High Rock Lake TAC Meeting Review

Pam Behm, DWR Modeling and Assessment Branch

Department of Environmental Quality

April 20, 2016

Technical Advisory Committee (TAC)

PURPOSE:

Assist DWQ with the development of mathematical tools for the management of nutrients and turbidity in High Rock Lake. DWQ expects this assistance to include providing input on levels of confidence for decision making and evaluating field and modeling studies for the reservoir.

High Rock TAC Members

- Winston-Salem
- Salisbury
- Kernersville
- Duke Energy
- Alcoa
- Yadkin Riverkeeper* (since Mar 2009)

- DWQ
- NC DOT
- DSWC
- Piedmont-Triad COG
- Keep Iredell Clean
- DEH*

  (since Sept 2009)

Meeting #21
March 2, 2016
Agenda

- What’s going on at DWR
- Lake Model
    - Review
    - Response
    - Applicability
    - Moving forward
- Next Steps

Meeting Summary

- EPA model developer Tim Wool attended
- Reviewed comments received on lake model and actions that were taken or will be taken to finalize model
- Discussed impact of NCDP on process
- Discussed finalizing the TAC (next meeting?)

Upcoming Target Dates

- EPA finalize model based on comments – End of April 2016
- EPA response to comments – End of May 2016
- DWR/EPA finalize report – End of May 2016
- Next TAC meeting – Summer 2016

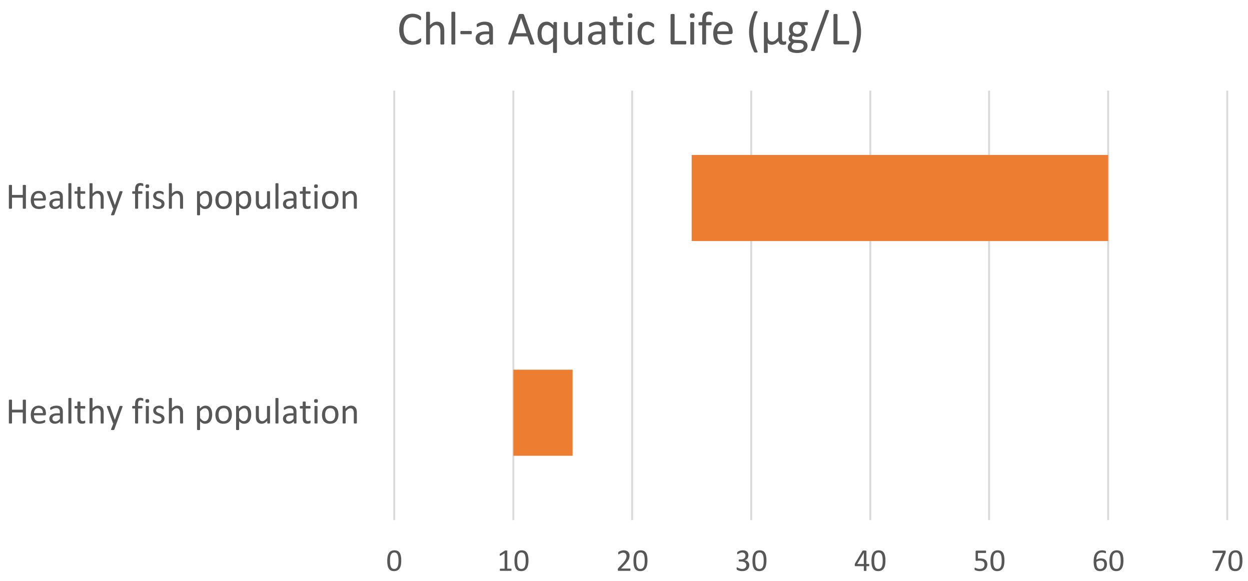
Indicator Ranges
compiled for
Scientific Advisory Council
meeting

April 20, 2016

Chlorophyll *a*

Indicator: Chlorophyll *a* (µg/L)						
WQ Goal: Aquatic Life	**Low**	**High**	**Range**	**Duration**	**Frequency**	**Special Considerations**
Healthy fish population	10	15	5			Maceina et al. 1996- Alabama reservoirs [M. Ardon]
Healthy fish population	25	60	35		GS Geomean	Low value based on concerns of adverse impact to recreational fishery; CHLA should not drop below this value. Use attainment status serves as basis for criteria implementation. See evaluation of HRL data for performance-based criteria recommendations and lake zones. [C. Bell]
Safe fish consumption			0			
Aesthetics						
Main body 1	42.67			see notes	see notes	Sample at HRL051, YAD152A & C, YAD169B & F [B. Hall]
Main body 2	45.59			see notes	see notes	Sample as above, minus HRL051 (due to turbidity) [B. Hall]
Abbotts Creek	37.34			see notes	see notes	Sample at HRL052, YAD169A [B. Hall]
Town Creek	56.28			see notes	see notes	Sample at YAD152 [B. Hall]
Second Creek	55.39			see notes	see notes	Sample at YAD156A, YAD1561A [B. Hall]
Arm	35.95			see notes	see notes	Sample at YAD169E [B. Hall]

Notes: Growing season (May-Sept) geomean; ≥ 1 sample/month; allowable exceedance return frequency once/3 years [B. Hall]



Indicator: Chlorophyll *a* (µg/L)

WQ Goal: Water Supply	Low	High	Range	Duration	Frequency	Special Considerations
Suitable drinking water source	~42			see notes	see notes	Compliance point: YAD169F (point of lake discharge) [B. Hall]
Suitable drinking water source						Low value derived from reservoirs that experience higher levels of algal toxins. Use attainment status serves as basis for criteria implementation. [C. Bell]
No untreatable taste and odor issues						T&O issues are treatable [C. Bell]
No untreatable taste and odor issues		15	10			Done to keep geosmin < 5 ng/L (Smith et al., 2002, L&RM) [J. Bowen]

Notes: Growing season (May-Sept) geomean; ≥ 1 sample/month; allowable exceedance return frequency once/3 years [B. Hall]

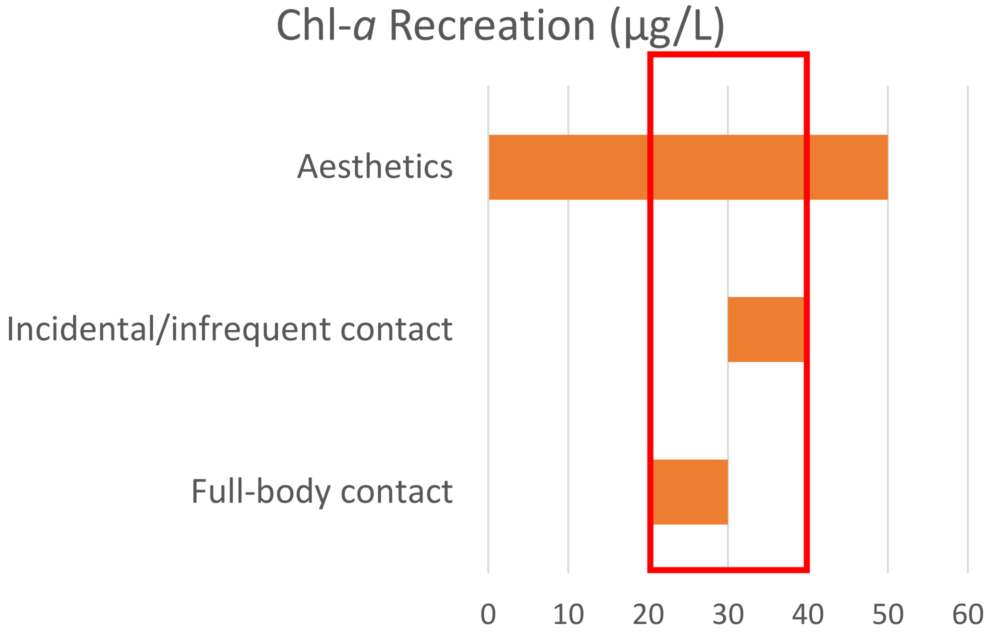
*Need to calculate highest measured growing season geomean at YAD169F (lake discharge)

Indicator: Chlorophyll *a* (µg/L)

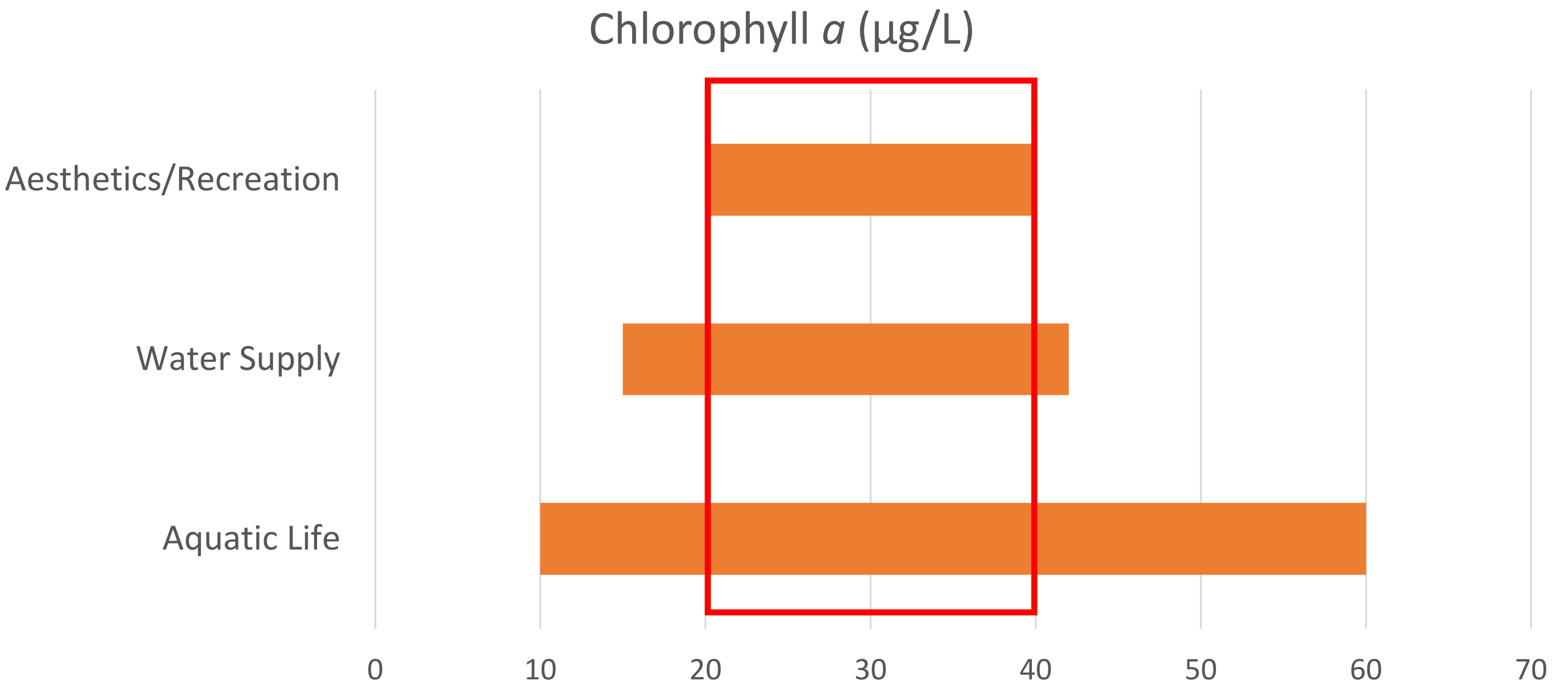
Water Quality Goal: Recreation	Low	High	Range	Duration	Frequency	Special Considerations
Full-body contact	20		10			Low value derived from reservoirs that experience higher level of algal toxins. Use attainment status serves as basis for criteria implementation. [C. Bell]
Incidental/infrequent contact	30		10			[C. Bell]
Aesthetics	30		10			[C. Bell]
Aesthetics	0	50	50	inst.	<10% summer	ref: Lake Pepin, MN (Wasley and Heiskary, 2009) [J. Bowen]
Aesthetics	0	30	30	inst.	max	ref: MN WCP shallow (Heiskary & Wilson, 2008) [J. Bowen]
Aesthetics	0	16	16	inst.	max	NY users rated as awful (Smith et al. 2009) [J. Bowen]
Aesthetics TX	0	25	25	inst.	max	TX users rated w/ signifcant impairment (Glass 2006) [J. Bowen]
Main body 1	42.67			see notes	see notes	Sample at HRL051, YAD152A & C, YAD169B & F [B. Hall]
Main body 2	45.59			see notes	see notes	Sample as above, minus HRL051 (due to turbidity) [B. Hall]
Abbotts Creek	37.34			see notes	see notes	Sample at HRL052, YAD169A [B. Hall]
Town Creek	56.28			see notes	see notes	Sample at YAD152 [B. Hall]
Second Creek	55.39			see notes	see notes	Sample at YAD156A, YAD1561A [B. Hall]
Arm	35.95			see notes	see notes	Sample at YAD169E [B. Hall]

Growing season (May-Sept) geomean; ≥ 1 sample/month; allowable exceedance return frequency once/3 years [B. Hall]

No max or range included. Range of 10 added for graphing purposes.



WQ Goal	**Low**	**High**	**Range**	**Duration**	**Notes**
Aquatic Life	10	60	50		
Water Supply	15	42	27		
Aesthetics/Recreation	20	40	20	Inst. Max	Low WQS (proposed): 20 full contact, 30 incidental contact
All Uses	36-56				



Algal Toxins

Indicator: Algal Toxins (mg/L)

WQ Goal: Aquatic Life	Low	High	Range	Duration	Frequency	Special Considerations
Healthy fish population			0			
Safe fish consumption	0.3	1.6	1.3			Linkage between seston toxin levels and fish levels has not been established. However, biodilution of microcystin has been demonstrated (Kozlowski-Suzuki et al. 2012). Therefore, protecting drinking water will protect fish consumption. [A. Schnetzer/H. Paerl/N. Hall]
Aesthetics	NA	NA	NA			

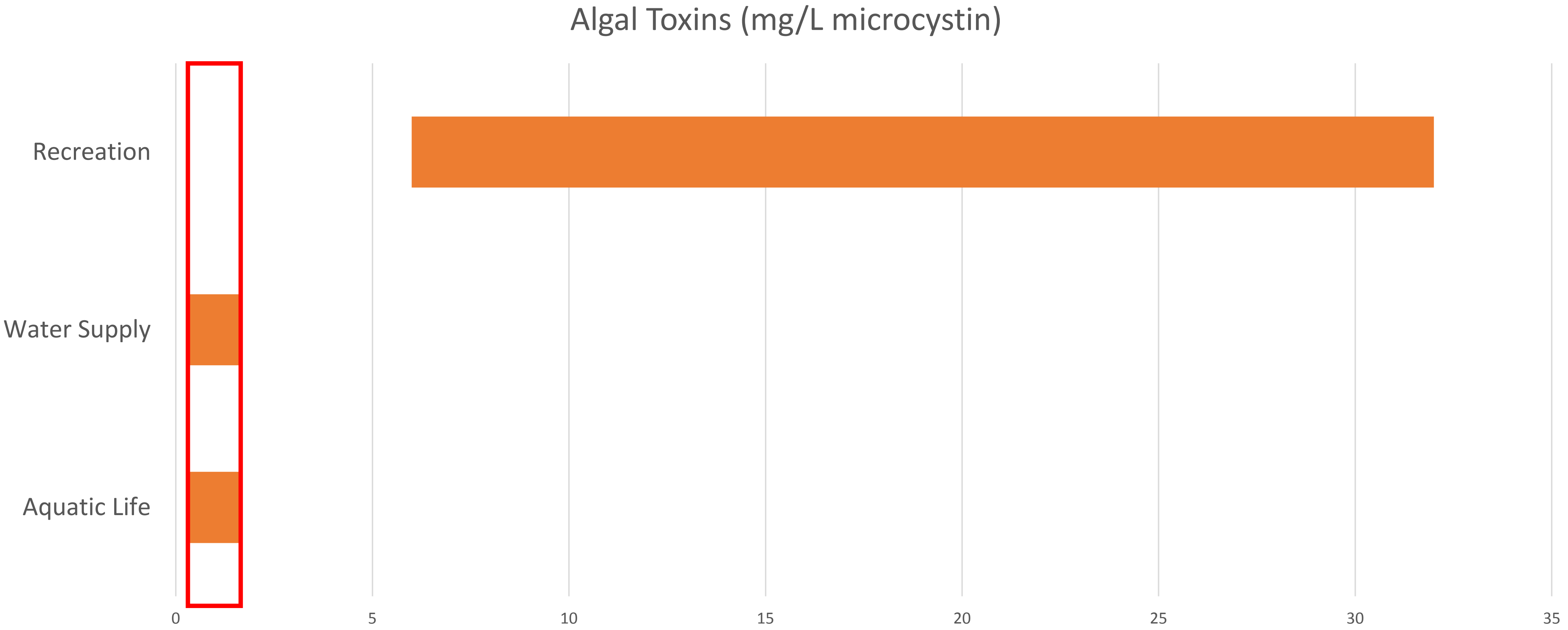
Indicator: Algal Toxins

WQ Goal: Water Supply	Low	High	Range	Duration	Frequency	Special Considerations
Suitable drinking water source	0.3	1.6	1.3	lifetime		Based on EPA 2015, 0.3 µg/L is for a small child, 1.6 µg/L is for children and adults, based on a study of liver disease in rats with an uncertainty (safety) factor of 1000 built in to account for 1) variability between exposed humans, 2) extrapolation from rats to humans, 3) extrapolation from "least" to "no" effect level, and 4) database insufficiencies and possibility that microcystin is also a tumor promoter, also assumes that water treatment is ineffective at removing toxin [Schnetzer/Paerl/Hall]
No untreatable taste/odor			0			

Indicator: Algal Toxins

Water Quality Goal: Recreation	Low	High	Range	Duration	Frequency	Special Considerations
Full-body contact	6	32	26			Based on accidental ingestion of 100 mL (WHO 1999) with the EPA standard for consumption of 2L of 0.3 µg/L (small children) and 1.6 µg/L (adults and children) microcystin containing water [A. Schnetzer/H. Paerl/N. Hall]
Incidental/infrequent contact			0			
Aesthetics			0			

WQ Goal	Low	High	Range	Duration	Frequency
Aquatic Life	0.3	1.6	1.3		
Water Supply	0.3	1.6	1.3		
Recreation	6	32	26		



Dissolved Oxygen

Indicator: Dissolved Oxygen (mg/L)

WQ Goal: Aquatic Life	Low	High	Range	Duration	Frequency	Special Considerations	Literature
Healthy fish population	1.7	5.5	3.8	(1)		Open Waters (2) [M. Lebo]	See top 2 sources in Lebo spreadsheet - match with ranges
Healthy fish population	1	2.3	1.3	(3)		Deep Waters (4) [M. Lebo]	
Healthy fish population	4	5	1	(5)		Current WQS [M. Lebo]	NCDEQ WQS code viewed online
Safe fish consumption			0				
Aesthetics			0				

Notes:

(1) low is instantaneous; high is for 30-day mean;

(2) open waters is the upper photic zone;

(3) low is instantaneous to protect benthic forage base; high is daily average of deep waters for protection of juvenile and adult fish;

(4) deep waters below photic zone/thermocline;

(5) minimum 4 mg/L and daily average of 5 mg/L.

