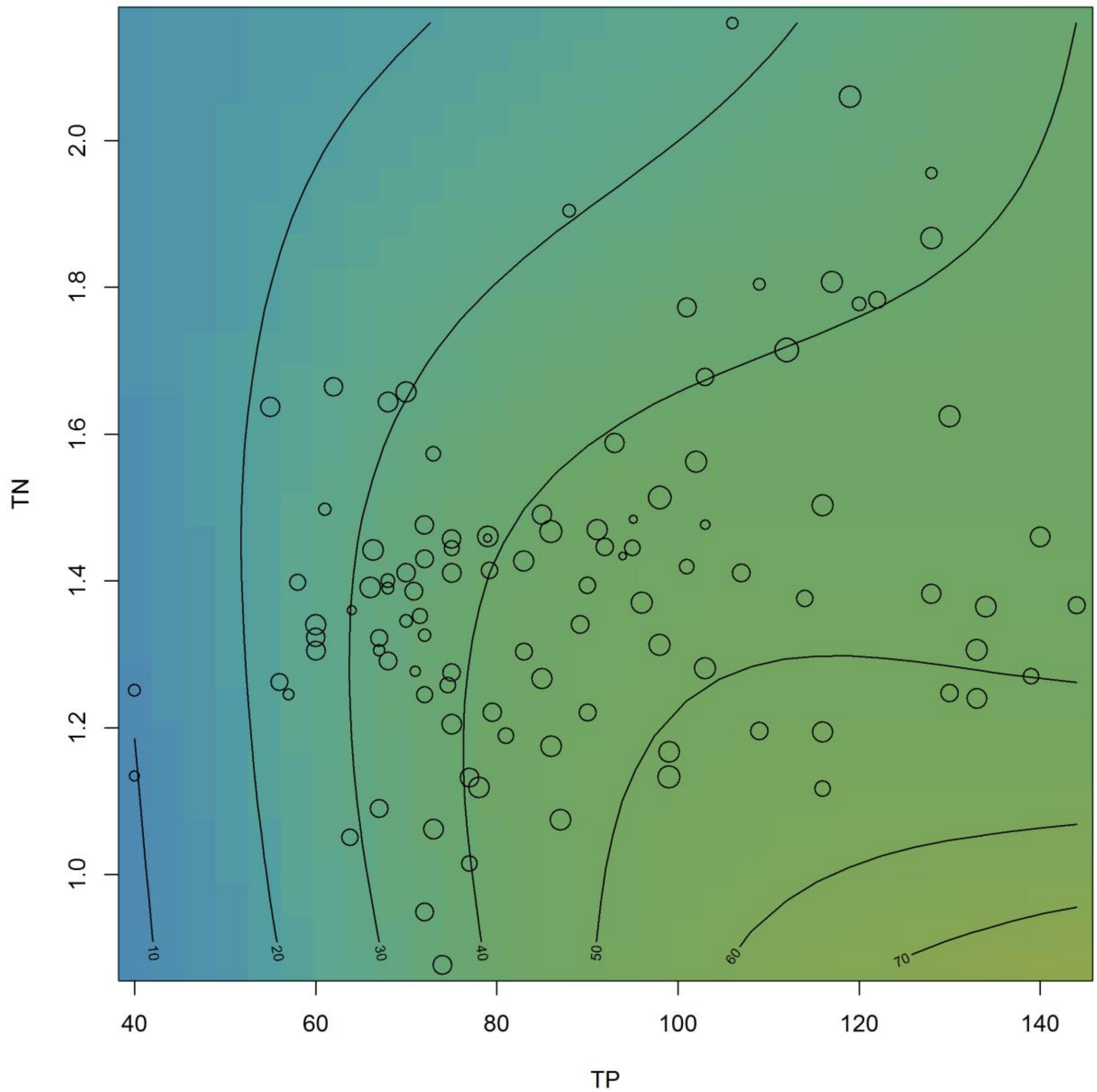


Figure 10. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and TN (mg/L) in Lake Wisconsin from Model #3 (Table 5). Circles are observations (diameter proportional to log(CHL) concentration).



Model diagnostics

Model diagnostic plots were created for both the entire dataset for each reservoir, which includes data from late April to late September (Figures 11-13), and for the CHL assessment period (July 15 – September 15; Figures 14-16). The plots show that the models are more accurate and less biased during the CHL assessment period, which supports their use for SSC development.

Boxplots of model residuals (observed – model estimated CHL) by monitoring station show that there are some differences in CHL response to the model variables among stations. In particular, for Petenwell and Castle Rock, after controlling for TP, JD, and Q, CHL decreases moving downstream in Petenwell and increases from the upstream to the lower two stations in Castle Rock. Lake Wisconsin has a similar pattern to Castle Rock, where the upstream station has lower residuals than the other two stations. We explored including station ID as a categorical variable in the models, but it complicated application of the models to the reservoir-wide simulations described below.

Plots of residuals vs estimated CHL indicate increased variance at low CHL, especially in Petenwell. Empirical cumulative frequency distribution (ECDF) plots show that the models overestimate low CHL and underestimate high CHL in all three reservoirs across the entire monitoring season. The most accurate frequency estimates on these plots are where the observed and estimated lines overlap. For example, in Lake Wisconsin, the observed and estimated frequencies of CHL in the range of 20-50 µg/L are almost identical. The degree of agreement between the observed and estimated CHL frequencies is higher for the CHL assessment period, and importantly, all three reservoirs appear to have unbiased estimates of the frequency of CHL in the range of 20 µg/L to the 70th percentile concentration, which is the range that will be expected to decrease below 20 µg/L under the SSC.

Figure 11. Model diagnostic plots for Petenwell Lake CHL model.

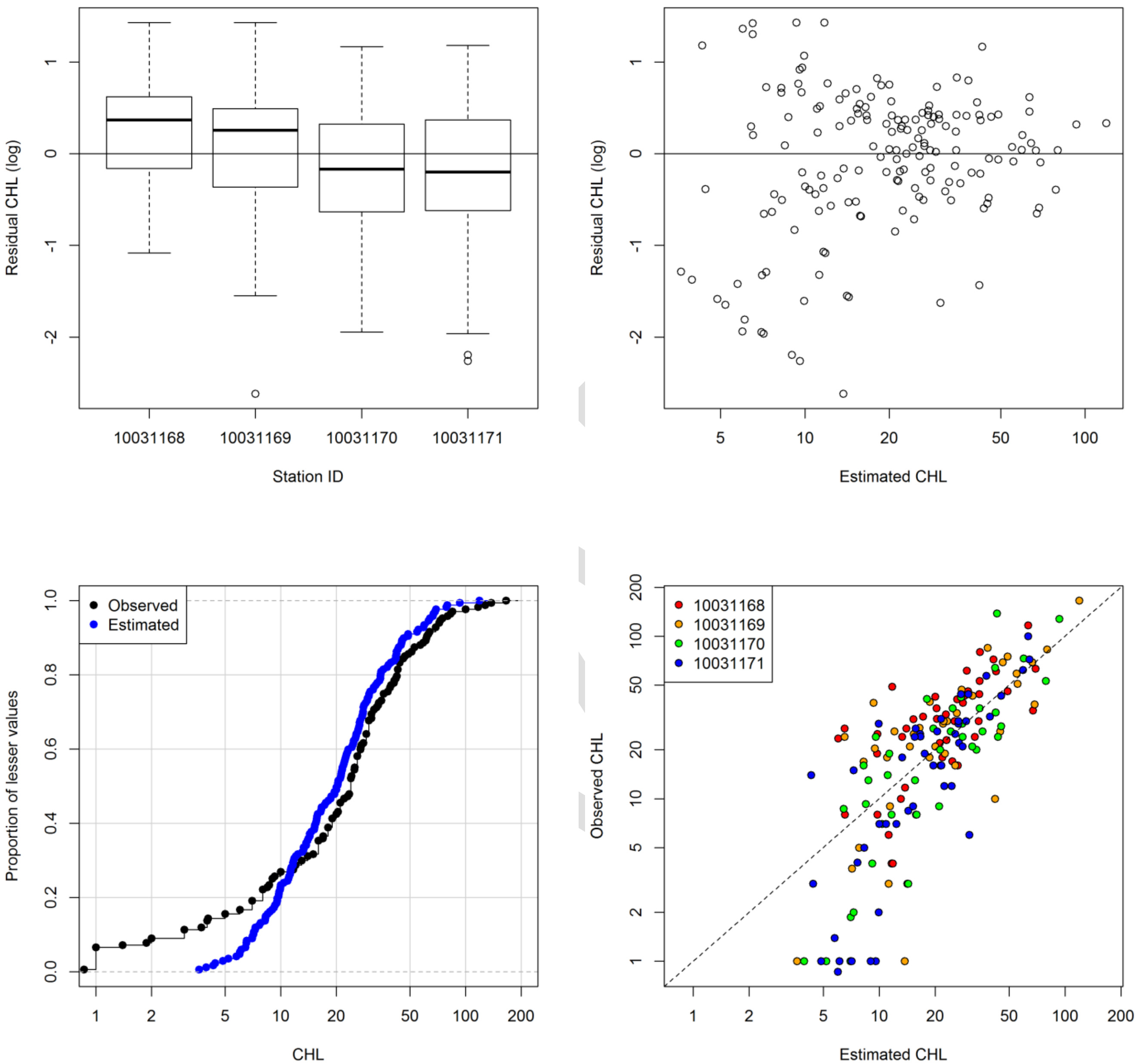


Figure 12. Model diagnostic plots for Castle Rock Lake CHL model.