Indicator: DO (mg/L)

WQ Goal: Water Supply	Low	High	Range	Duration	Frequency	Special Considerations
Suitable drinking water source			0			I am not aware of defined ranges in DO for protection of water supply. [M.Lebo]
No untreatable taste and odor issues			0			

pH

Indicator: pH (SU)						
WQ Goal: Aquatic Life	**Low**	**High**	**Range**	**Duration**	**Frequency**	**Special Considerations**
Healthy fish population	6.0	9.5	3.5	Annual or seasonal 90th percentile	1 in 3 years	Assumes salmonids absent. Assumes low levels of pH-dependent toxics (e.g., ammonia). Option: Use all epilimnetic observations, not just surface. Option: Lump all samples from lake mainstem. [C. Bell]
Safe fish consumption			0			
Aesthetics			0			

Indicator: pH (SU)						
WQ Goal: Water Supply	**Low**	**High**	**Range**	**Duration**	**Frequency**	**Special Considerations**
Suitable drinking water source	6.0	9.5	3.5	Annual or seasonal 90th percentile	1 in 3 years	Based on optimizing treatability and aesthetic issues, not human health. Could be based on spatially-integrated conditions or conditions near intake(s), not just surface samples at individual points. [C. Bell]
No untreatable taste and odor issues						pH is readily adjusted during treatment. [C. Bell]

Water Clarity

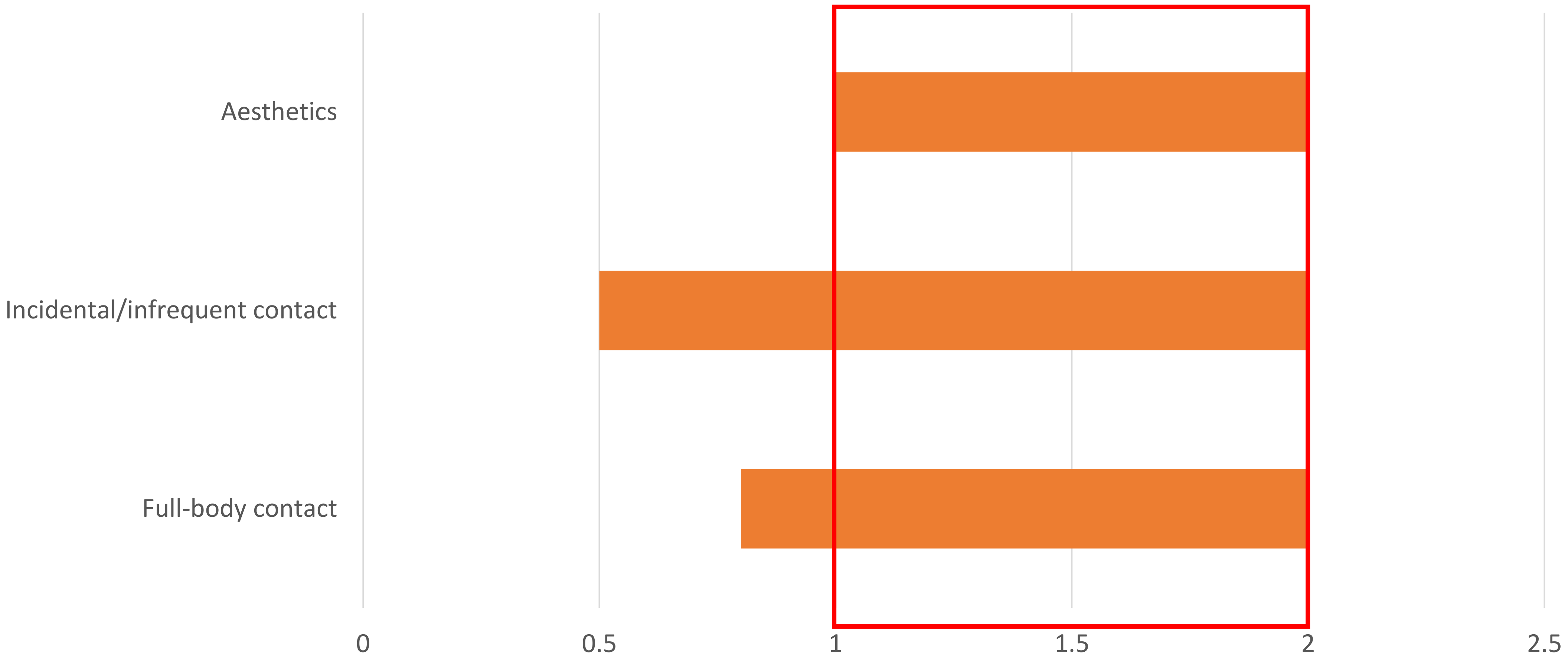
Indicator: Clarity (Secchi Depth, m)

WQ Goal: Aquatic Life	Low	High	Range	Duration	Frequency	Special Considerations	Literature
Healthy fish population	0.8	1.2	0.4			excellent to good; good to acceptable range	Burden et al. 1985, Younos 2007
Safe fish consumption			0				
Aesthetics			0				

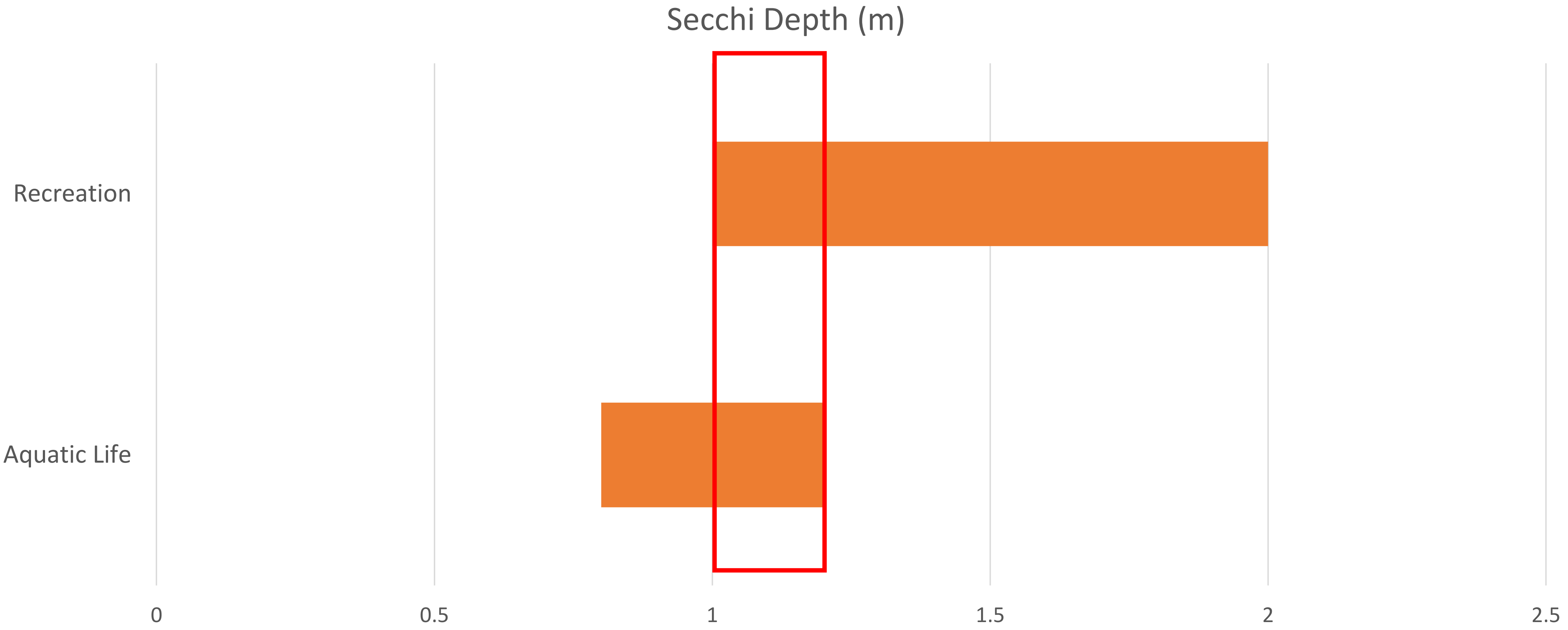
Indicator: Clarity (Secchi Depth, m)

Water Quality Goal: Recreation	Low	High	Range	Duration	Frequency	Special Considerations	Literature
Full-body contact	0.8	2	1.2				Smith et al. 1995, Younos 2007
Incidental/infrequent contact	0.5	2	1.5			0.5 hypereutrophic, no recreation	Lee et al. 1995, Younos 2007
Aesthetics	1	2	1			>1 clear, no blooms	Barica 1975, Younos 2007: Burkart et al. 2008

Secchi Depth (m) - Recreation



Clarity	Low	High	Range	Duration	Frequency
Aquatic Life	0.8	1.2	0.4		
Recreation	1	2	1		



Fisheries

Large mouth bass

Indicator: Fish						
WQ Goal	**Low**	**High**	**Range**	**Duration**	**Frequency**	**Special Considerations**
Abundance (CUE/hour)	50	105	55			Based on samples every 3 years by NCWRC [M. Ardon]
Composition (length/weight) (length)	50	550	500			
Condition (safe for consumption)			0			There haven't been any advisories for Large mouth bass. There have been for catfish. [M. Ardon]

Crappie

Indicator: Fish						
WQ Goal	**Low**	**High**	**Range**	**Duration**	**Frequency**	**Special Considerations**
Abundance (CUE night)	4	31	27			Sampled every 3 years by NCWRC [M. Ardon]
Composition (length/weight)			0			
Condition (safe for consumption)			0			

Remaining Indicators

Remaining Indicators

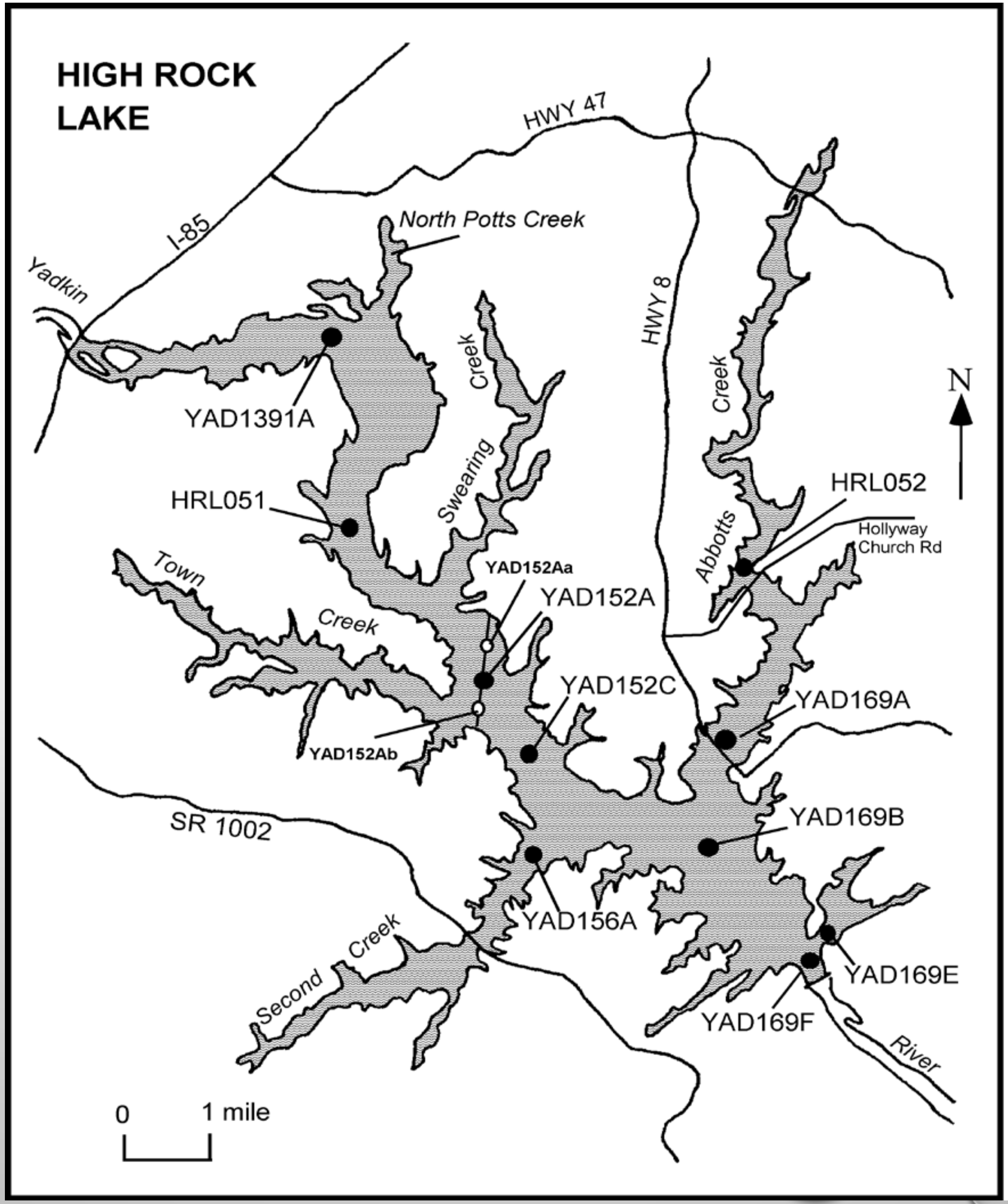
- Phytoplankton community structure
  - Percent composition cyanobacteria
- Dissolved organic matter
- Nitrate
- Ammonia
- Turbidity

EXISTING CHLOROPHYLL-A CONCENTRATIONS IN HIGH ROCK LAKE

WILLIAM T. HALL

HALL & ASSOCIATES

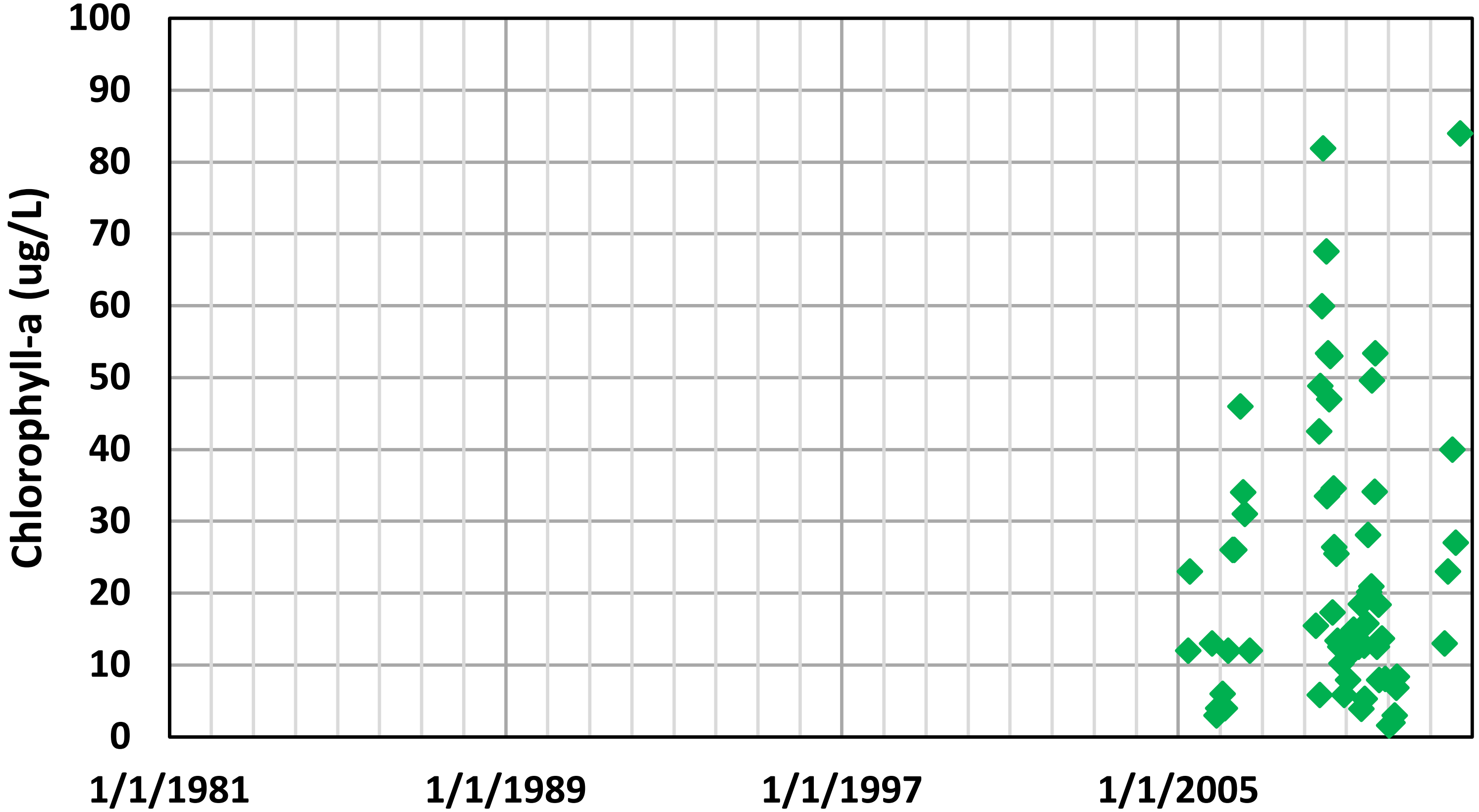
APRIL 20, 2016

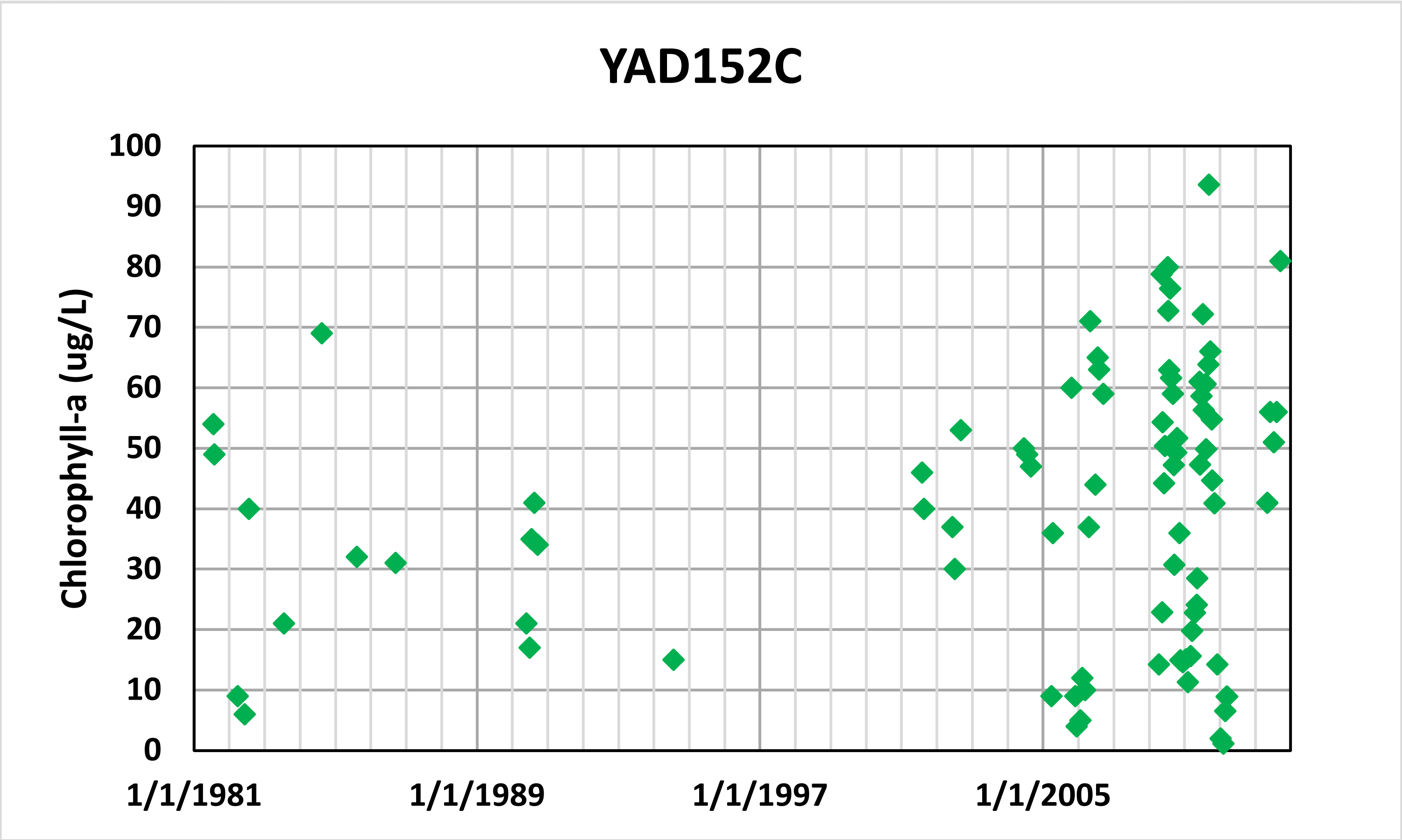

HIGH ROCK LAKE
HWY 47
I-85
Yadkin
North Potts Creek
YAD1391A
Creek
Swearing
HWY 8
Creek
Abbotts
N
HRL052
Hollyway Church Rd
HRL051
Town
Creek
YAD152Aa
YAD152A
YAD152C
YAD169A
YAD152Ab
YAD169B
SR 1002
YAD156A
Second
Creek
YAD169E
YAD169F
River
0
1 mile

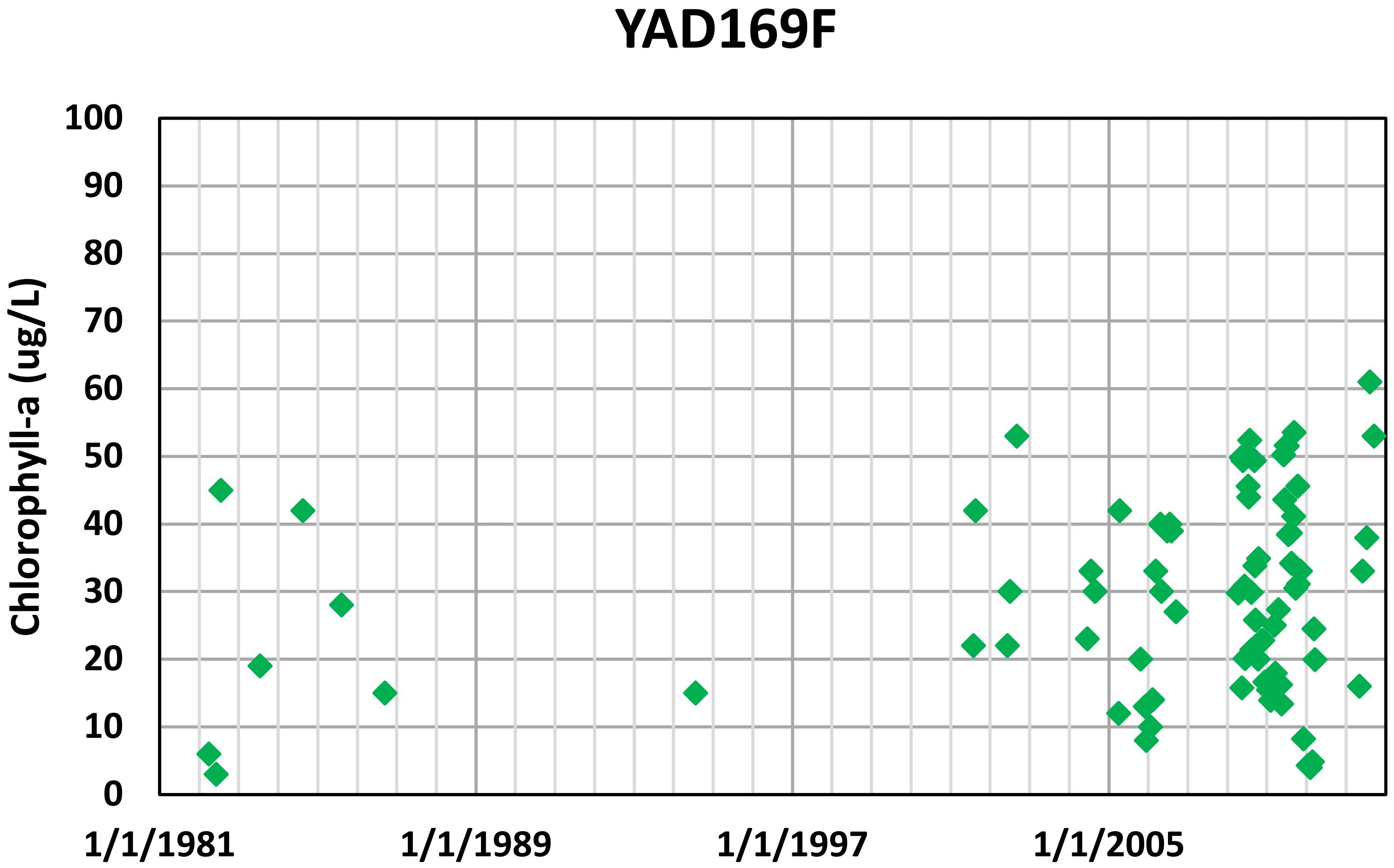
DATA EVALUATIONS

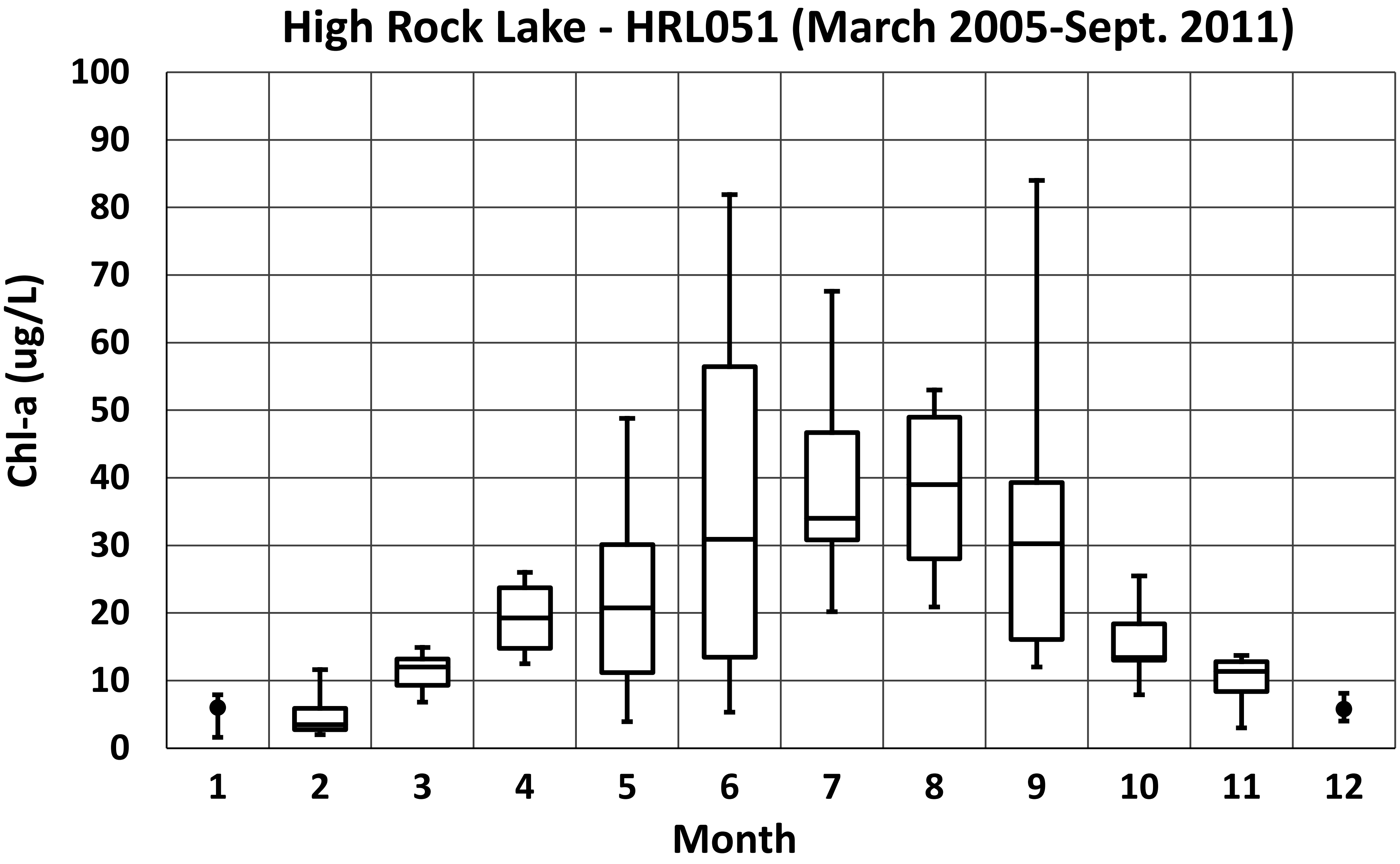
- CHLOROPHYLL-A
  - LONG TERM TRENDS
  - SEASONAL VARIABILITY
  - GROWING SEASON GEOMETRIC MEANS
- NUTRIENTS
- DISSOLVED OXYGEN

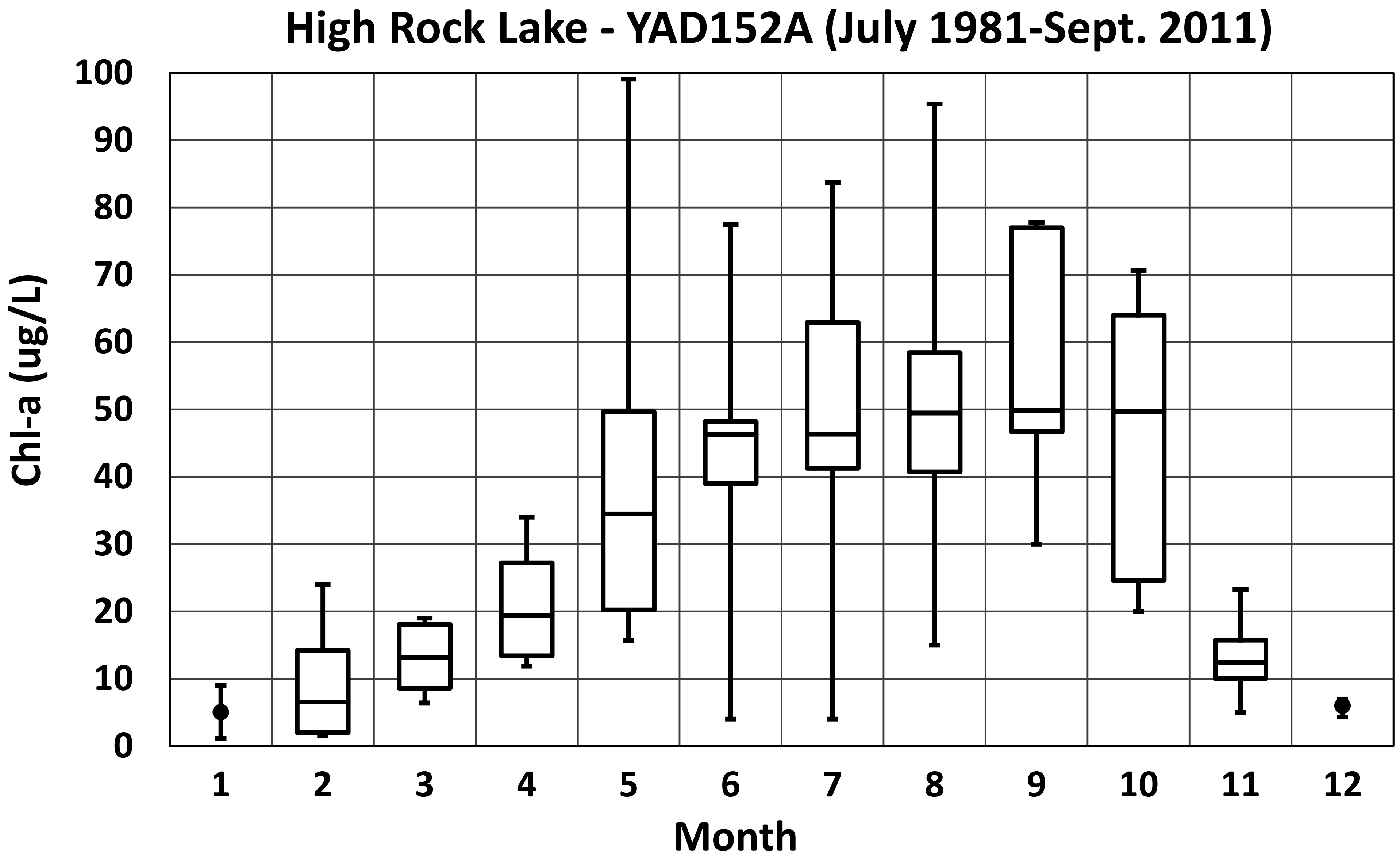
HRL051


Chlorophyll-a (ug/L)
100
90
80
70
60
50
40
30
20
10
0
1/1/1981
1/1/1989
1/1/1997
1/1/2005


YAD152C
Chlorophyll-a (ug/L)
100
90
80
70
60
50
40
30
20
10
0
1/1/1981
1/1/1989
1/1/1997
1/1/2005


YAD169F
Chlorophyll-a (ug/L)
100
90
80
70
60
50
40
30
20
10
0
1/1/1981
1/1/1989
1/1/1997
1/1/2005


High Rock Lake - HRL051 (March 2005-Sept. 2011)
Chl-a (ug/L)
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
Month


High Rock Lake - YAD152A (July 1981-Sept. 2011)
Chl-a (ug/L)
0
10
20
30
40
50
60
70
80
90
100
1
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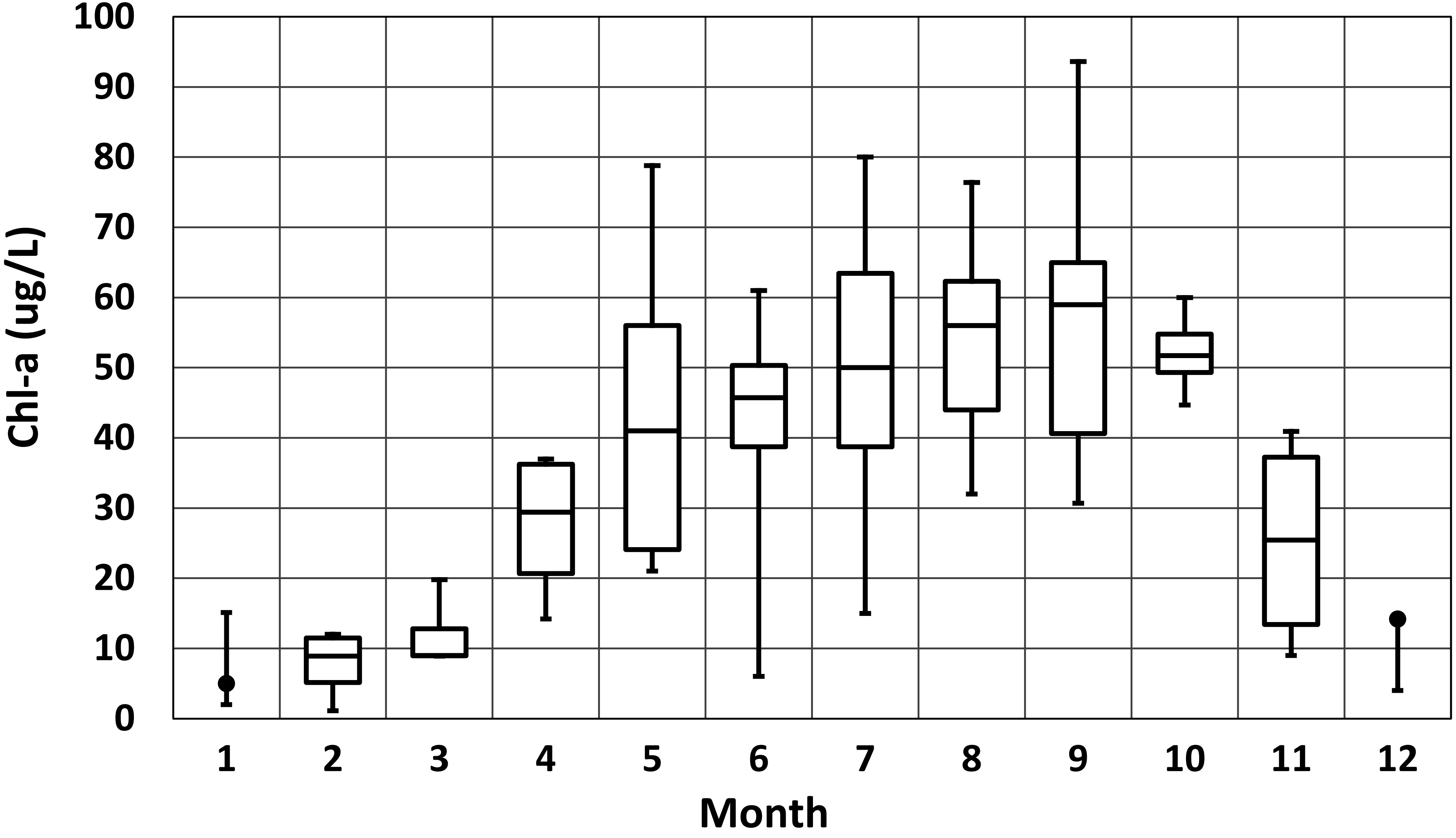
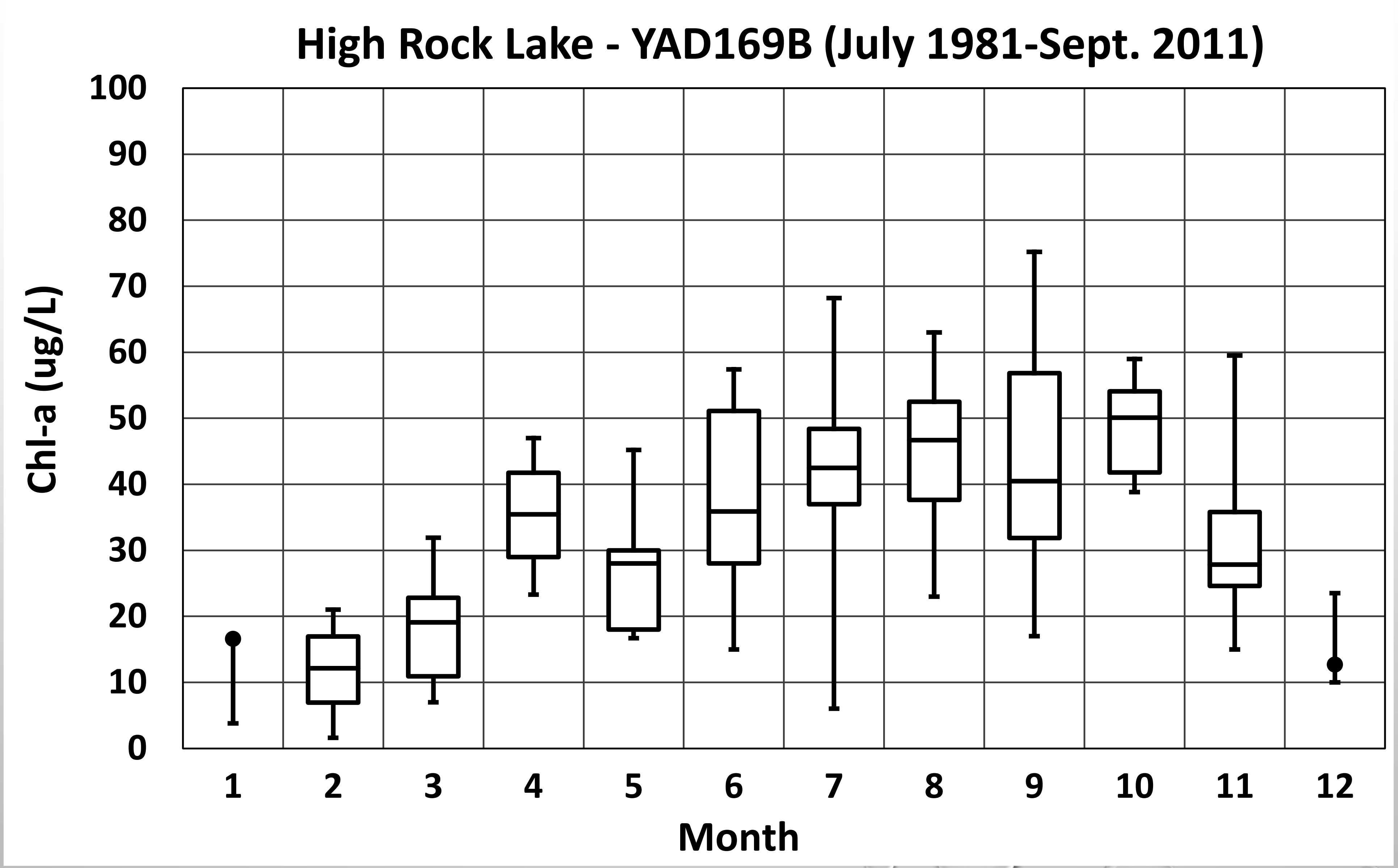
6
7
8
9
10
11
12
Month

High Rock Lake - YAD152C (July 1981-Sept. 2011)