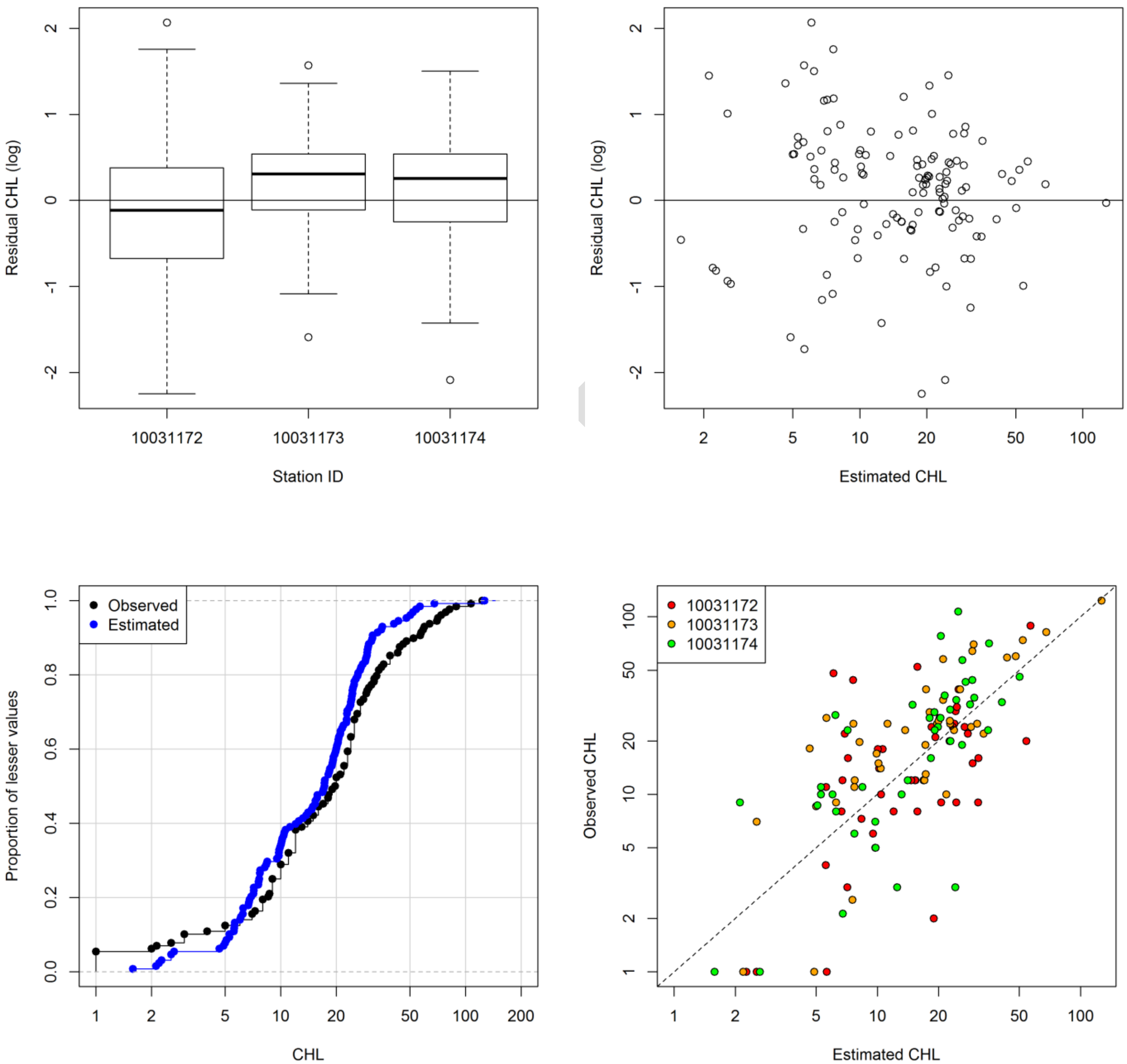


Figure 13. Model diagnostic plots for Lake Wisconsin CHL model.

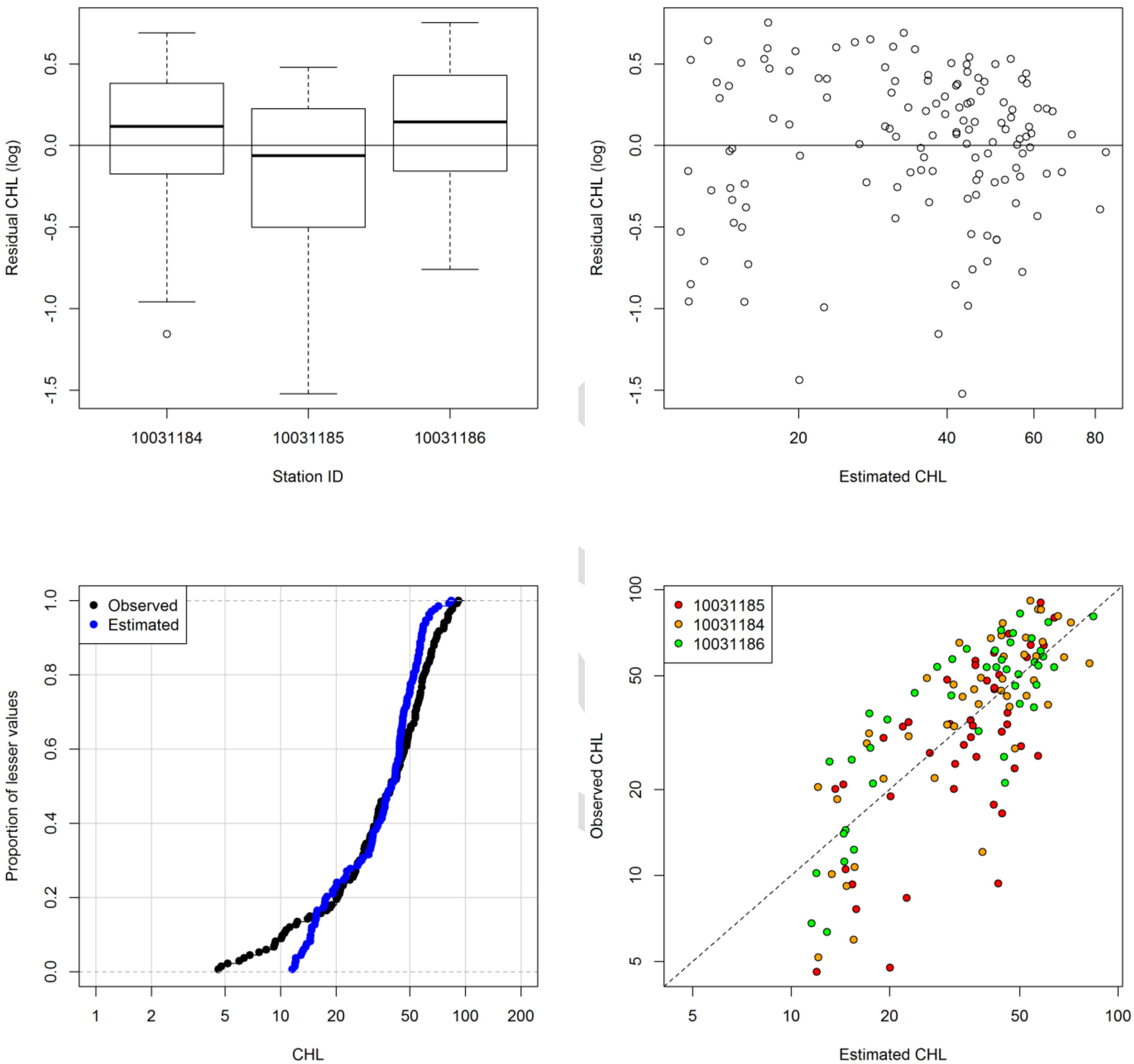


Figure 14. Model diagnostic plots for Petenwell Lake CHL model (CHL assessment period: July 15 – September 15).