High Rock Lake - YAD169B (July 1981-Sept. 2011)
Chl-a (ug/L)
100
90
80
70
60
50
40
30
20
10
0
1
2
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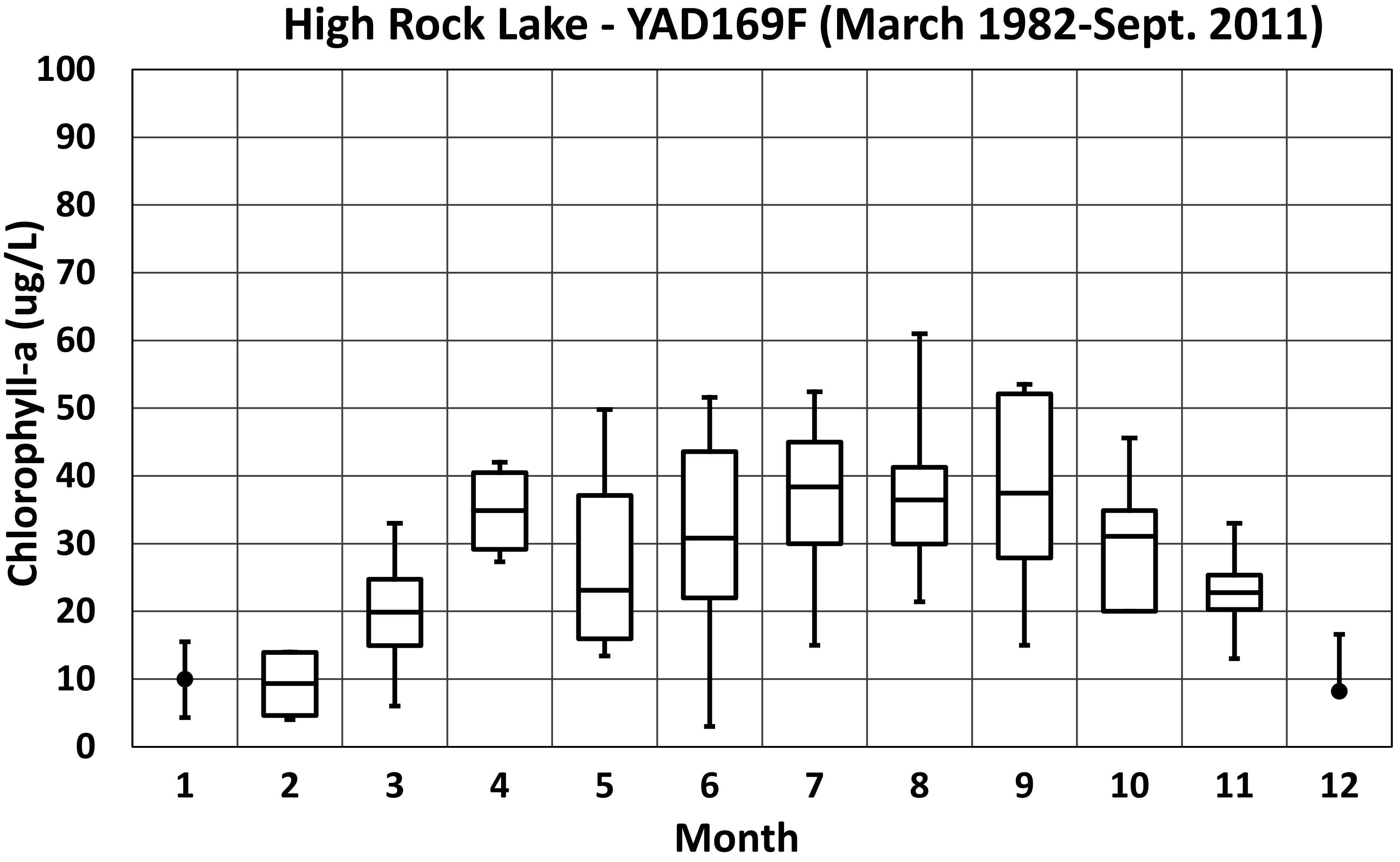
4
5
6
7
8
9
10
11
12
Month


High Rock Lake - YAD169F (March 1982-Sept. 2011)
Chlorophyll-a (ug/L)
100
90
80
70
60
50
40
30
20
10
0
1
2
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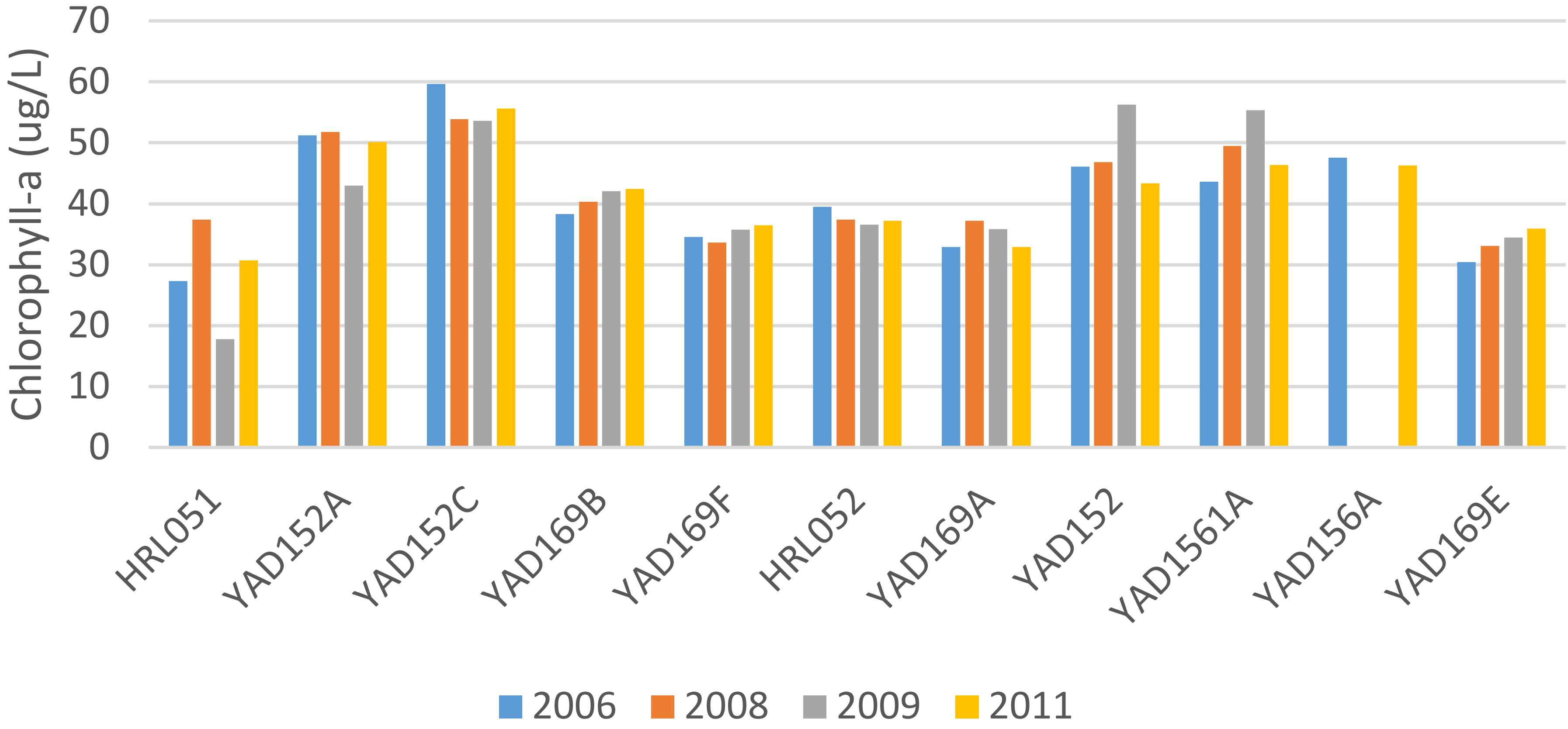
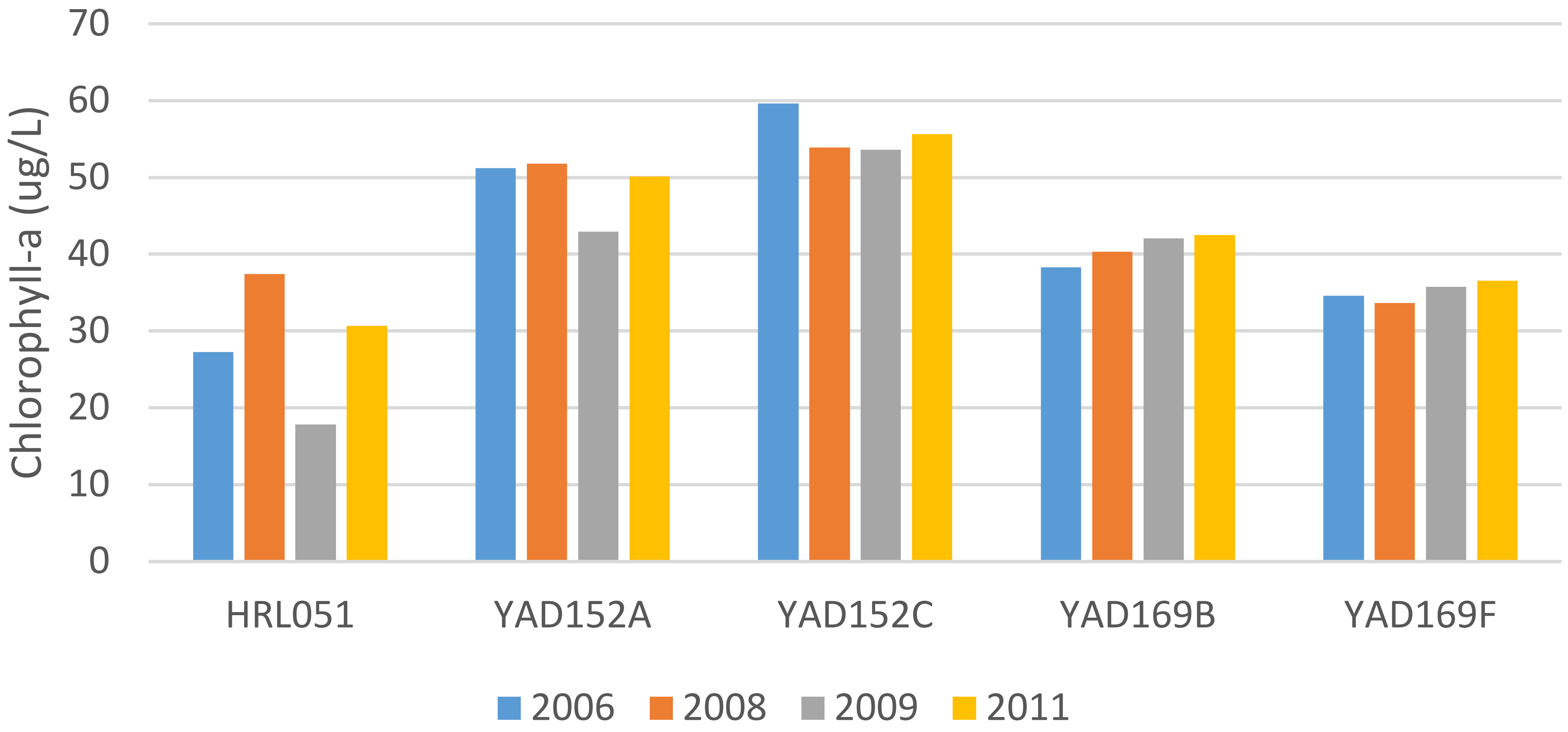
10
11
12
Month

High Rock Lake
Growing Season Geometric Mean

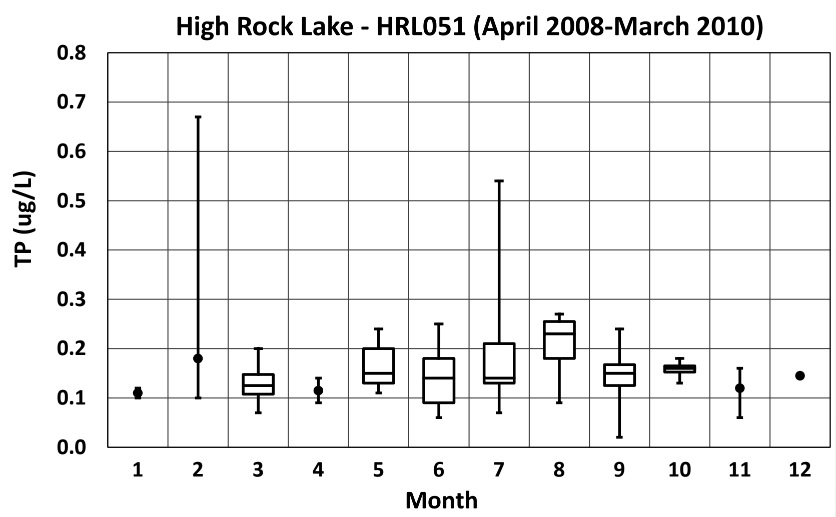


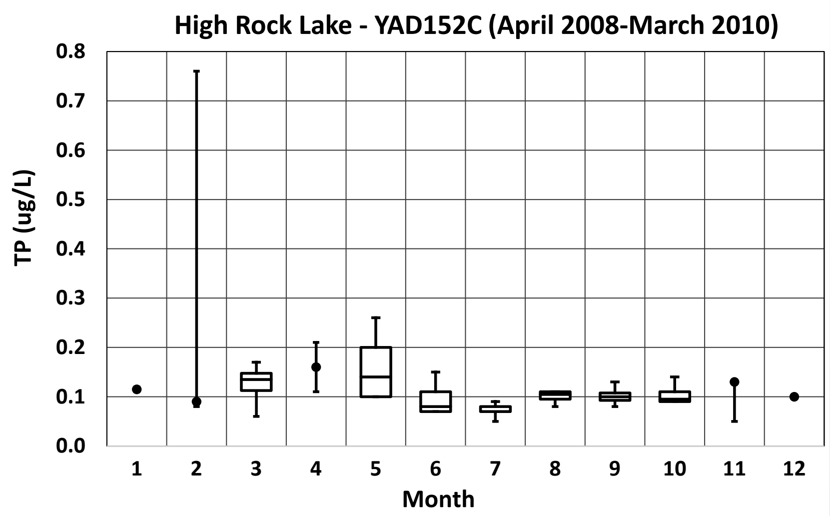
High Rock Lake - Center Line Stations
Growing Season Geometric Mean