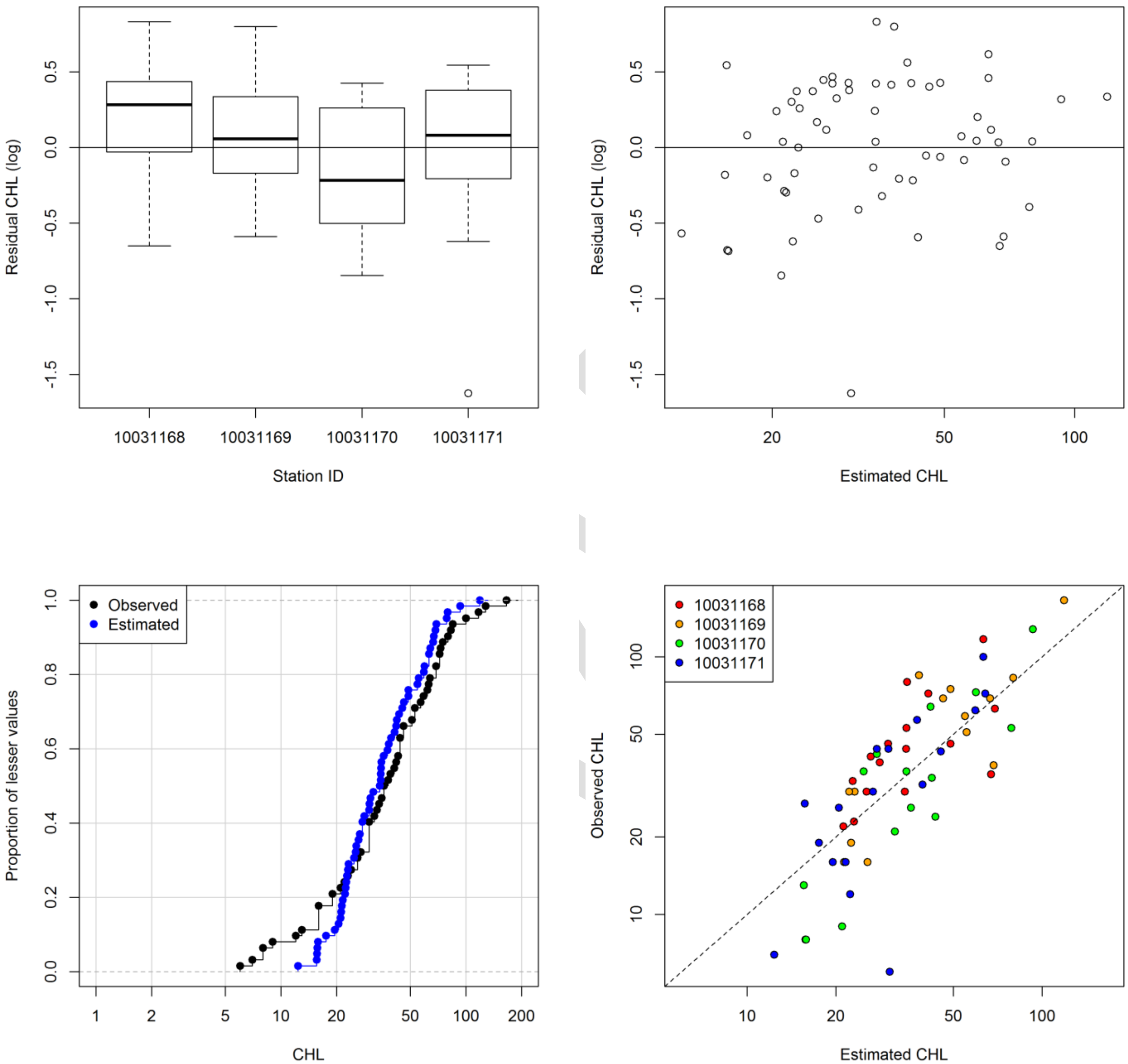


Figure 15. Model diagnostic plots for Castle Rock Lake CHL model (CHL assessment period: July 15 – September 15).

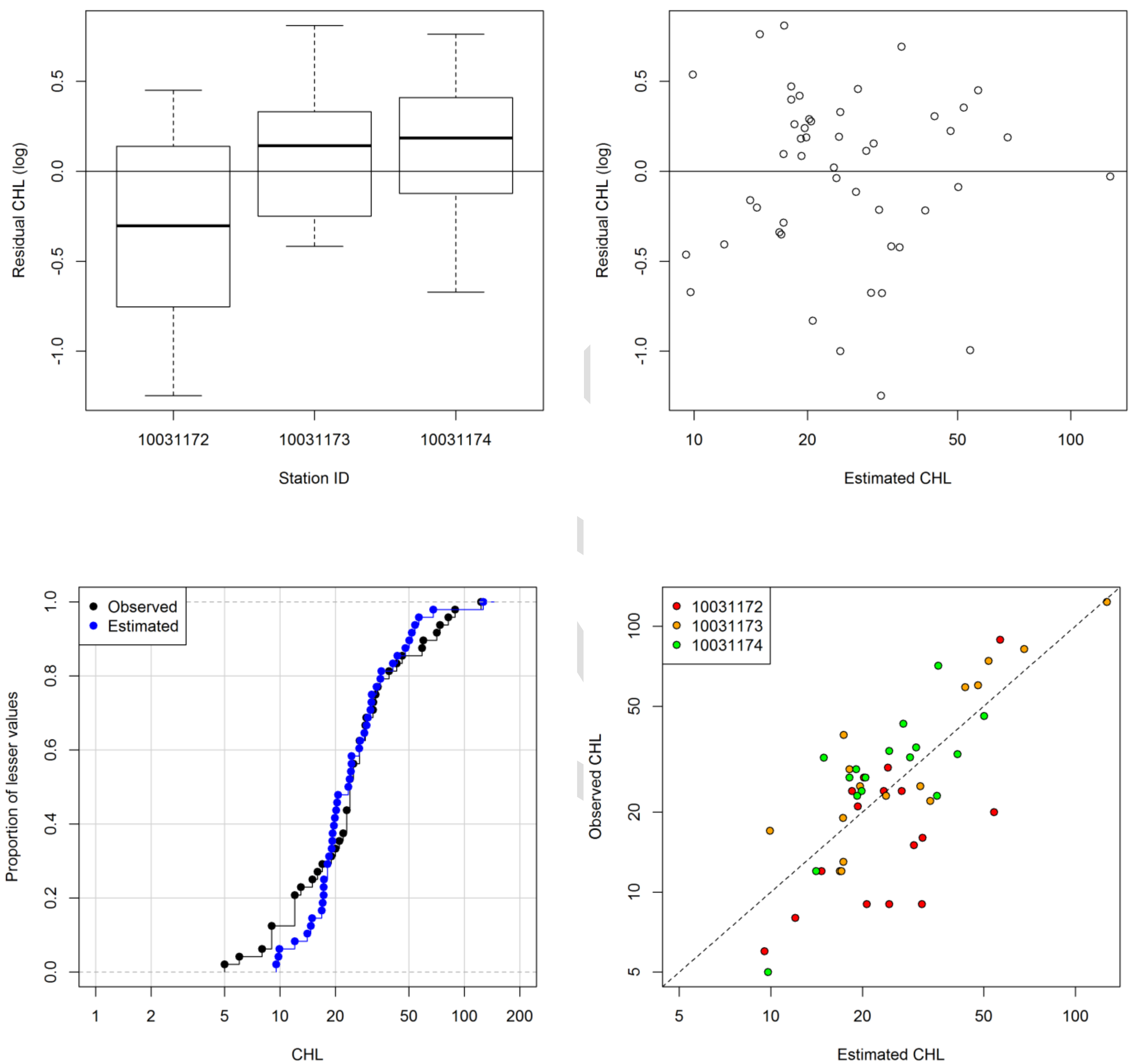
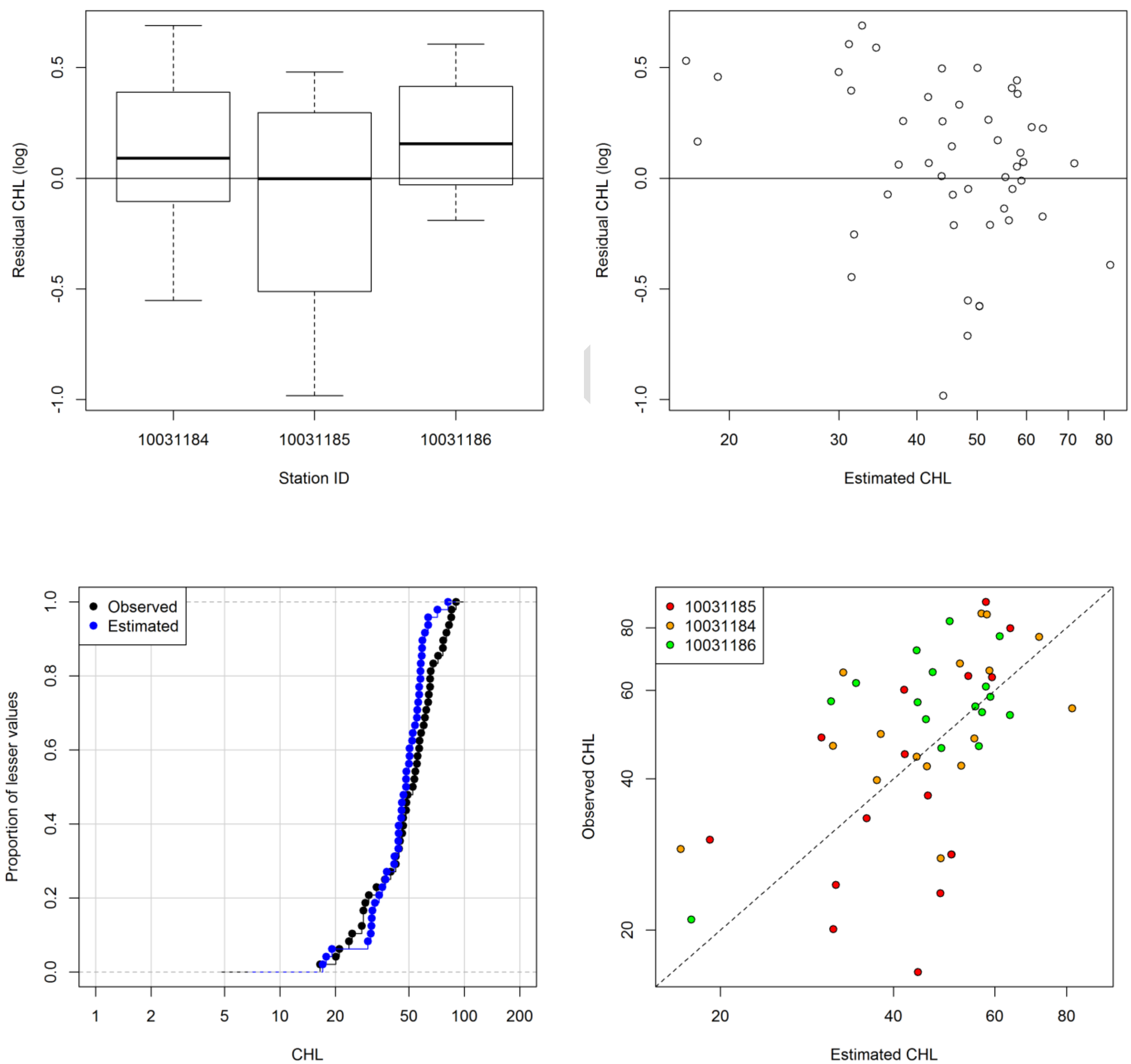


Figure 16. Model diagnostic plots for Lake Wisconsin CHL model (CHL assessment period: July 15 – September 15).



Model simulations

The CHL models were then used to simulate daily CHL concentrations across the monitoring seasons of 2010-13. TP concentrations on unmeasured days were estimated by linear interpolation between measured values. Plots of measured and simulated CHL are shown in Figures 17-19. The patterns of simulated CHL generally match the observed patterns well, including the seasonal trend, occasional sharp decreases due to high flow events, and interannual variability (lower peak CHL in 2012 in Petenwell and Castle Rock and slightly higher peak CHL in 2012 in Lake Wisconsin).

The CHL models were then paired with TP models for each reservoir to simulate CHL response to TP load reductions, and to determine the TP load and in-lake TP concentration that will meet the CHL target for recreational use.

In Petenwell and Castle Rock Lakes, the Jensen models described in Appendix G were used to simulate daily TP concentrations for each reservoir. As described in the Jensen model methods, the simulated TP concentrations for each reservoir represent the median across all stations. The Petenwell/Castle Rock CHL model was then used to simulate baseline CHL concentrations for each reservoir. Then, through trial and error, TP loading was reduced until the target for recreational use (70^{th} percentile CHL < 20 µg/L during July 15 – September 15) was met. Specifically, a uniform percent reduction was applied to each daily inflow TP concentration, including outside the CHL assessment period, which assumes that as overall loading decreases, the temporal pattern of TP loading will remain the same. Figures 20 and 21 show simulated time series of TP and CHL for both baseline and site-specific criterion scenarios for Petenwell and Castle Rock Lakes.

In Lake Wisconsin, the BATHTUB model described in Appendix H indicated that reservoir TP concentrations were equal to inflow concentrations. Therefore, simulating the effects of reduced TP loading simply entailed reducing each daily reservoir TP concentration by a uniform percentage until the target for recreational use (70^{th} percentile CHL < 20 µg/L during July 15 – September 15) was met. To make the assessment comparable to Petenwell/Castle Rock, baseline reservoir TP was estimated by calculating the median reservoir TP across the three monitoring stations on each sampling date, and then linearly interpolating between these values to estimate daily TP concentrations. Baseline CHL was then predicted from this reservoir-median daily TP dataset, along with measured daily discharge at the Prairie du Sac dam. As with Petenwell/Castle Rock, the TP reductions required to meet the CHL target in late summer in Lake Wisconsin were applied across the entire year. Figure 22 shows simulated time series of TP and CHL for both baseline and site-specific criterion scenarios for Lake Wisconsin.

Based on this analysis, the recommended SSC for **Petenwell and Castle Rock are 53 and 55 µg/L TP**, respectively, as a summer (June 1 – September 15) mean concentration, which is higher than the existing criteria (40 µg/L TP). The recommended SSC for **Lake Wisconsin is 47 µg/L TP**, which is lower than the existing criterion (100 µg/L TP).

Figure 17. Observed (circles) and simulated (lines) chlorophyll *a* (µg/L) in Petenwell Lake. Dashed line is recreational chlorophyll *a* target (20 µg/L). Shaded areas are chlorophyll *a* assessment periods.

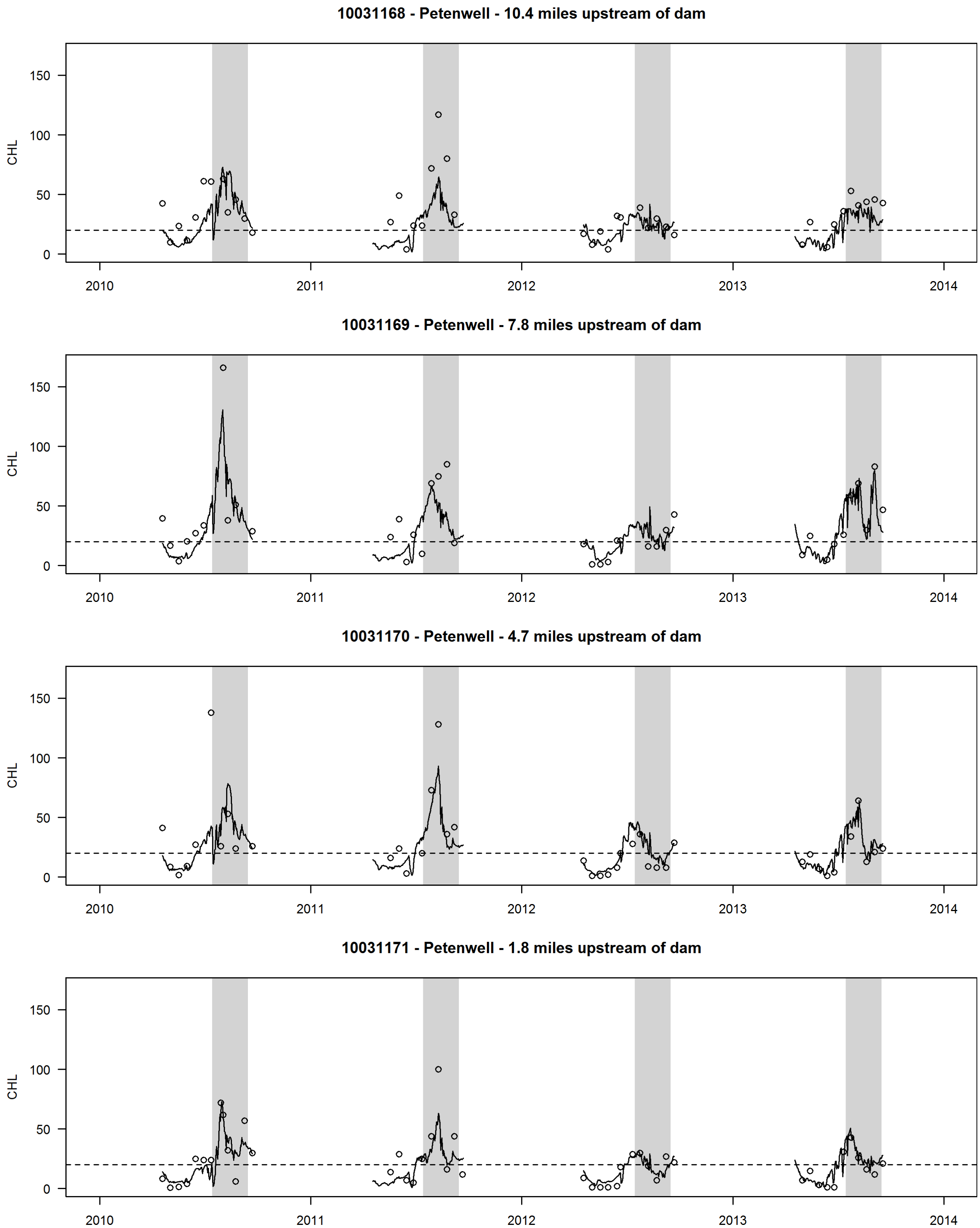


Figure 18. Observed (circles) and simulated (lines) chlorophyll *a* (µg/L) in Castle Rock Lake. Dashed line is recreational chlorophyll *a* target (20 µg/L). Shaded areas are chlorophyll *a* assessment periods.