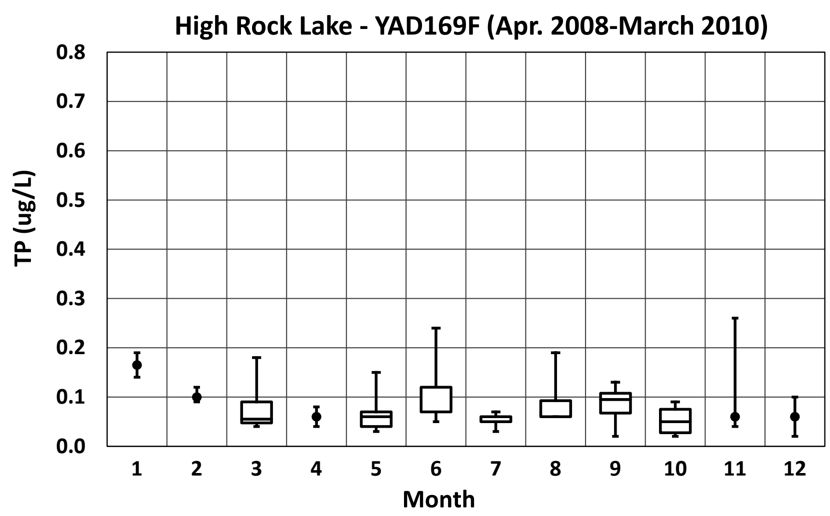


High Rock Lake
Growing Season Geometric Mean

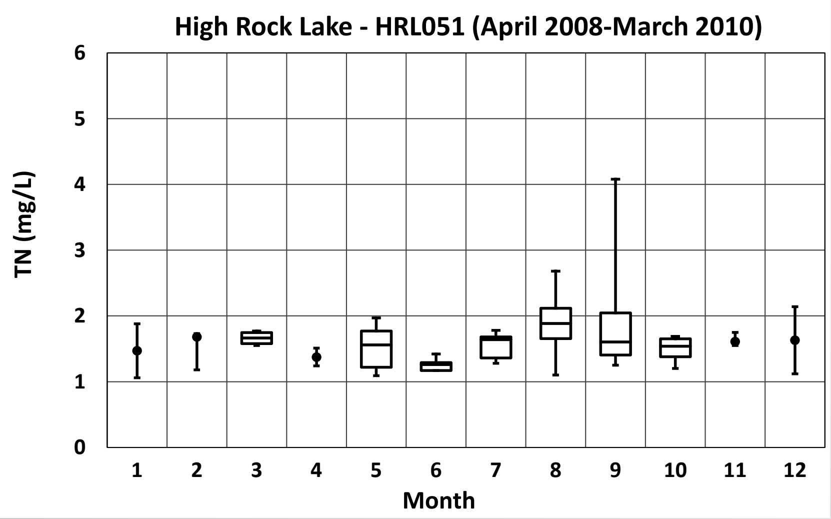
TOTAL PHOSPHORUS

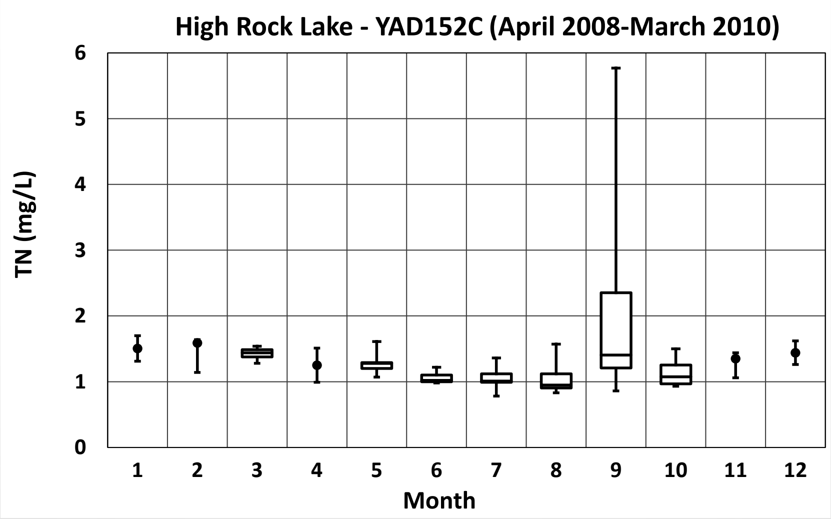


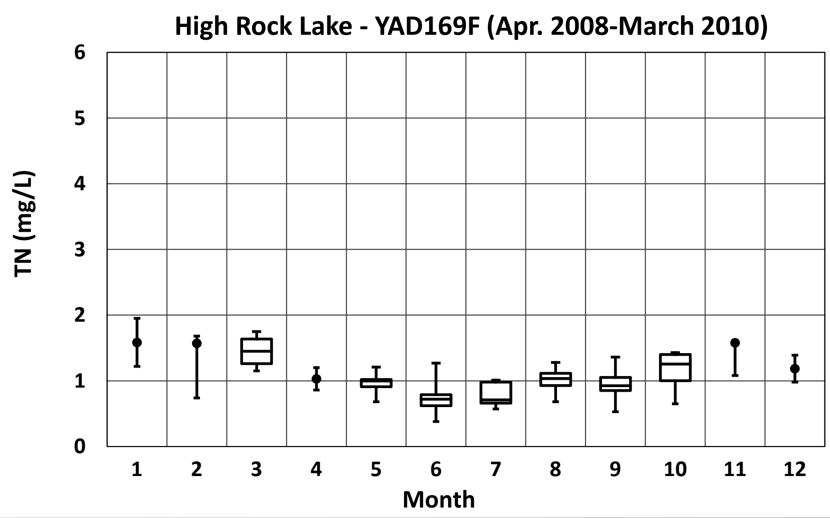




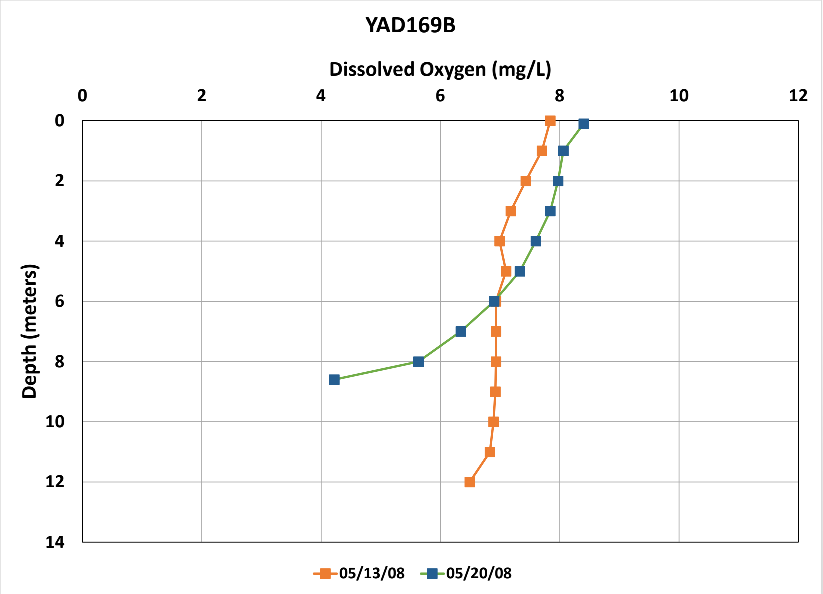
TOTAL NITROGEN



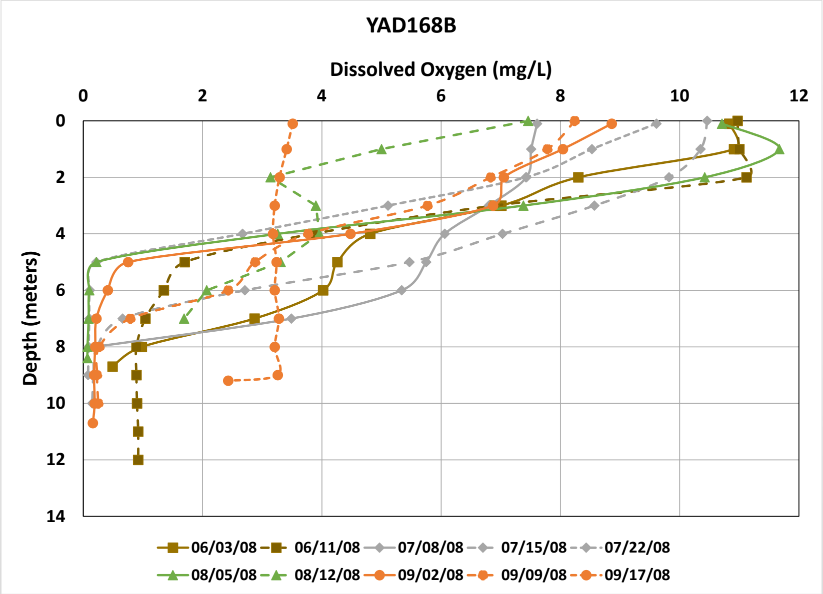




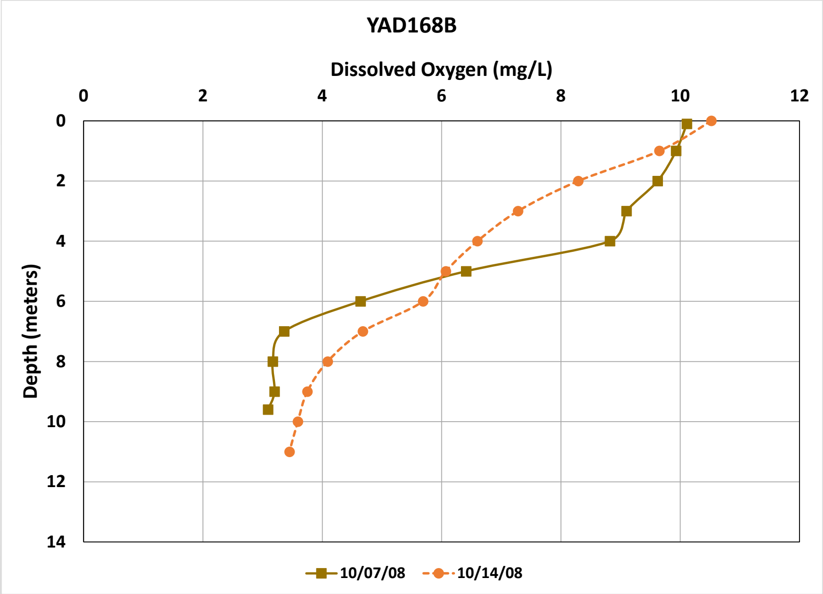
DISSOLVED OXYGEN



May



June - September



October

LITERATURE SURVEY

CLIFTON BELL

BROWN AND CALDWELL

LITERATURE SURVEY: OVERVIEW AND CAVEATS

- CHLA ASSOCIATED WITH A NUMBER OF EFFECTS ON USES, POSITIVE AND NEGATIVE
- LARGE VARIABILITY IN ACCEPTABLE CHLA LEVELS ASSOCIOATED WITH USE SUPPORT
  - BETWEEN REGIONS
  - EVEN WITHIN REGIONS
- SOURCES DO NOT ALWAYS CLARIFY THE DURATION/STATISTIC, AND LITTLE ON FREQUENCY

RESERVOIRS WITH VERY DIFFERENT CHLA “POTENTIALS” ARE MANAGED FOR THE SAME USES

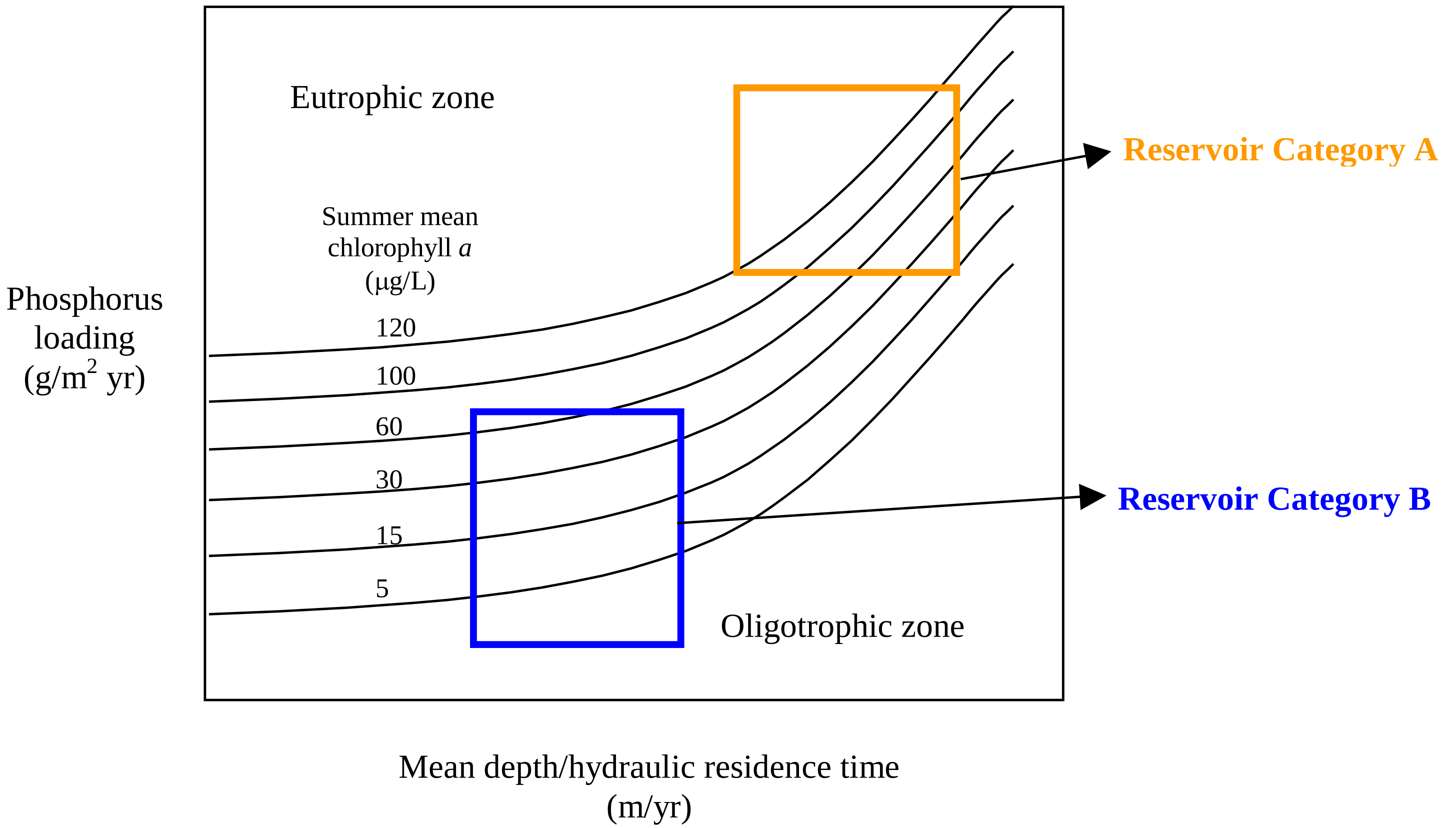
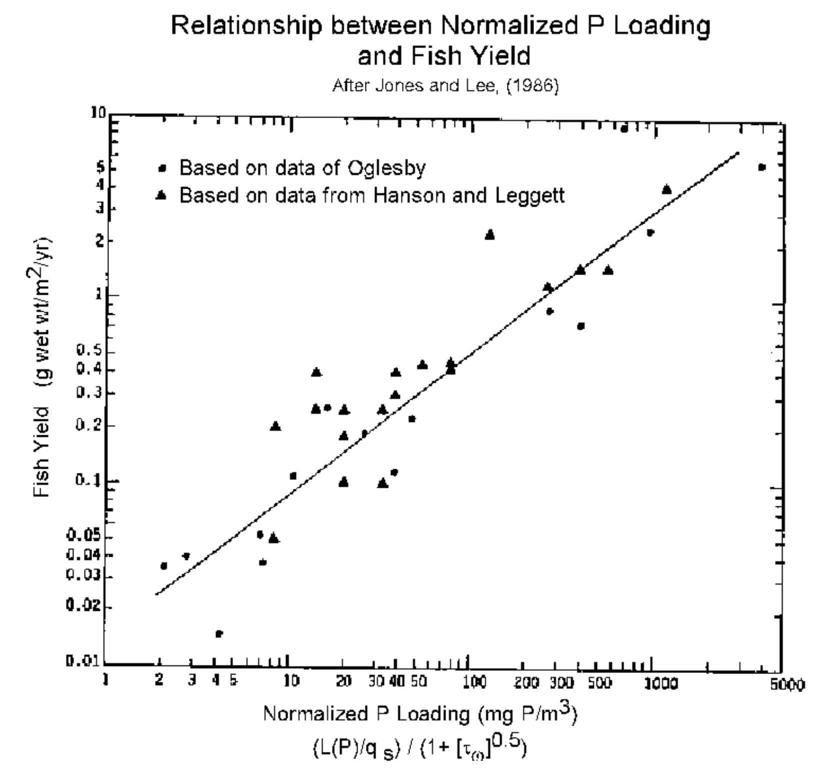


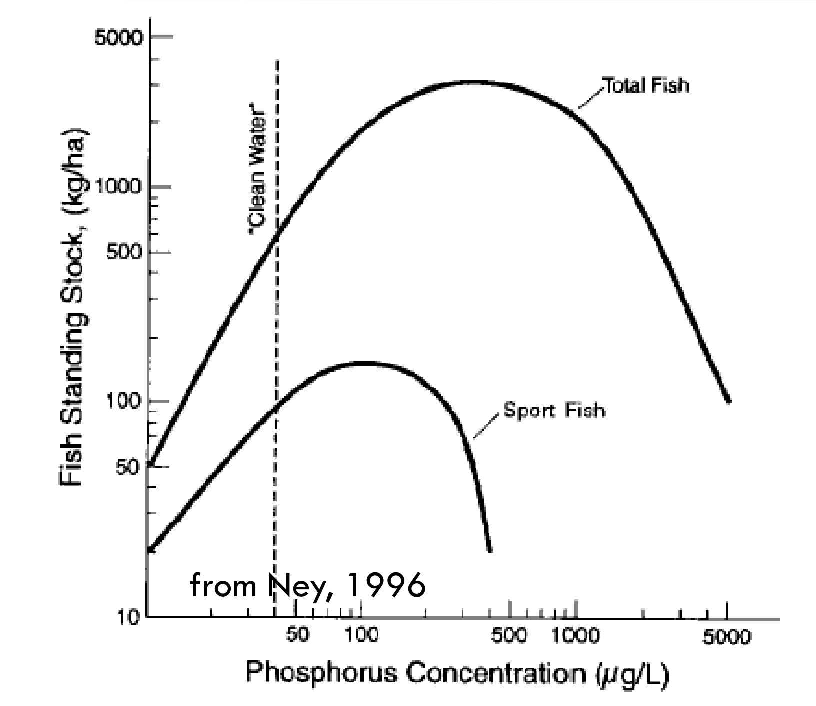
Figure 1: Conceptual application of generalized model results. Basic chart form after Rast and Lee (1978).

RECREATIONAL FISHERIES – DIRECT RELATIONSHIP WITH P / CHLA – TO A POINT



Relationship between Normalized P Loading and Fish Yield

After Jones and Lee, (1986)



from Ney, 1996

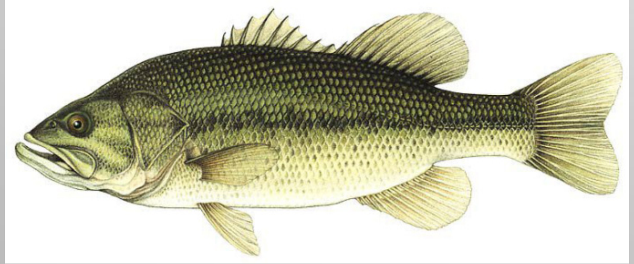
FIGURE 3.—Generalized relation of total and sport fish standing stock to total phosphorus concentration and trophic status in temperate-latitude reservoirs. Standing stock values are representative of southeastern U.S. reservoirs to 100 μg/L total phosphorus. Standing stocks at higher phosphorus concentrations are hypothetical.

EXAMPLES OF CHLA VALUES THAT SUPPORT RECREATIONAL FISHERIES - COLDWATER

CHLA (ug/L)	**Source/Notes**
7-10	Chl a and secchi depth from Minnesota Lakes (Schupp and Wilson, 1993)
5-15	Supports Lake Erie walleye population (Anderson et al, 2001)
15 30	Growing Season Mean Growing season maximum (Nevada Division of Environmental Protection, 2008)-Lakes and Reservoirs in Nevada
15	Trout waters (McGhee, 1983)

EXAMPLES OF CHLA VALUES THAT SUPPORT RECREATIONAL FISHERIES - WARMWATER

CHLA (ug/L)	Source/Notes
40-60	Fertilization to achieve Chl a concentrations for production of bass and sunfish (Maceina, 2001)
40	Bachman et al. 2002 confirms trophy fish are more abundant in more eutropic lakes
40	Non-trout waters (McGhee, 1983)-North Carolina
25	Warmwater fisheries only (Dillon et al, 1975)
60-70	Ponds managed for fishing, not recreation (Lee et al, 1995)
20	Black crappie fisheries peak (Schupp and Wilson, 1993)
60	White crappie fisheries peak (Schupp and Wilson, 1993)
10-15	These Chl a levels not necessarily detrimental to black bass and crappie fisheries (Reckhow et al, 1980)
20	Growth of crappie and largemouth bass increased up to this Chl a level (Maciena, 1996)
25 40	Growing Season Mean Growing season maximum (Nevada Division of Environmental Protection, 2008)-Lakes and Reservors in Nevada



RECREATION – SWIMMING/AESTHETICS

- RECREATIONAL TARGETS GENERALLY LOWER THAN THOSE FOR WARMWATER FISHERIES.
- CHLA TARGETS VARY GREATLY DEPENDING ON THE LEVEL OF CLARITY THE PUBLIC IS “USED TO”.
- AT SIMILAR CHLA LEVELS, CONDITIONS MAY OR MAY NOT BE “NUISANCE” DEPENDING ON FORM (DISPERSED VS. SCUMS, FLOATING MATS).
- POTENTIAL FOR HEALTH EFFECTS DEPENDENT ON TOXIN LEVELS, WHICH VARY BY WATER BODY.

EXAMPLES OF CHL-A TARGETS RELATED TO SWIMMING/AESTHETICS

CHLA (ug/L)	**Source/Notes**
10 50 5,000	Mild/low probability of health effects Moderate probability of short term health effects High risk of long-term health effects (Pilotto et al., 1997)
0-10 10-20 20-30 >30	No problems Scums Nuisance Severe Nuisance (Walmsley, 1984)-South African Reservior
14 30 32	"Excellent to Good" "Good to Acceptable" "Acceptable to Marginal" (Burden et al., 1985)-Louisiana
0-25 25-100 100-200	Clear, no blooms Moderate blooms Dense colonies and scums (Barica, 1975)-Canadian prairie ponds

EXAMPLES OF CHLA TARGETS RELATED TO SWIMMING/AESTHETICS (CONT.)

CHLA (ug/L)	**Source/Notes**
<1 1-5 5-10 10-15 15-30 >30	"Excellent" "Very Good" "Good" "Fair" "Poor" "Very Poor" (Lillie and Mason, 1983)-Wisconsin
6-7 9-10 12-15 15-20 20-25 30-80	Algae begins to be noticeable Definite observable levels of algae Algae levels moderate. Swimming uses begin to be impaired Algae levels high. Contact recreation impaired No swimming due to concerns for human health Severe algal scums. Recreational/aesthetics severely impaired Kansas Lakes (Carney, 1998)
>30	Swimming considered impaired in northern locales (Minnesota, Wisconsin) (Smeltzer et al, 1990)
40-60	Nuisance to severe nuisance, no swimming (Smeltzer et al, 1990)

PUBLIC WATER SUPPLY

- CHLA RELATED CONCERNS:
  - TASTE & ODORS (E.G., GEOSMIN, MIB)
  - TOXINS
- DEPENDENT UPON CYANOBACTERIAL DOMINANCE & ACTUAL TOXIN PRODUCTION
- CONTINUING WITH THE THEME, THESE VARY GREATLY BETWEEN RESERVOIRS

EXAMPLES OF CHLA TARGETS ASSOCIATED WITH DRINKING WATER USES

CHLA (ug/L)	Source/Notes
30	Chl a values above 30 µg/l increase the risk of algal-related health problems (Heath et al, 1998)
9-10 15-20 20-80	Taste and odor problems become noticeable Water supply use impaired Consumptive uses severely impaired Kansas Lakes (Carney, 1998)
10 50	Relatively low probability of adverse health effects Moderate probability of adverse health effects (assumes cyanobacteria dominance) Chorus & Bartram, 1999

Questions?

Potential pH Targets for High Rock Lake

Science Advisory Council | April 20, 2016

Clifton Bell

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Existing pH Criteria

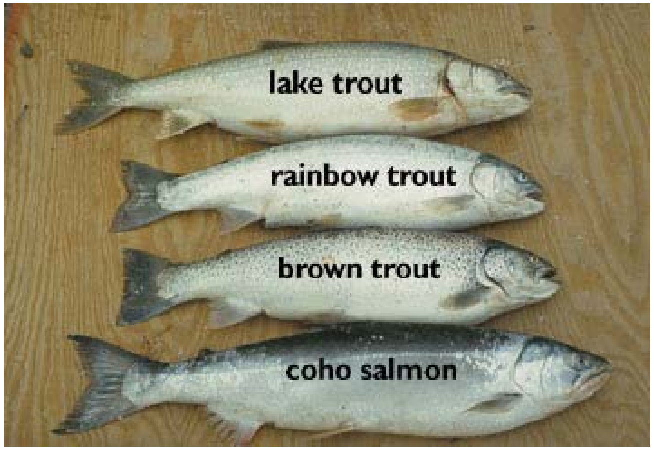
- USEPA
  - 6.5 – 9.0
  - Dates to 1976 “Red Book”, repeated in 2986 “Gold Book”.
  - Very limited literature citations
- North Carolina
  - “pH shall be normal for the waters in the area, which range between 6.0 and 9.0…”
  - Narrative standard?
  - No explicit duration or frequency components.

Three major categories of high pH Effects on aquatic life

- Increasing the toxicity of other substances
  - e.g. ammonia, cyanide
- Disrupting electrolytic balance and metabolism
  - e.g., Fish: Increased electrolyte or ammonia levels in plasma
  - Organisms can compensate to varying degrees
  - Biggest effects from “shock” exposure, or organisms with high sensitivity to ammonia toxicity (e.g. salmonids)
- Physical damage to tissues such as gills, eyes, or skin.

Upper limit of Red/Gold Book pH criteria based on two lines of reasoning

- General statements about the effect of pH on the toxicity of other substances
- Literature review performed by European Inland Fisheries Advisory Commission (1969):
  - "Chronic exposure to pH values above 10.0 are harmful to all species studied, while salmonid and some other species are harmed at values above 9.0."