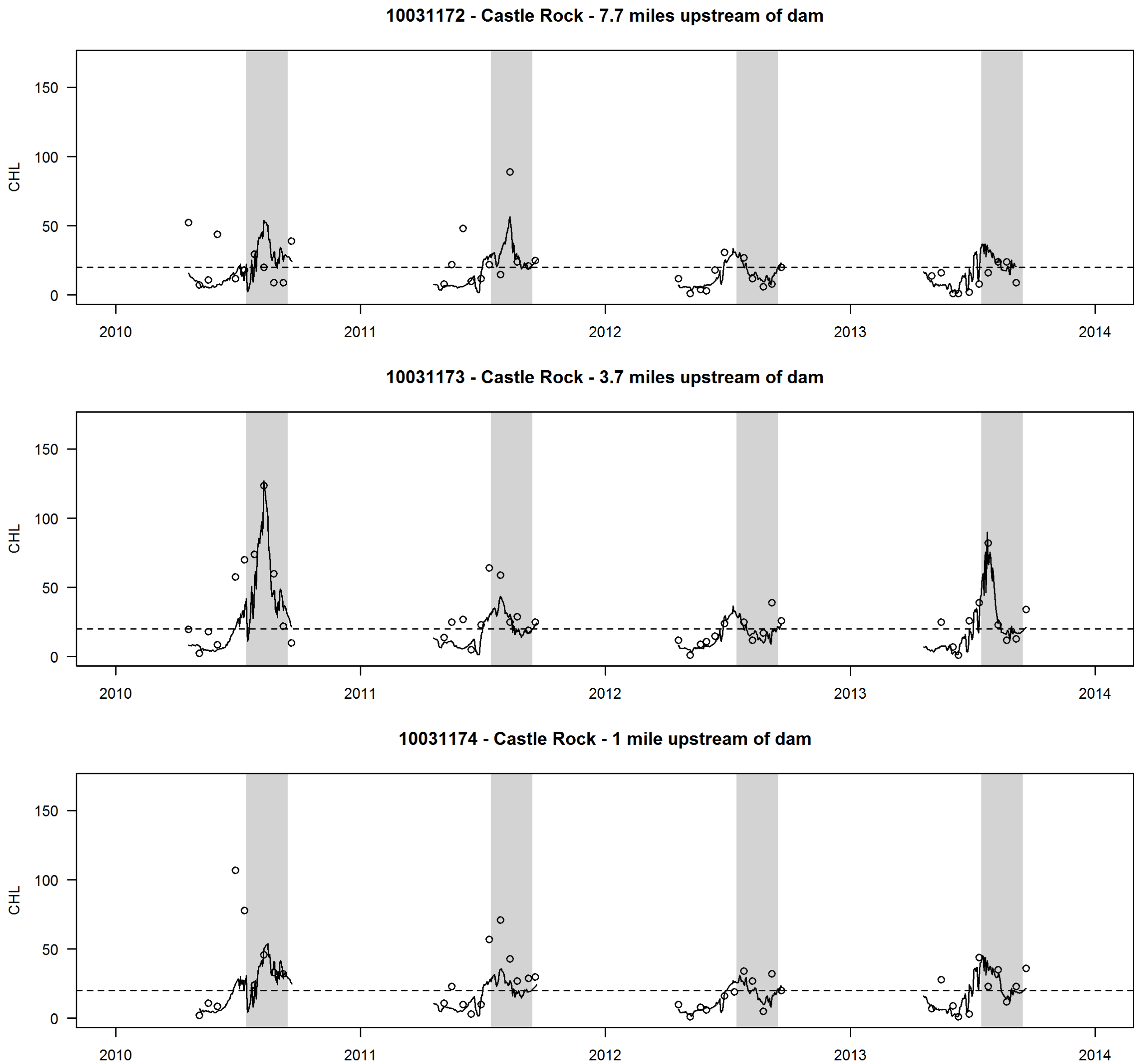


Figure 19. Observed (circles) and simulated (lines) chlorophyll *a* (μg/L) in Lake Wisconsin. Dashed line is recreational chlorophyll *a* target (20 μg/L). Shaded areas are chlorophyll *a* assessment periods.

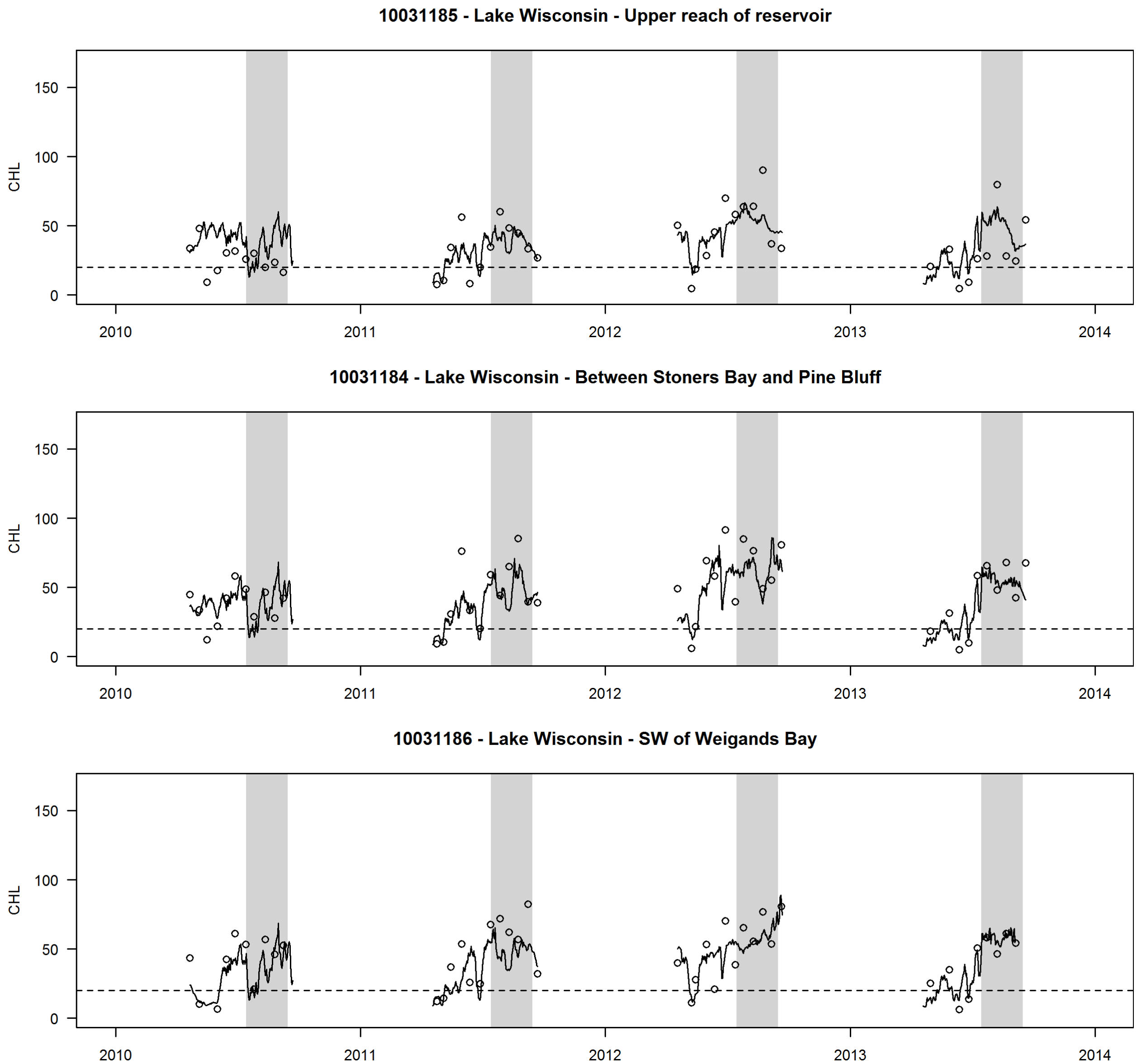


Figure 20. Current condition (black) and site-specific criterion (red) scenarios for total phosphorus (TP; µg/L) and chlorophyll *a* (CHL; µg/L) in Petenwell Lake. Dashed lines are recommended TP site-specific criteria (53 µg/L) and recreational chlorophyll *a* target (70th percentile = 20 µg/L). Shaded areas are assessment periods for each parameter.

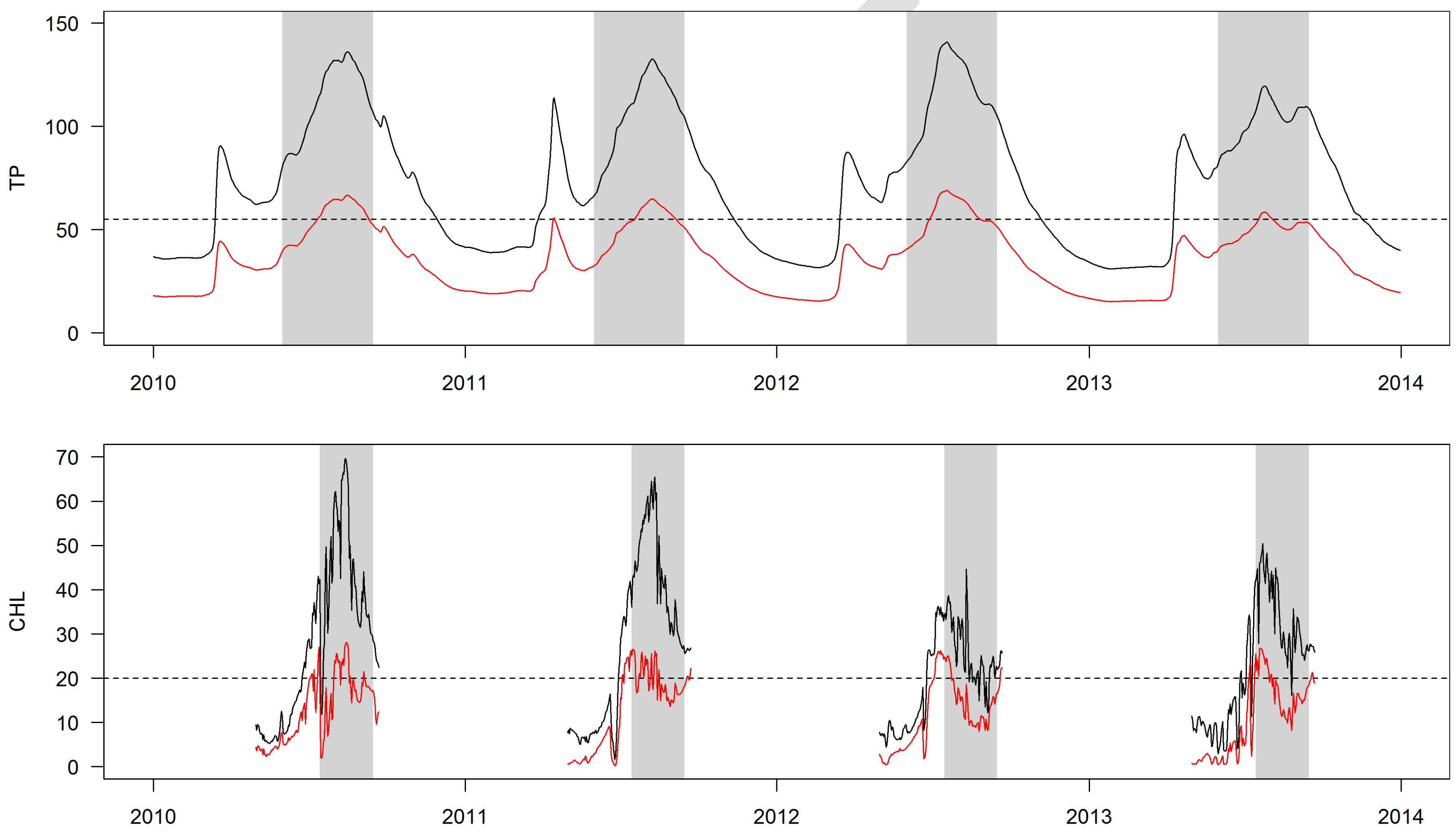


Figure 21. Current condition (black) and site-specific criterion (red) scenarios for total phosphorus (TP; µg/L) and chlorophyll *a* (CHL; µg/L) in Castle Rock Lake. Dashed lines are recommended TP site-specific criteria (55 µg/L) and recreational chlorophyll *a* target (70th percentile = 20 µg/L). Shaded areas are assessment periods for each parameter.

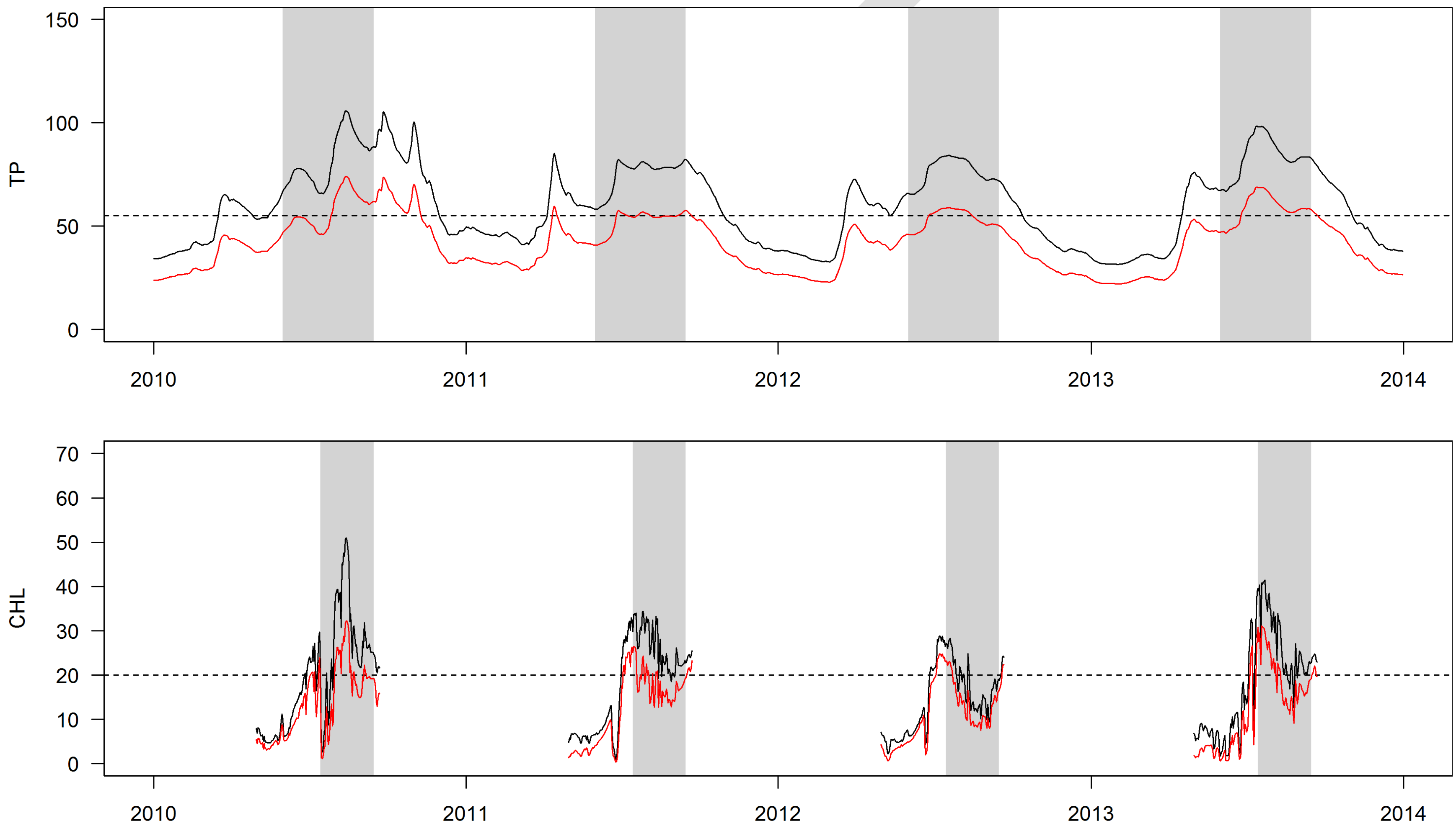
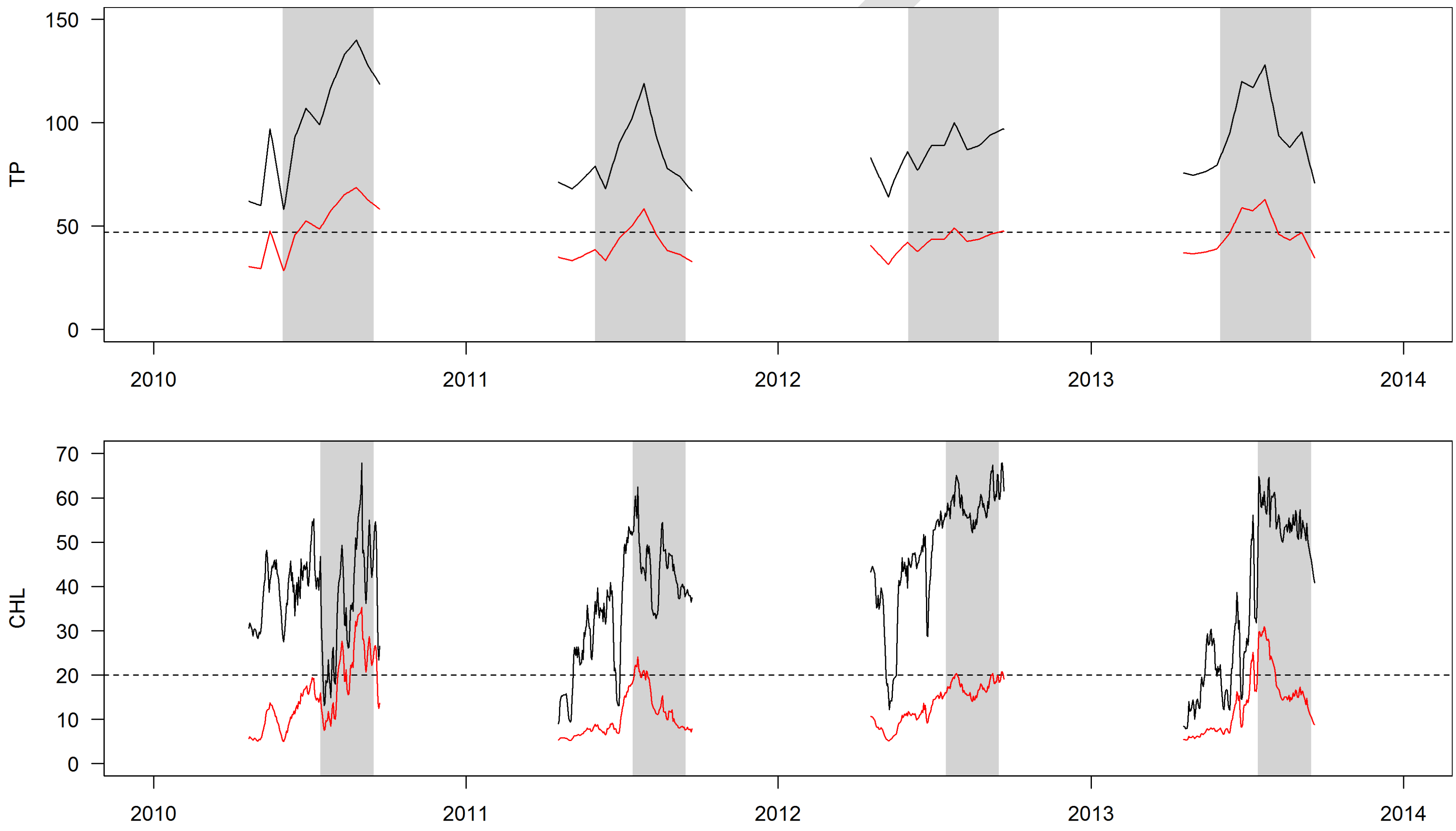


Figure 22. Current condition (black) and site-specific criterion (red) for total phosphorus (TP; µg/L) and chlorophyll *a* (CHL; µg/L) in Lake Wisconsin. Dashed lines are recommended TP site-specific criteria (47 µg/L) and recreational chlorophyll *a* target (70th percentile = 20 µg/L). Shaded areas are assessment periods for each parameter.