Wider literature review confirms higher sensitivity of salmonids

pH Range	Effect on Aquatic Species
3.0-3.5	Unlikely that fish can survive for more than a few hours in this range although some plant and invertebrates can be found at pH levels this low.
3.5-4.0	Known to be lethal to all salmonids.
4.0-4.5	All fish, most frogs and insects are not present.
4.5-5.0	Mayfly and many other insect species are not found. Most fish eggs will not hatch.
5.0-5.5	Bottom-dwelling decomposing bacteria begin to die off. Leaf litter and dead plant and animal materials begin to accumulate. Plankton begin to disappear.
6.0-6.5	Freshwater shrimp are not present.
6.5-8.5	Optimal for most organisms.
8.5-9.0	Unlikely to be harmful to fish, but indirect effects from chemical changes in the water may occur.
9.0-9.5	Likely to be harmful to salmonids and perch if present for a considerable length of time.
9.5-10.0	Lethal to salmonids over a prolonged period of time, but can be withstood for short periods. May be harmful to development stages of some species.
10.0-10.5	Can be withstood by roach and salmonids for short periods but lethal over a prolonged period.
10.5-11.0	Prolonged exposure is lethal to carp and perch.
11.0-11.5	Lethal to all species of fish.

Sources: Alabaster and Lloyd (1980); Cleveland (1998)

What about “perch”?

- Basis of EIFAC was a single 1930s-era study of a European variety of perch
- More common in NC: Yellow perch (*Perca flavescens*)
  - Common in reservoirs with pH up to 9.5 (Johnson and others, 1977)
  - pH associated with lethality by chronic exposure is10.4 (Rahel, 1983

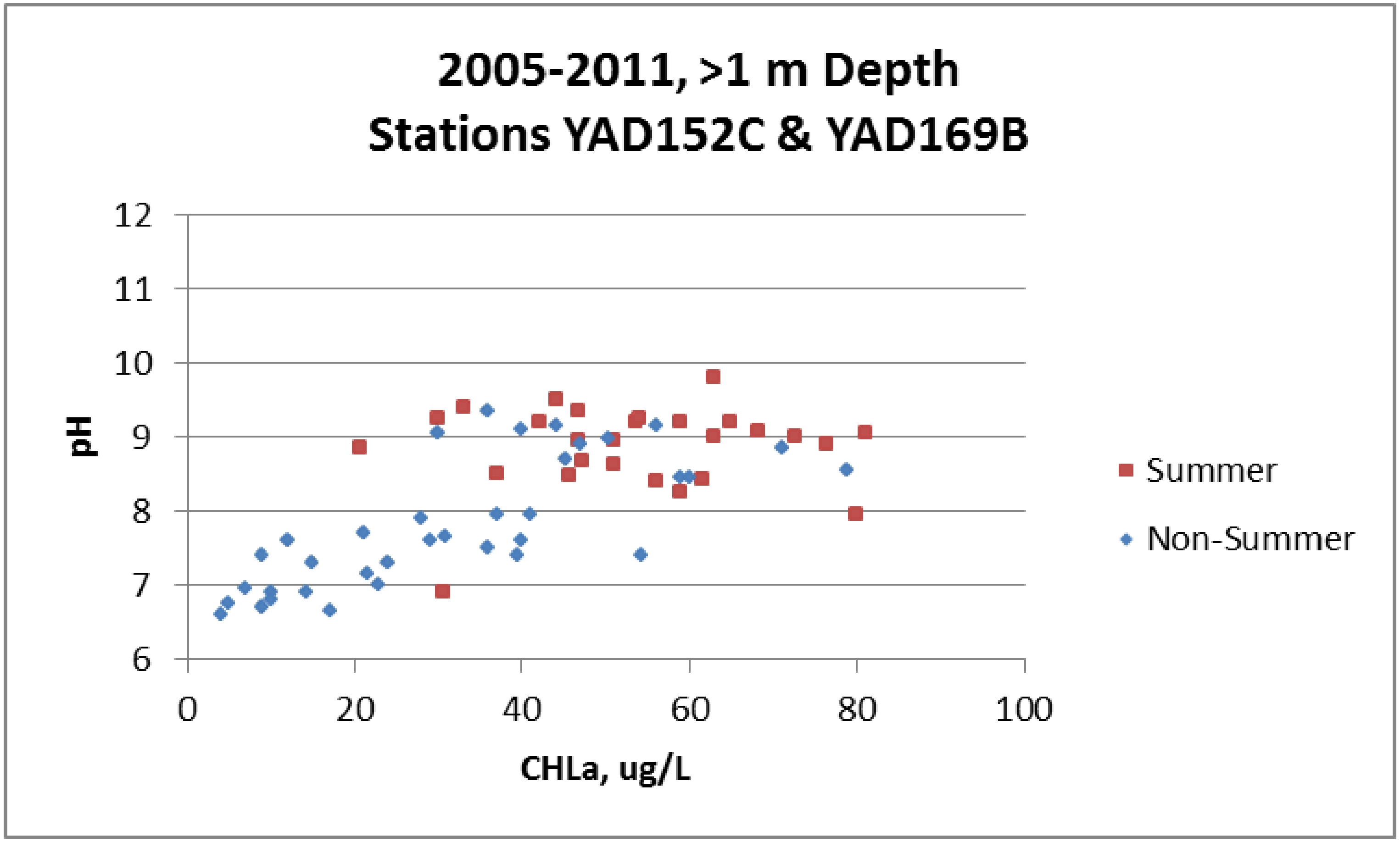
Public water supply considerations

- USEPA Gold Book (1986):
  - "Since pH is relatively easily adjusted prior to and during water treatment, a rather wide range is acceptable for waters serving as a source of water supply. A range of pH from 5.0 to 9.0 would provide a water treatable by typical…treatment plant processes. As the range is extended, the cost of neutralizing chemicals increases."
- World Health Organization (1996)
  - "The optimum pH will vary in different supplies according to the composition of the water and the nature of the construction materials used in the distribution system, but is often in the range 6.5–9.5."

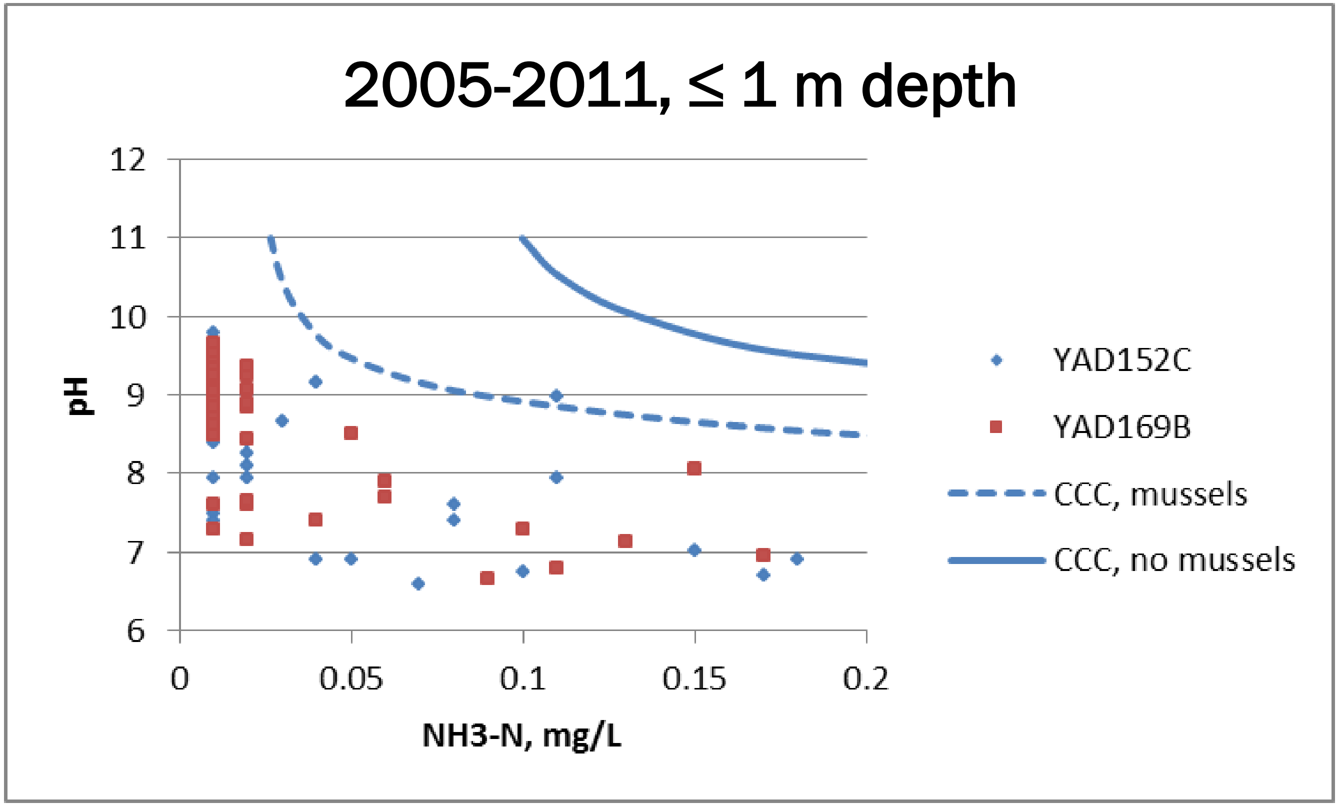
Two mainstem segments of HRL commonly exceed 9.0, rarely exceed 9.5

Percentile pH	YAD152C	YAD169B
50th	8.50	8.78
75th	9.04	9.20
85th	9.20	9.30
90th	9.20	9.37

Summer pH not strongly correlated with chlorophyll-*a* in HRL



Ammonia concentrations are low in HRL



Blue lines represent chronic ammonia criteria from USEPA (2013), assuming that early life stages are present.

Proposed Protective pH Range of 6.0 – 9.5

- Lower end of range identical to NC’s existing criterion
- Higher end of range protective of aquatic life
  - Existing fishery healthy
  - Reservoir not managed for salmonids
- Acceptable for public water supply
  - pH “easily adjusted during treatment”

Frequency & duration considerations

- Current criteria have no explicit duration or frequency components.
- But most underlying studies examine longer-term (30+ day) impacts
- Under current assessment method, pH treated like a multi-year 90th percentile
- Option: Keep as is
- Option: Express as annual or seasonal 90th percentile

Spatial Considerations

- Given that pH concerns are primarily related to chronic impacts on mobile species, no particular reason to assess pH at surface only.
- Option: Use all epilimnetic samples
- Option: Aggregate data from reservoir mainstem

NC STATE
UNIVERSITY

In situ detection approach to screen for cyanotoxins

SAC Meeting, April 2016

Astrid Schnetzer

Mark Vander Borgh and Linda Ehrlich

DWR
Division of Water Resources

SPIROGYRA DIVERSIFIED
ENVIRONMENTAL SERVICES
Water Resource Management and Analytical Services

Cyanotoxins: Who makes them and who is present in High Rock Lake?

- Microcystins
  - ***Anabaenopsis***, ***Aphanizomenon***, *Dolichospermum*, *Limnothrix*, ***Microcystis***, *Oscillatoria*, *Planktothrix*, ***Woronichina*** & *Snowella*

- Cylindrospermopsin
  - ***Aphanizomenon***, ***Cylindrospermopsis***, *Lyngbya*, *Raphidiopsis*
- Anatoxins

  - ***Aphanizomenon***, ***Cylindrospermopsin***, *Cuspidothrix*, *Oscillatoria*, ***Pseudanabaena***

Cyanotoxins: Detection and screening methods

- Types of samples:
  - Particulate, dissolved and total toxins

- *Chromatography* (compound specific)
  - separation of a mixture by passing it in solution or as a vapor through a medium in which components move at different rates

- *Bioassays* (class specific)
  - use of live animal, tissue or uses biological activity of a substance; eg., enzyme-linked immunosorbent assay (ELISA), mouse assays, phosphate inhibition assay (PPIA)

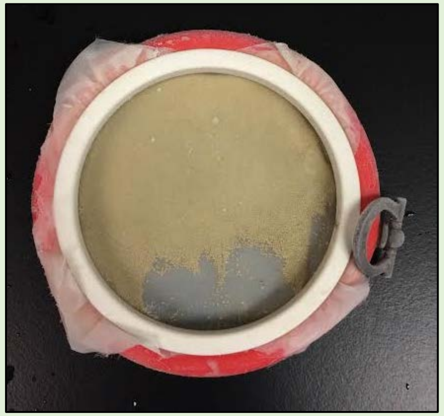
ELISA test
(hadlemosdeciencia.wordpress.com)

Solid Phase Adsorption Toxin Tracking - SPATT

- A simple and sensitive *in situ* (monitoring) method
  - involves the passive adsorption of biotoxins onto porous synthetic resin filled sachets (SPATT bags) and their subsequent extraction and analysis. *MacKenzie et al. (2004) Toxicon*

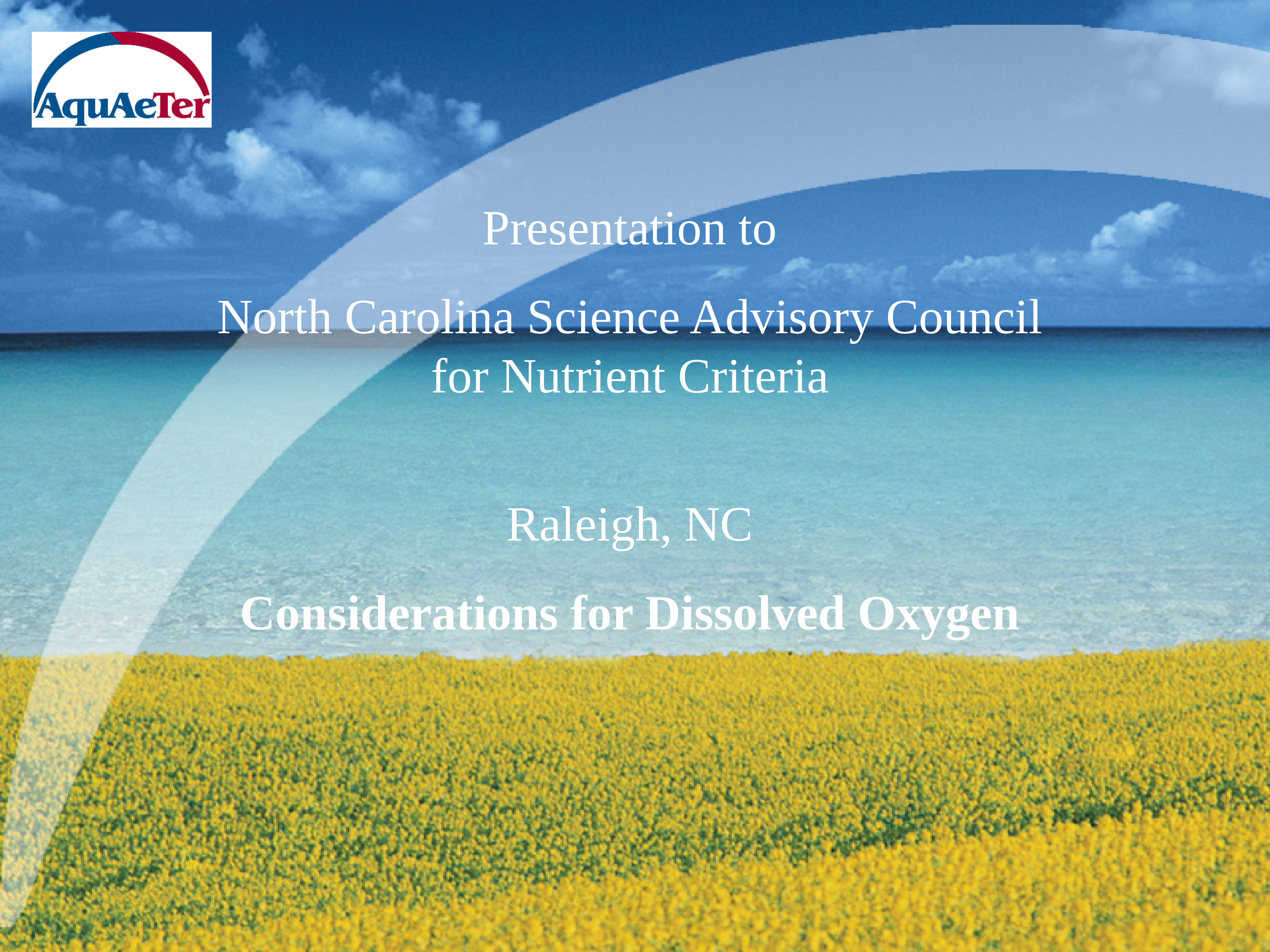
PROS

- Time-integrative signal
- Low detection limit
- Fresh to marine application
- Multiple toxin detection
- Easy to deploy and recover



CONS

- Semi-quantitative
- No link to regulatory limit



Presentation to

North Carolina Science Advisory Council
for Nutrient Criteria

Raleigh, NC

Considerations for Dissolved Oxygen

Dissolved Oxygen Standards
Current Condition

- 1986 Gold Book provided recommended values for 30-day (5.5 mg/L) and 1-day (5.0 mg/L) DO.
- Species used to develop the DO levels are many of the fish contained in High Rock Lake.
- Current standard for Class B waters would be a daily average of 5.0 mg/L with an instantaneous minimum of 4.0 mg/L.
- Lower values could occur in deeper waters or isolated coves if from natural causes.
- Application of current standard to the photic zone seems appropriate – no need to derive a new standard for consideration.

Dissolved Oxygen Standard
Reservoir Deep Layer – Chesapeake Bay Example

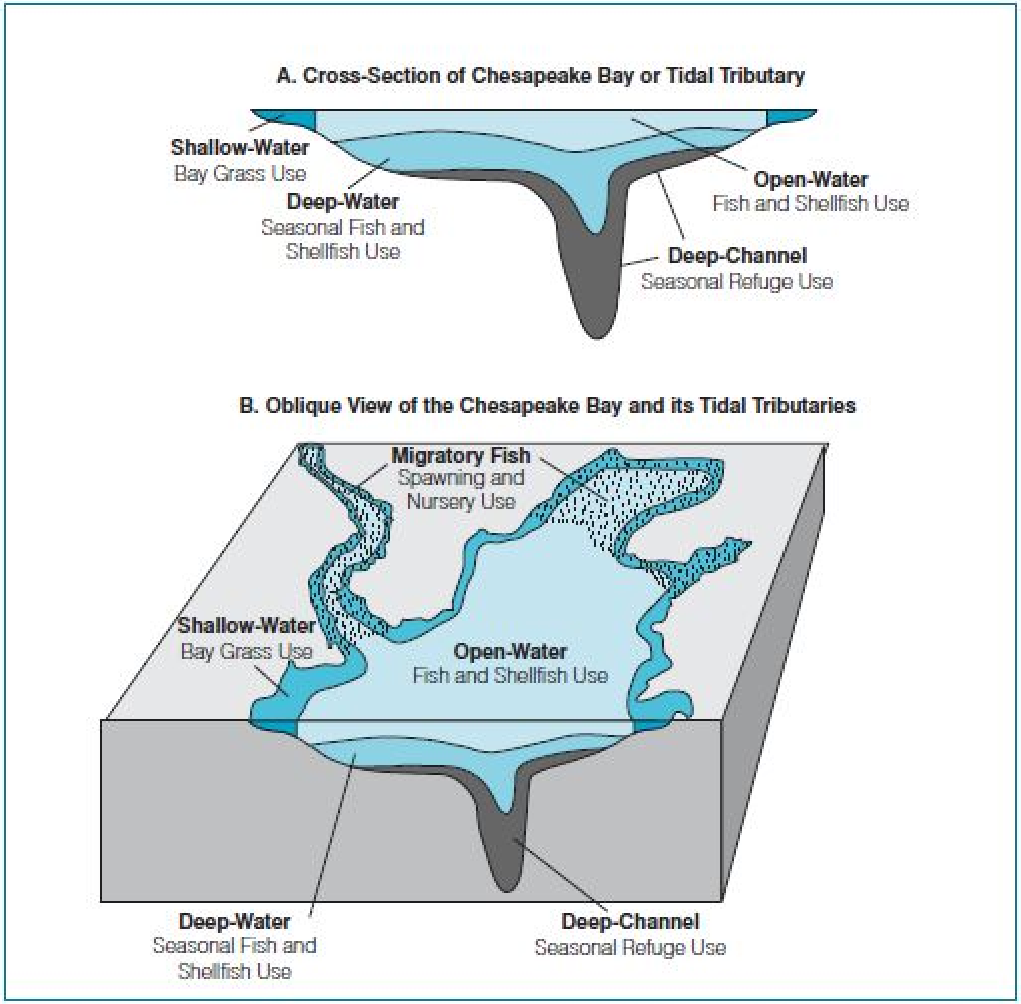


Figure 1. Conceptual illustration of the five Chesapeake Bay tidal water designated use zones.

EPA developed a layered approach to DO for the Chesapeake Bay.

Approach linked DO values to the primary aquatic life to protect for each layer.

This concept would be appropriate for a contrived reservoir system such as High Rock Lake.

Upper photic zone would retain the current standard.

Lower value for deeper waters to protect benthic invertebrates.

Dissolved Oxygen Standard
Reservoir Deep Layer – Chesapeake Bay Example

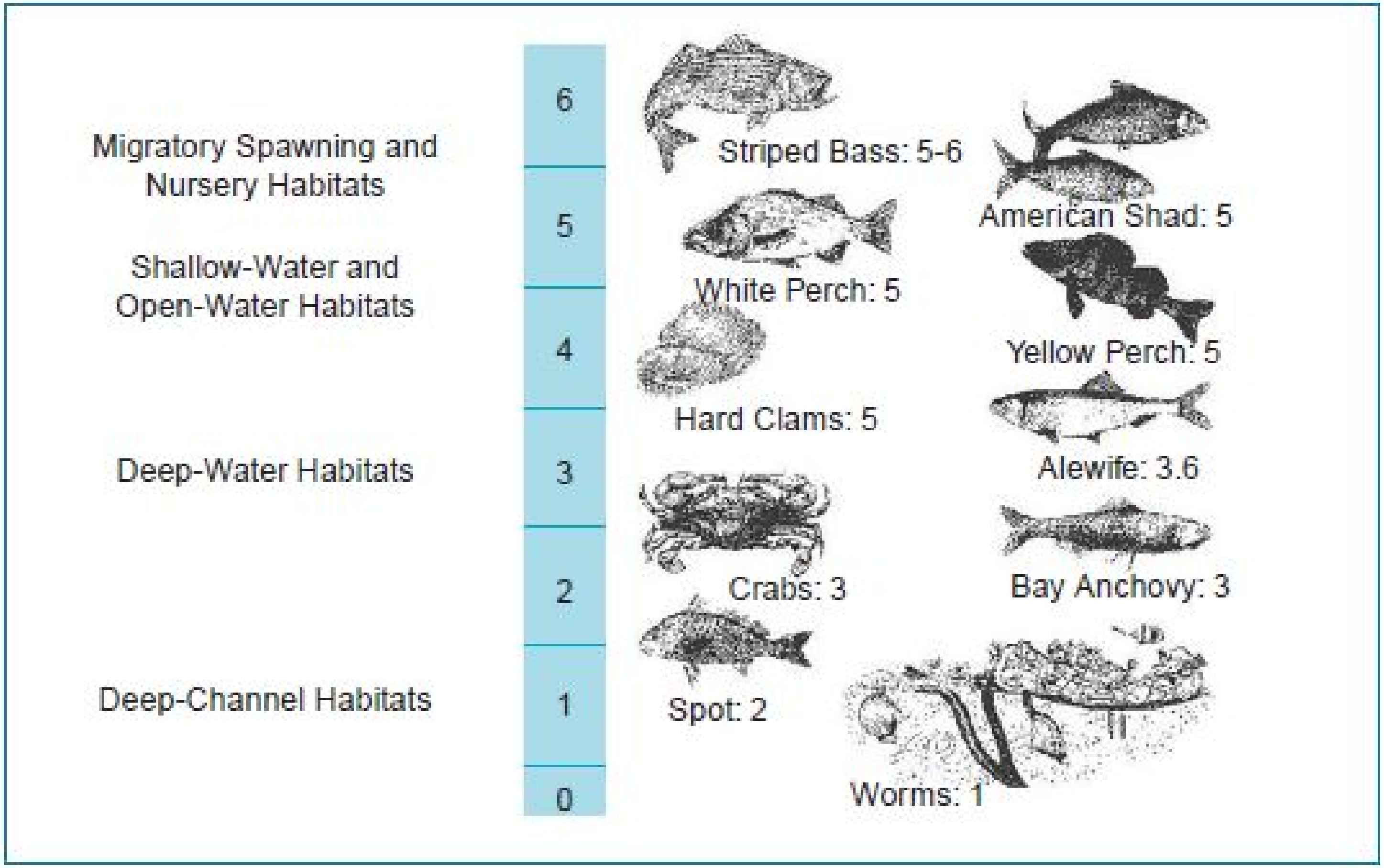


Figure 2. Dissolved oxygen (mg liter^{-1}) concentrations required by different Chesapeake Bay species and communities.

Dissolved Oxygen Standard
Reservoir Deep Layer – Chesapeake Bay Example

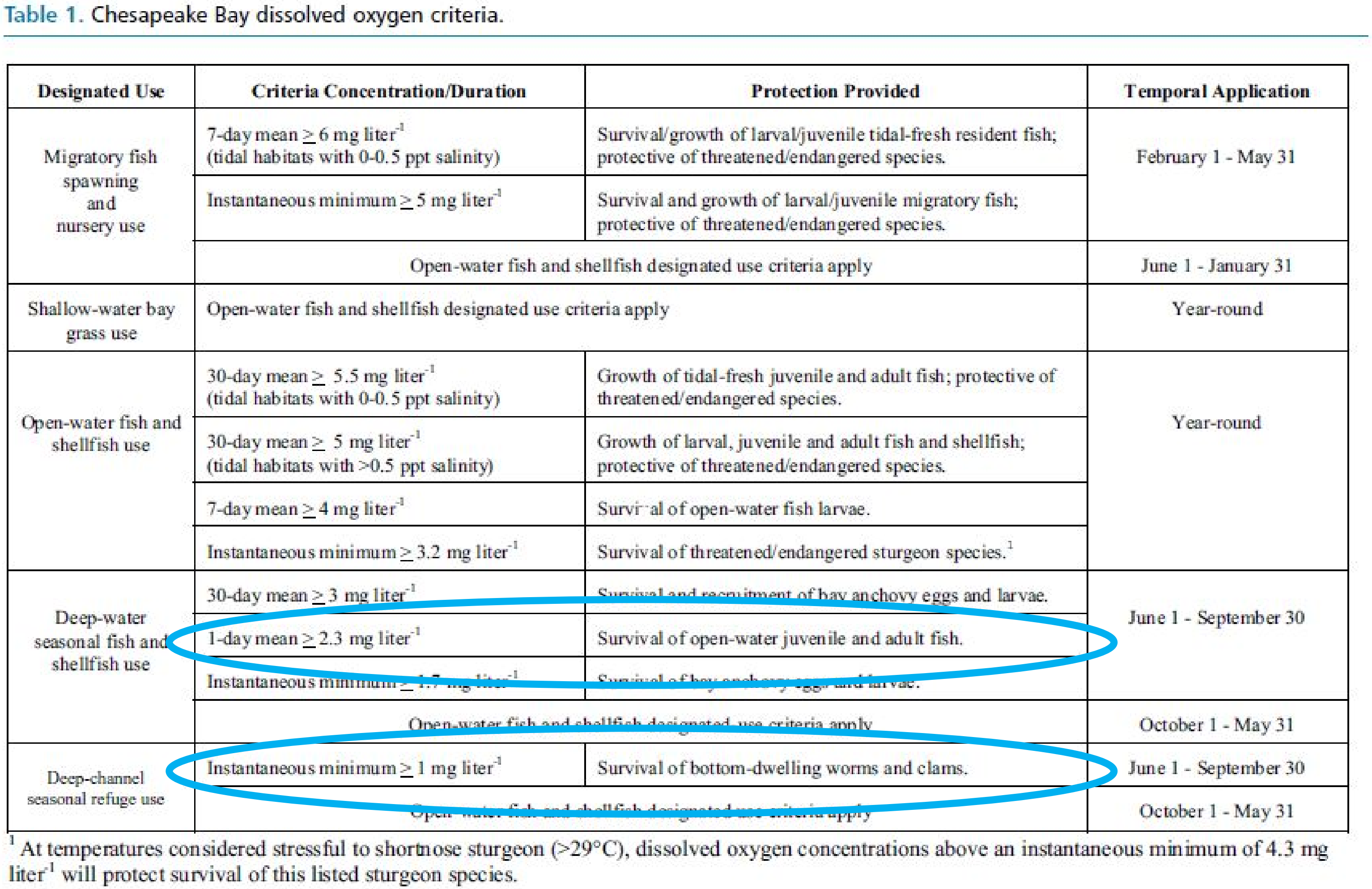


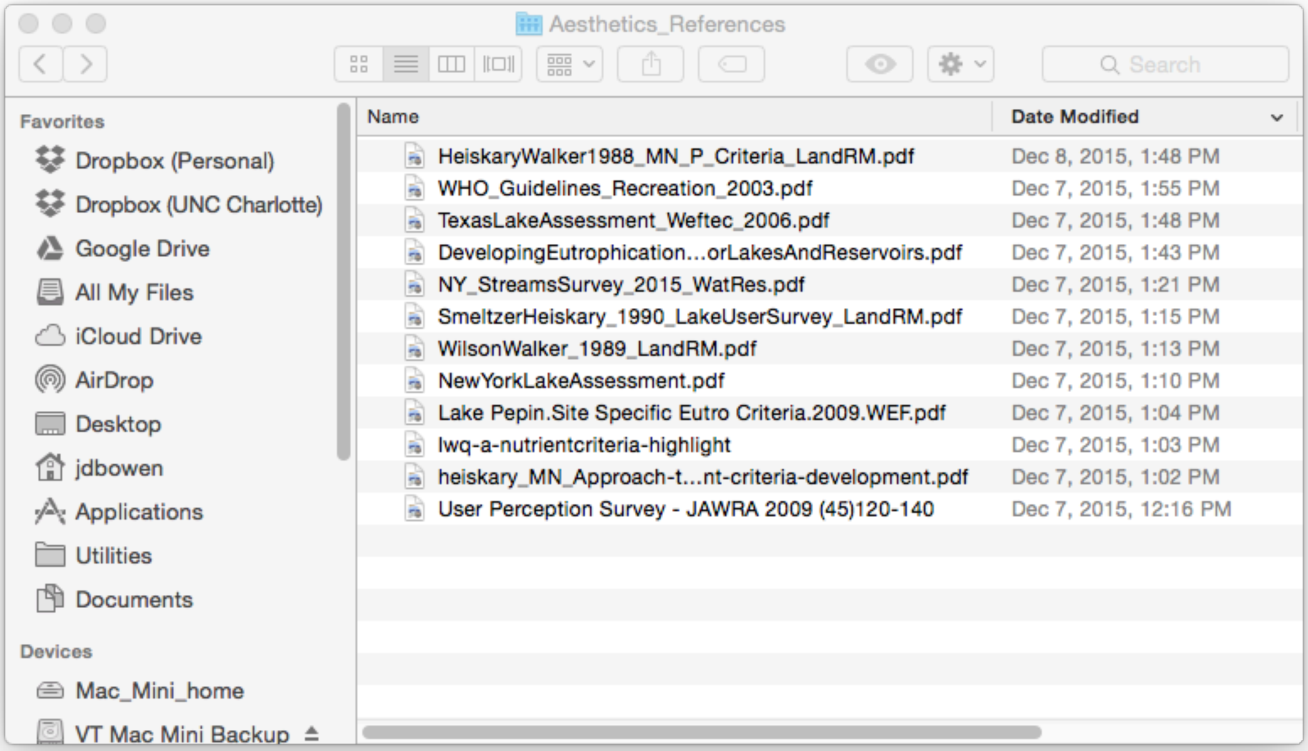
Table 1. Chesapeake Bay dissolved oxygen criteria.

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use	7-day mean $\geq$ 6 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum $\geq$ 5 mg liter^{-1}	Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species.	
	Open-water fish and shellfish designated use criteria apply		June 1 - January 31
Shallow-water bay grass use	Open-water fish and shellfish designated use criteria apply		Year-round
Open-water fish and shellfish use	30-day mean $\geq$ 5.5 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species.	Year-round
	30-day mean $\geq$ 5 mg liter^{-1} (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean $\geq$ 4 mg liter^{-1}	Survival of open-water fish larvae.	
	Instantaneous minimum $\geq$ 3.2 mg liter^{-1}	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean $\geq$ 3 mg liter^{-1}	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean $\geq$ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum $\geq$ 1.7 mg liter^{-1}	Survival of bay anchovy eggs and larvae.	
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31
Deep-channel seasonal refuge use	Instantaneous minimum $\geq$ 1 mg liter^{-1}	Survival of bottom-dwelling worms and clams.	June 1 - September 30
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31

[1] At temperatures considered stressful to shortnose sturgeon (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

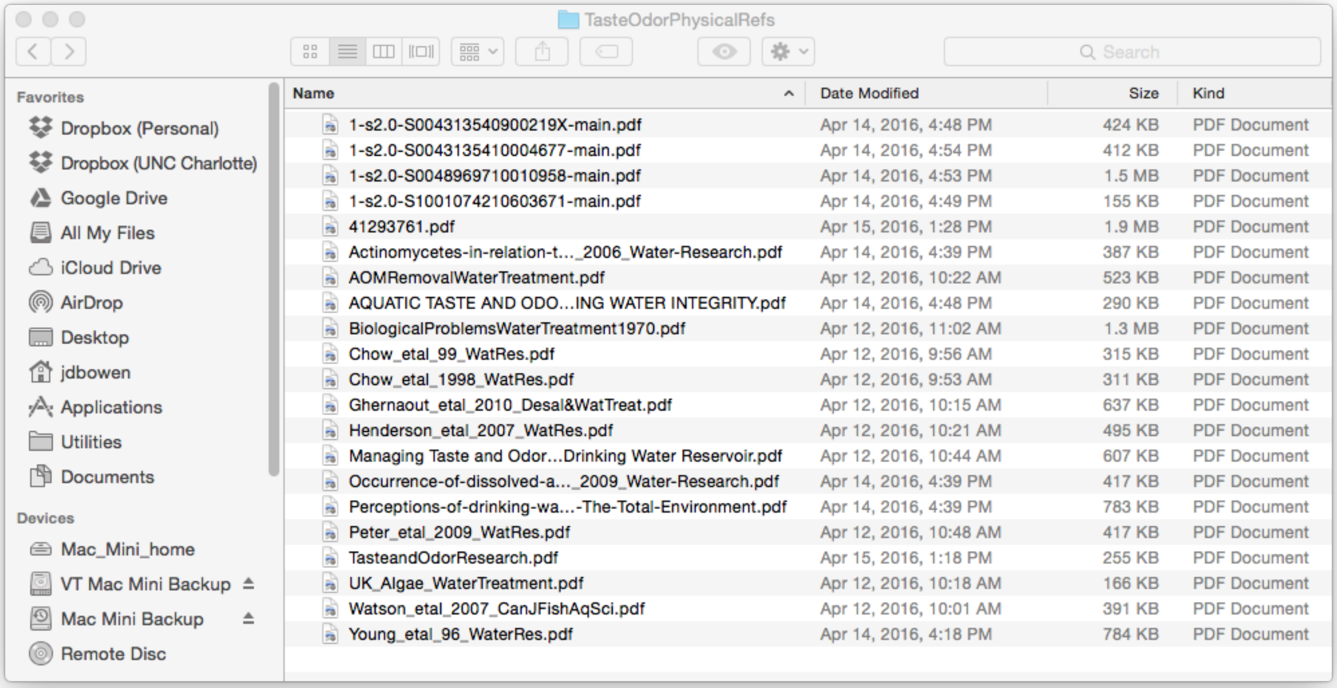
Dissolved Oxygen Standards Thoughts for Consideration

- **Current standard for Class B waters would be a daily average of 5.0 mg/L with an instantaneous minimum of 4.0 mg/L – apply to photic zone.**
- **Consideration of seasonal lower value for waters below photic zone:**
  - Current standard applies for cold months
  - Warm months daily average DO of 2.3 mg/L
  - Warm months minimum DO of 1.0 mg/L
- **Further consideration would be if a value is set for High Rock Lake – would a similar process need to be done for other reservoirs in North Carolina**



Aesthetics_References

Name	Date Modified
HeiskaryWalker1988_MN_P_Criteria_LandRM.pdf	Dec 8, 2015, 1:48 PM
WHO_Guidelines_Recreation_2003.pdf	Dec 7, 2015, 1:55 PM
TexasLakeAssessment_Weftec_2006.pdf	Dec 7, 2015, 1:48 PM
DevelopingEutrophication…orLakesAndReservoirs.pdf	Dec 7, 2015, 1:43 PM
NY_StreamsSurvey_2015_WatRes.pdf	Dec 7, 2015, 1:21 PM
SmeltzerHeiskary_1990_LakeUserSurvey_LandRM.pdf	Dec 7, 2015, 1:15 PM
WilsonWalker_1989_LandRM.pdf	Dec 7, 2015, 1:13 PM
NewYorkLakeAssessment.pdf	Dec 7, 2015, 1:10 PM
Lake Pepin.Site Specific Eutro Criteria.2009.WEF.pdf	Dec 7, 2015, 1:04 PM
lwq-a-nutrientcriteria-highlight	Dec 7, 2015, 1:03 PM
heiskary_MN_Approach-t…nt-criteria-development.pdf	Dec 7, 2015, 1:02 PM
User Perception Survey - JAWRA 2009 (45)120-140	Dec 7, 2015, 12:16 PM



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Actinomycetes-in-relation-t..._2006_Water-Research.pdf	Apr 14, 2016, 4:39 PM	387 KB	PDF Document
AOMRemovalWaterTreatment.pdf	Apr 12, 2016, 10:22 AM	523 KB	PDF Document
AQUATIC TASTE AND ODO...ING WATER INTEGRITY.pdf	Apr 14, 2016, 4:48 PM	290 KB	PDF Document
BiologicalProblemsWaterTreatment1970.pdf	Apr 12, 2016, 11:02 AM	1.3 MB	PDF Document
Chow_etal_99_WatRes.pdf	Apr 12, 2016, 9:56 AM	315 KB	PDF Document
Chow_etal_1998_WatRes.pdf	Apr 12, 2016, 9:53 AM	311 KB	PDF Document
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Managing Taste and Odor...Drinking Water Reservoir.pdf	Apr 12, 2016, 10:44 AM	607 KB	PDF Document
Occurrence-of-dissolved-a..._2009_Water-Research.pdf	Apr 14, 2016, 4:39 PM	417 KB	PDF Document
Perceptions-of-drinking-wa...-The-Total-Environment.pdf	Apr 14, 2016, 4:39 PM	783 KB	PDF Document
Peter_etal_2009_WatRes.pdf	Apr 12, 2016, 10:48 AM	417 KB	PDF Document
TasteandOdorResearch.pdf	Apr 15, 2016, 1:18 PM	255 KB	PDF Document
UK_Algae_WaterTreatment.pdf	Apr 12, 2016, 10:18 AM	166 KB	PDF Document
Watson_etal_2007_CanJFishAqSci.pdf	Apr 12, 2016, 10:01 AM	391 KB	PDF Document
Young_etal_96_WaterRes.pdf	Apr 14, 2016, 4:18 PM	784 KB	PDF Document

Site Specific Eutrophication Criteria for Lake Pepin

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ABSRACT

The State of Minnesota promulgated lake eutrophication standards in 2008. These standards were developed for natural glacial lakes characterized by long hydraulic residence times and relatively small watersheds. Our lake standards specifically allow for site specific standards for reservoirs and riverine lakes. Lake Pepin is a unique natural lake on the Mississippi River formed by the alluvial fan of the Chippewa River. Lake Pepin has a surface area of about 40 square miles and a mean depth of 18 feet. Pepin is characterized by two somewhat distinct segments. The inflow segment accounts for about 40% of the lake by area (~10,700 acres) but only about 28% by volume because it is very shallow (mean depth ~12 feet) and is more “river-like” in nature. The lower segment is somewhat deeper (mean depth ~22 feet) and accounts for about 72% of the lake by volume and is more “lake-like” as compared to the upper segment. Lake Pepin’s 48,634 square mile watershed contains five separate Level III Ecoregions. The watershed-to-lake ratio for Lake Pepin of about 1,225:1 promotes short water residence times that range from 6 to 47 days, with an average of 16 days.

Eutrophication is most problematic on Lake Pepin during summer (June-September) low-to-median flow conditions. We used multiple lines of evidence, including sediment diatom reconstruction of historical total phosphorus (TP) concentrations, to determine the appropriate TP criterion (100 µg/L) for Lake Pepin. The Upper Mississippi River-Lake Pepin linked hydrodynamic and water quality model (UMR-LP) was used to predict chlorophyll-a (32 µg/L) and Secchi criteria (0.8 m) that would be expected if our TP criterion was achieved. Model predictions of the frequency of nuisance blooms (chl-a >50 µg/L), percent composition of blue-green algae and user perceptions factored into the decision as well. Even though the TP and chlorophyll-a criteria for Lake Pepin are slightly higher than our criteria (standards) for glacial lakes, we believe they are fully supportive of aquatic recreational use, as required by the Clean Water Act (CWA), because Lake Pepin produces less chlorophyll-a per unit TP, the frequency of nuisance blooms is low, and blue-green algae are a smaller proportion of the algal community in Lake Pepin as compared to glacial lakes.