Discussion

The empirical models described in this report estimate the TP concentrations that are expected to meet the chlorophyll *a* (CHL) target for recreational use (70th percentile CHL < 20 µg/L during July 15 – September 15) in Petenwell and Castle Rock Lakes and Lake Wisconsin. These models are based on four years of biweekly monitoring data. The models indicate that variation in CHL in these reservoirs is primarily driven by total phosphorus, but that river discharge and seasonal variation also play a role. High river discharge probably reduces CHL because it flushes algae through more quickly and is associated with turbid water that reduces light availability for algal growth. The seasonal pattern observed in Petenwell and Castle Rock Lakes (after controlling for TP and Q) is probably related to variation in solar radiation and possibly algal grazing by zooplankton in May-June (which is a common period of clear water in many lakes), and possibly algal taxonomic succession, where taxa with low chlorophyll density dominate in May-June, and taxa with high chlorophyll density dominate in July-August. The lack of influence of nitrogen on CHL variation suggests that it rarely limits algal growth in these reservoirs. This is somewhat surprising, given that inorganic nitrogen (the form available for algal uptake) dropped to undetectable levels several times during the late summers of 2010-13 in in Petenwell and Castle Rock Lakes. One possible explanation for this phenomenon is that algal taxa that can fix atmospheric nitrogen (e.g., cyanobacteria) became dominant during these conditions, and kept CHL production high.

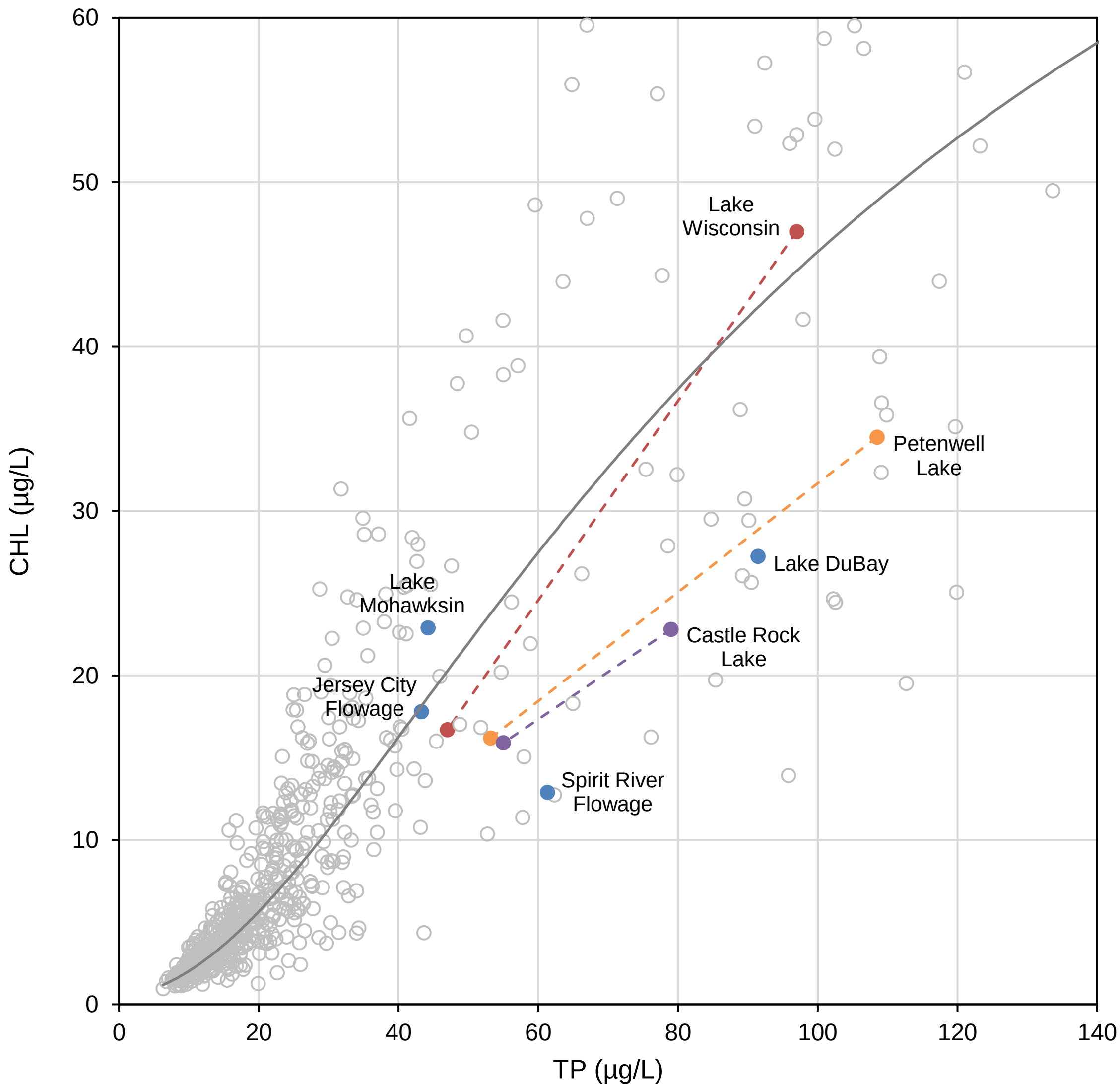
Comparison of the two reservoir models indicates that Lake Wisconsin produces more CHL per unit TP than Petenwell and Castle Rock Lakes, particularly during low flow conditions. For example, at the lowest flows observed during 2010-13 (1,000-1,500 cfs in Petenwell/Castle Rock and 2,000-3,000 cfs in Lake Wisconsin), the Lake Wisconsin model estimates that an increase in TP from 60 to 120 µg/L would increase CHL from about 30 to 90 µg/L, while this same TP range in Petenwell/Castle Rock would only increase CHL from about 20 to 30 µg/L. This difference can also be seen in the data plots of the dry summer of 2012, where Petenwell/Castle Rock had the lowest CHL of the four-year period, and Lake Wisconsin had the highest CHL (Figures 17-19). The lower sensitivity to TP in Petenwell/Castle Rock at low flows is the reason that the recommended SSCs are higher for these reservoirs.

Figure 23 provides another way to visualize the predicted sensitivity of CHL to TP in these reservoirs, and to put it in context of assessments of other lakes and reservoirs. There are four reservoirs on the Wisconsin River or its tributaries upstream of Petenwell Lake that have been assessed for TP and CHL. The predicted CHL/TP ratios of Petenwell and Castle Rock Lakes and Lake Wisconsin are within the range of values in these upstream reservoirs. For example, when TP is 53 µg/L in Petenwell Lake, CHL is predicted to be 17 µg/L, giving a ratio of 0.32. It is unclear what causes the large range in CHL/TP ratios among these reservoirs – from 0.21 in Spirit River Flowage to 0.52 in Lake Mohawksin. The predicted response of CHL to TP reductions in Petenwell and Castle Rock Lakes and Lake Wisconsin is similar to the overall CHL/TP relationship among all Wisconsin lakes and reservoirs (gray line in Figure 23). The response of CHL to TP reductions is steeper in Lake Wisconsin than the other two reservoirs, but the CHL/TP ratio in Lake Wisconsin in the SSC scenario is still projected to be higher than the other two reservoirs.

Figures 20-22 illustrate the large reductions in CHL from current conditions that are expected when the proposed SSC are achieved. In particular, CHL in Petenwell Lake and Lake Wisconsin currently frequently exceeds 50 µg/L during the summer recreation season but would only rarely exceed 30 µg/L when the SSC are achieved. In these two lakes, CHL would likely exceed 20 µg/L for a short time in early July (just before the assessment period) in some years, but if the recreation season was defined as June-August, CHL would exceed 20 µg/L fewer than 30% of the days in this period.

Ultimately, the SSC estimated by this analysis are predictions outside of the range of observed conditions (i.e., extrapolation). The accuracy of extrapolated relationships is always less certain than when the projected condition is within the range of observations (i.e., interpolation). In this situation, the risk of significant errors can be mitigated by evaluating alternative models, by comparing the estimated relationships with theoretical expectations, and by comparing the projections with other water bodies that are already in the range of the projections. If the SSC for TP are met, but CHL is still exceeding targets, new TP SSC may be estimated and adopted.

Figure 23. TP:CHL relationships for Wisconsin River reservoirs. All TP and CHL values are geometric mean values for assessment periods. Blue circles are reservoirs upstream of Petenwell Lake. Circles and dashed lines for Petenwell, Castle Rock, and Lake Wisconsin represent current conditions (high TP/CHL) and SSC conditions (low TP/CHL). Gray circles are all other Wisconsin lakes and reservoirs that had at least six concurrent TP and CHL samples. Gray line is a 3[rd]-order polynomial regression fit to the log(CHL)~log(CHL) relationship for the gray circles.



Aquatic Plant Indices

As shown in Table 1, two aquatic plant indices are applicable to the aquatic life use of Petenwell and Castle Rock Lakes. These indices were recently developed by the Department. The general disturbance index (MAC) is proposed for inclusion in the next version of the Department's assessment guidance (WisCALM). The phosphorus response index (MAC-P) is included in proposed revisions of chapter NR 102. Both indices are based on macrophyte species composition and abundance. The MAC-P version of the index was developed because the MAC is sensitive to types of disturbance other than nutrient enrichment. A statistical analysis was conducted to estimate the probability of attaining the MAC-P threshold (Phosphorus-sensitive species > 42%) at the TP and CHL concentrations that support recreational uses of Petenwell and Castle Rock Lakes. The details of this analysis are described below, but the results were inconclusive.

In general, the characteristics of aquatic plant communities and their response to TP and CHL in large reservoirs are not well understood. Aquatic plant surveys of the type needed to calculate these metrics have not been conducted on any Wisconsin River reservoirs, and the dataset used to develop these metrics only included one large reservoir, Puckaway Lake, on the Fox River system. Puckaway Lake has significantly higher TP and chlorophyll than are expected for the Wisconsin River reservoir SSCs, so the condition of its aquatic plants cannot be used to infer future conditions in the Wisconsin River reservoirs. The relationship between water column phosphorus and aquatic plant species composition may be different in large lakes than in smaller lakes because the effect of wind-driven turbulence may limit the occurrence of some rooted plant species that would otherwise be present at a given water column phosphorus concentration. In addition, the characteristics of bed sediments in reservoirs may be different than in natural lakes because of their recent history as upland soils, and this may influence aquatic plant species composition.

Based on these analyses, it remains unclear whether the aquatic plant metrics that are applicable to the aquatic life use are more or less sensitive than the recreational chlorophyll *a* criteria in these reservoirs. This uncertainty is mainly due to the lack of aquatic plant data on these specific reservoirs, and on other similar large reservoirs in general. Because the relationship between phosphorus and chlorophyll *a* is much better defined and appears likely to be the most sensitive use, the proposed SSCs are based on this relationship.

Analysis Details

There is a total of 434 surveys on 191 southern drainage lakes and reservoirs in the Department's aquatic plant database. Of these, 218 surveys on 99 lakes had corresponding TP and CHL data, which was defined as the geometric mean concentration in the year closest to, and within 5 years of, the plant survey year. For each year, geometric mean concentrations were calculated from monthly geometric means for the summer assessment periods for each parameter (June 1 – September 15 for TP and July 15 – September 15 for CHL), for years with samples from at least two months in the assessment period.

A mixed effects model fit with the lme4 package in R was used to estimate the probability of attaining the MAC-P threshold as a function of TP and CHL. The model formula is: glmer(MACP ~ log(R) + (1 | WBIC), data, family="binomial"), where MACP is a binary code for MAC-P attainment, R is TP or CHL, and WBIC is lake ID as a random effect to account for multiple surveys in some lakes. Confidence intervals on the effects of TP and CHL on MAC-P attainment were estimated by bootstrapping with the bootMer function in lme4. The models indicate that the probability of MAC-P attainment with TP at the recreational criteria (53-55 µg/L) is 17%, but with a wide (1-54%) 90% confidence interval (Figure 24). The TP concentration that equates to a 50% probability of MAC-P attainment is 41 µg/L. This finding suggests that the MAC-P is a more sensitive use than the recreational CHL criterion. In contrast, the probability of MAC-P attainment with CHL at the recreational criteria (geometric mean = 16 µg/L) is 66%, also with a wide (37-99%) 90% confidence interval (Figure 25). This finding indicates that the lower than average CHL/TP ratio in Castle Rock and Petenwell Lakes may also mean that the aquatic plant community will attain a better condition than expected based on TP alone.

Figure 24. Regression relationship between TP and probability of MAC-P attainment for southern Wisconsin drainage lakes and reservoirs. Dashed lines are 90% confidence interval. The “rugs” of tick marks on the top and bottom of the plot are the TP values where the MAC-P threshold was attained and not attained, respectively. Vertical lines at 55 and 53 µg/L TP are expected geometric mean TP in Castle Rock and Petenwell Lakes, respectively, when recreational criteria are met. Note log TP scale.

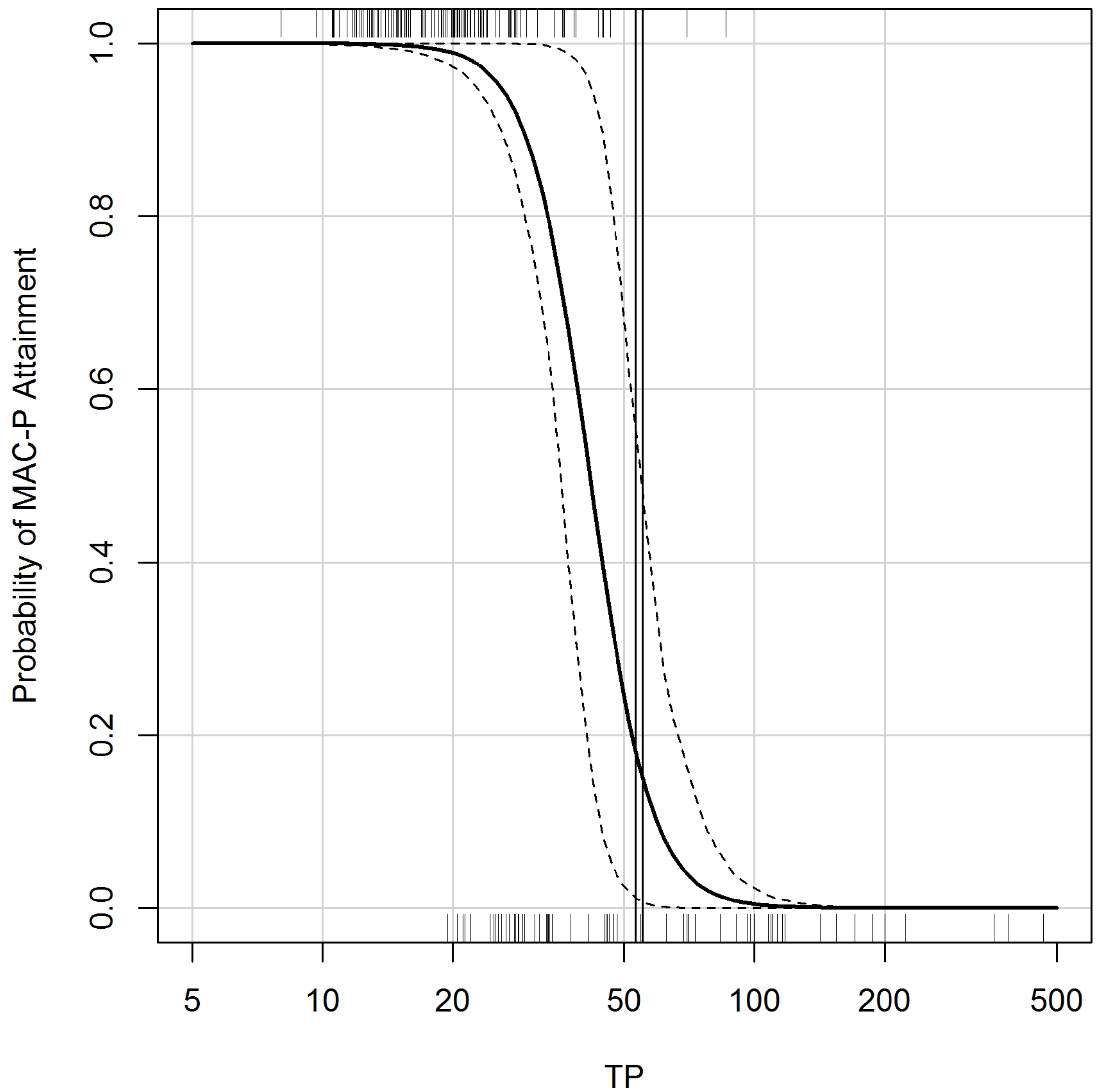


Figure 25. Regression relationship between CHL and probability of MAC-P attainment for southern Wisconsin drainage lakes and reservoirs. Dashed lines are 90% confidence interval. The "rugs" of tick marks on the top and bottom of the plot are the CHL values where the MAC-P threshold was attained and not attained, respectively. Vertical line at 16 µg/L CHL is expected geometric mean CHL in Castle Rock and Petenwell Lakes when recreational criteria are met. Note log CHL scale.