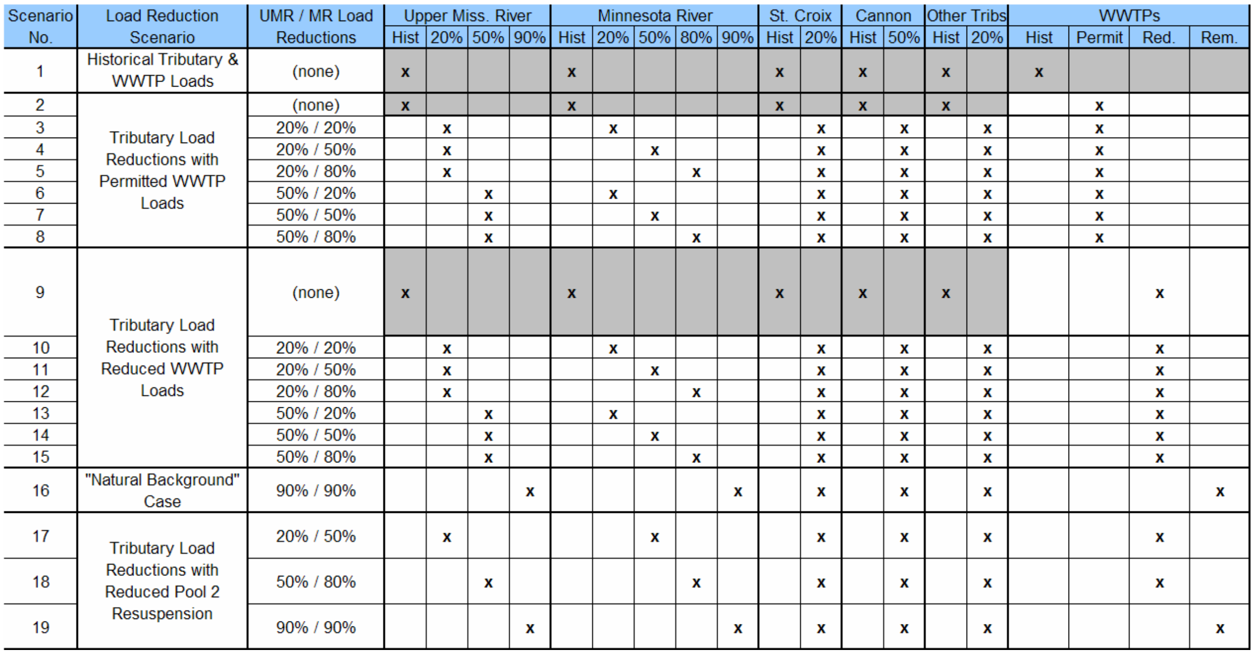
KEYWORDS

Phosphorus, Lake, Pepin, Mississippi, Eutrophication, Criteria

INTRODUCTION

Lake Pepin is a natural lake on the Mississippi River. The lake formed about 10,000 years ago behind an alluvial fan of the Chippewa River, which dammed the Mississippi after outflow from

Table 5. UMR-LP Scenario viewer. Overview of load reduction scenarios, variables, draft targets, temporal approach, and applicable locations.



Scenario No.	Load Reduction Scenario	UMR / MR Load Reductions	Upper Miss. River				Minnesota River					St. Croix		Cannon		Other Tribs		WWTPs			
			Hist	20%	50%	90%	Hist	20%	50%	80%	90%	Hist	20%	Hist	50%	Hist	20%	Hist	Permit	Red.	Rem.
1	Historical Tributary & WWTP Loads	(none)	x				x					x		x		x		x			
2	Tributary Load Reductions with Permitted WWTP Loads	(none)	x				x					x		x		x			x		
3		20% / 20%		x				x					x		x		x		x		
4		20% / 50%		x					x				x		x		x		x		
5		20% / 80%		x						x			x		x		x		x		
6		50% / 20%			x			x					x		x		x		x		
7		50% / 50%			x				x				x		x		x		x		
8		50% / 80%			x					x			x		x		x		x		
9	Tributary Load Reductions with Reduced WWTP Loads	(none)	x				x					x		x		x				x	
10		20% / 20%		x				x					x		x		x			x	
11		20% / 50%		x					x				x		x		x			x	
12		20% / 80%		x						x			x		x		x			x	
13		50% / 20%			x			x					x		x		x			x	
14		50% / 50%			x				x				x		x		x			x	
15		50% / 80%			x					x			x		x		x			x	
16	"Natural Background" Case	90% / 90%				x					x		x		x		x				x
17	Tributary Load Reductions with Reduced Pool 2 Resuspension	20% / 50%		x					x				x		x		x			x	
18		50% / 80%			x					x			x		x		x			x	
19		90% / 90%				x					x		x		x		x				x

Summer-mean chlorophyll-a response, expressed as a function of TP, varies among years (Figure 12). In addition to TP, residence time (flushing rate), turbidity (light), and chlorophyll-a loads from the rivers are important factors and contribute to the observed variability. TP reductions over range from ~200 – 100 µg/L elicit minimal response in chlorophyll-a. As TP falls below 100 µg/L reductions in chlorophyll-a are evident with the most marked reductions noted as TP falls below 70-80 µg/L (Figure 12).

Nuisance bloom frequency is a much more responsive metric by comparison. For the Lake Pepin TMDL nuisance blooms are defined as the frequency of chlorophyll-a >50 µg/L. Relatively steady declines are noted over the range from ~200-100 µg/L TP (Figure 13). In the initial scenarios (case 1) nuisance blooms may range from about 10-25 days (8-20% of summer) dependant on the particular year (summer). At a TP of 100 µg/L or lower nuisance bloom frequency falls below 10 days (<10% of summer).

Nuisance bloom frequency and summer-mean chlorophyll-a are closely linked. As summer-mean falls below 34 µg/L nuisance bloom frequency falls below 15 days and by 32 µg/L all values are <10 days (Figure 14). As TP and chlorophyll-a are reduced the percentage of blue-green algae, as a portion of the overall algal population, is predicted to decline as well (Figure 15) and measurable reductions are noted over the range from ~200 – 100 µg/L.

Lake and Reservoir Management 24:282-297, 2008

Minnesota's approach to lake nutrient criteria development

Steven Heiskary and Bruce Wilson
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Abstract

Heiskary, S.A. and C.B. Wilson. 2008. Minnesota's approach to lake nutrient criteria development. Lake Reserv. Manage. 24:282-297.

Ecoregion-based phosphorus "criteria" that reflect the diversity of lake condition, varying from deep pristine lakes in the north to shallow hypereutrophic lakes in the south, were developed by the Minnesota Pollution Control Agency (MPCA) in the late 1980s. Since then the criteria, including several refinements, have been widely used for local, state, and federal lake watershed management efforts in Minnesota. More recently, the criteria have been used to define thresholds for Clean Water Act Section 303(d) listing of nutrient-impaired lakes and are being advanced as lake standards to protect a wide diversity of beneficial uses. This paper summarizes the evolution of these criteria and describes data and research used in their development. A weight-of-evidence approach describes how this information was used to refine the criteria values.

Key words: ecoregions, eutrophication, nutrient criteria, water quality standards

Minnesota has a diverse lake resource ranging from its northern boreal forests with cold/cool water fisheries to very productive shallow water lakes of the predominantly agricultural south. As such, substantial geographic patterns in lake water quality, morphometry, fisheries, and even user perceptions of what constitutes acceptable water quality are evident. Understanding of these regional patterns advanced substantially with the introduction of United States Environmental Protection Agency's (USEPA) aquatic ecoregion framework in the mid-1980s that ultimately became a foundation for organizing and communicating lake and watershed management information in Minnesota. This manuscript describes Minnesota's approach to developing nutrient criteria to provide a potential framework for states, provinces, or other entities that may need to develop eutrophication criteria to manage their lakes.

A single total phosphorus (TP) value could not be adopted as a statewide criterion for lake protection in Minnesota due to regional differences and diversity of lake types (Heiskary *et al.* 1987). Rather, a methodology was needed for developing phosphorus (P) criteria on a regional and lake/watershed specific basis. The methodology for establishing P criteria in Minnesota considered the following (Heiskary and Walker 1988):

1) P impacts on lake condition (as measured by chlorophyll *a*, bloom frequency, transparency, and hypolimnetic oxygen depletion)
2) impacts on lake users (*e.g.*, aesthetics, recreation, fisheries, water supply)
3) linkages of watershed mass-balance and associated goal setting approaches.

An important first step of the criteria-setting process requires the definition of "most sensitive uses" of lakes. A sensitive use of a lake is defined as a beneficial use (or uses) that can be affected or even lost as a result of an increase in the trophic status of the lake, such as coldwater fisheries and aquatic recreational use (*e.g.*, swimming). In a coldwater fishery, increased nutrient loading results in a reduction of oxygen in the hypolimnion, and die-offs of coldwater species may occur as these populations are driven into warmer metalimnetic and epilimnetic waters. For aquatic recreational use, excess P stimulates algal growth that can lead to frequent and severe nuisance blooms and reduced transparency that will limit use of the resource. Most sensitive uses have been identified for each region and appropriate TP, chlorophyll *a* (Chl-*a*) and Secchi disk transparency (referred to as Secchi hereafter) criteria, deemed to be protective of that use, are defined (Table 1). These criteria are ecoregion-based and reflect several considerations, including: regional patterns in lake condition; detailed information from ecoregion reference

Table 1.-Minnesota's lake eutrophication criteria. Criteria are defined by ecoregion for specific lake types and uses (official use classification noted). TP and chlorophyll *a* should remain below these concentrations and Secchi should be not less than this value to ensure that the specific use is maintained.

Ecoregion – lake type (use classification[1])	TP µg/L	Chl-*a* µg/L	Secchi meters
NLF – Designated Lake trout (Class 2A)	12	3	4.8
NLF – Designated Stream trout (Class 2B)	20	6	2.5
NLF – Aquatic Rec. Use (Class 2B)	30	9	2.0
CHF – Designated Stream trout (Class 2B)	20	6	2.5
CHF – Aquatic Rec. Use – Deep (Class 2B)	40	14	1.4
CHF – Aquatic Rec. Use – Shallow (Class 2B)	60	20	1.0
WCP&NGP – Aquatic Rec. Use – Deep (Class 2B)	65	22	0.9
WCP&NGP – Aquatic Rec. Use - Shallow (Class 2B)	90	30	0.7

[1] Aquatic life and recreation use class as defined in Minn. R. 7050.0140, subp. 3 and Minn. R. 7050.0222 (Minnesota Rules Chapter 7050 2007). Class 2A is used for waters supporting a cold water fishery and refers specifically to lakes that support natural populations of lake trout. Stream trout refers to all other designated (managed) trout lakes. Class 2B is designation for waters supporting cool or warm water fishery and is the default classification for the majority of Minnesota's lakes.

lakes; background trophic status based on sediment diatom reconstruction of TP; interrelationships among TP, Chl-*a*, Secchi and nuisance algal bloom frequency; lake morphometry; lake-user perception; and lake ecology (including fishery composition and rooted macrophyte extent and diversity).

The following sections of the manuscript describe how the criteria are derived:

- *Methods and Database Development* section describes the data used to develop the criteria.
- *Results* section describes regional patterns, interrelationships among important parameters (*e.g.*, TP, Chl-*a*, Secchi, nuisance bloom frequency) and factors such as fishery composition, macrophyte diversity, and user perception that were essential to identifying criteria thresholds.
- *Discussion* section describes how these patterns, databases, and interrelationships are used in a weight-of-evidence approach to select criteria values. An ecoregion-specific example provides details on how this was done for one of the ecoregions.

Methods and database development

Several databases are referred to in this report. Brief descriptions are presented for the four primary databases: *assessment*, *reference*, *diatom-inferred phosphorus* and *USEPA criteria*. Each database is important to the overall assessment of Minnesota lakes and criteria development efforts. Water quality data from all databases may be found in STORET. Relevant field and laboratory methods and quality assurance information, which applies to the three Minnesota databases, are summarized.

Field and laboratory methods

Water quality data were collected during the summer (Jun to Sep). Sampling stations were typically located at mid-lake at the greatest lake depth. Surface samples were generally collected with a 2-m long, 3.2 cm i.d. PVC tube that integrates a 2-L sample from the upper 2 m of the lake. Field measurements routinely include Secchi transparency, dissolved oxygen (DO), and temperature profiles, and subjective measures of the physical appearance and recreational suitability of the lake.

The Minnesota Department of Health (MDH) laboratory analyzed samples collected by the Minnesota Pollution Control Agency (MPCA). Total P and total Kjeldahl nitrogen (TKN) samples were acid-preserved at the time of collection. Chlorophyll *a* samples were chilled and kept in the dark immediately after collection. Samples were filtered through 0.45-µm diameter glass fiber filters within 8 hr of collection and kept frozen until analyzed. Samples were analyzed by spectrophotometer and corrected for pheophytin. Commonly measured analytes, methods, reporting limits, and laboratory precision were summarized (Table 2).

Databases

Assessment database

The *assessment* database includes all Minnesota lake stations in STORET with data for one or more of the trophic status

Initial efforts focused on defining relationships among TP, Chl-*a*, and Secchi transparency using Carlson's TSI scale (Carlson 1977). Following Carlson's methodology, Minnesota-based regressions were developed based on the *reference lake* data (in m and µg/L):

$$\mathrm{Log}_{10}\ \mathrm{Chl}\text{-}a = 1.31\ \mathrm{Log}_{10}\ \mathrm{TP} - 0.95 \qquad (1)$$
$R^2 = 0.88$; n = 108

$$\mathrm{Log}_{10}\ \mathrm{Secchi} = -0.59\ \mathrm{Log}_{10}\ \mathrm{Chl}\text{-}a + 0.89 \qquad (2)$$
$R^2 = 0.85$; n = 108

$$\mathrm{Log}_{10}\ \mathrm{Secchi} = -0.81\ \mathrm{Log}_{10}\ \mathrm{TP} + 1.51 \qquad (3)$$
$R^2 = 0.81$; n = 108

Comparative studies of freshwater eutrophication strongly suggest that efforts to control external nutrient loading to lakes tend to achieve similar reductions in their average algal biomass (Smith 2003). However, Smith notes that growing season average biomass (Chl-*a*) is probably not consciously measured by lake users as a primary index of impairment, hence the need to define peak events that occur over the summer growing season. The *reference lake* data provide a basis for predicting extreme Chl-*a* values as a function of the summer-mean:

$$\mathrm{Chl}\text{-}a\ (\mathrm{max}) = 1.33\ \mathrm{Chl}\text{-}a\ (\mathrm{mean}) + 5.15 \qquad (4)$$
$R^2 = 0.89$; n = 108

Walker (1984) took this relationship a step further by associating the mean with the frequency of various classes or levels of Chl-*a*, referred to as "bloom frequency." An expansion on this approach examined the interrelationships of TP, Chl-*a*, and transparency (*i.e.*, "lake response") by using cross-tabulation based on about 640 paired TP, Chl-*a*, and Secchi measurements from the reference database (Heiskary and Walker 1988). The resulting relationship among TP and nuisance-level frequencies of Chl-*a* (Fig. 2a) provided a basis for assessing the "risk" of encountering nuisance level frequencies of Chl-*a*. Nuisance levels were defined based on previous work by Walmsley (1984) for South African reservoirs and perceptions of Minnesota lake users: Chl-*a* > 10 µg/L = mild bloom; > 20 µg/L = nuisance bloom; > 30 µg/L = severe nuisance bloom; and > 60 µg/L = very severe nuisance bloom. The phrase "nuisance criteria" refers to specific Chl-*a* or transparency levels that result in perceived impairment, and these perceptions may vary among states and ecoregions. The State of Florida, for example, uses Chl-*a* > 40 µg/L as an indication of an algal bloom (Bachmann *et al.* 2003).

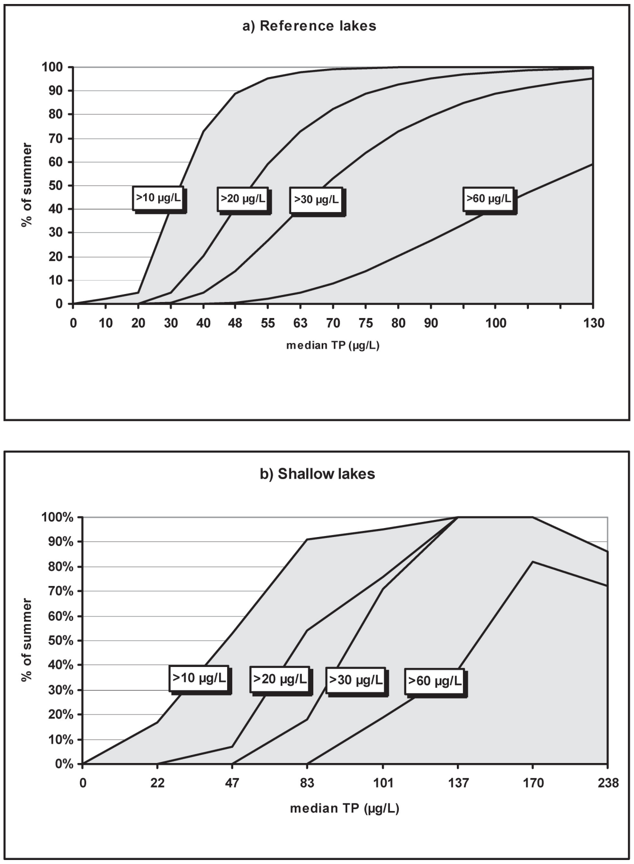

Figure 2.-Algal bloom frequency as a function of total phosphorus (TP) for: (a) reference lakes (based on 641 paired TP and Chl-*a* measurements) and (b) shallow lakes (based on 170 paired measurements). Median TP for the interval noted. Four "classes" of bloom intensity noted ranging from "mild bloom" (Chl-*a* > 10 µg/L) to "very severe nuisance blooms" (Chl-*a* > 60 µg/L).

Analysis of 170 pairs of TP and Chl-*a* data from the *shallow lakes* showed a slightly different "bloom frequency" response (Fig. 2b) as compared to the *reference lakes* (Fig. 2a). As TP increase from about 50 to 75 µg/L, the frequency of severe nuisance blooms increases rather dramatically; however, very severe nuisance blooms remain at a relatively low frequency (Fig. 2b). A second inflection point occurs as TP increases from about 90 µg/L to 120 µg/L, whereby the frequency of severe nuisance blooms increases to about 70% of the summer and very severe nuisance blooms (Chl-*a* > 60 µg/L) occur about 40% of the summer.

Regional patterns: lake morphometry, mixing, and trophic status

Previous investigators recognized that lake morphometry, in addition to watershed factors, plays an important role in determining lake productivity (Rawson 1952, Riley and Prepas 1985). These factors must also be considered when developing lake nutrient criteria because they may influence TP, Chl-*a*, and Secchi relationships; species of fish that may be found in the lake; internal nutrient recycling; and/or whether primary productivity is expressed primarily through rooted submerged vegetation or through phytoplankton.

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Observer rating of recreational use in wadeable streams of New York State, USA: Implications for nutrient criteria development

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A B S T R A C T

Like most other States and Tribes in the United States, New York State has been working with the United States Environmental Protection Agency to develop numeric nutrient criteria. These criteria are to protect water use such as drinking water supply, aquatic life, and recreation. Although extensive research exists related to the effects of eutrophication on human health and aquatic life, limited information is available on perceived impairment of recreational opportunities in rivers and streams. We present an approach to assess impacts to recreation using information collected by New York State's (NYS) monitoring program. This approach involved a questionnaire adapted from lake management surveys in which field crews rated their perceptions of recreational ability at each site. The ratings were then used to assess the relationship between perceived impact to recreational use and water quality. We include in our analyses the primary nutrient criteria variables total phosphorus (TP), total nitrogen (TN), suspended chlorophyll-a (SChl-a), and turbidity (Tb), as well as biological condition (benthic macroinvertebrate community assessment). We sampled 203 wadeable stream locations throughout NYS between July and September 2008–2012. Field crews ranked most locations as having "Minor aesthetic problems," but still considered them excellent for both primary (34%) and secondary (37%) contact recreation. Field crew rankings of recreational ability coincided with a gradient of nutrients (TP and TN), SChl-a, and Tb concentration. Logistic regression models were developed that identified significant predictors affecting field crew decisions about recreation. These included water clarity, periphyton cover, and odor. Analysis of variance using NYS's multimetric assessment of biological condition and a nutrient specific community metric suggest significant differences in metric scores among recreational use categories. These results indicate correlation of impairment of recreational use with impairment of aquatic life use from nutrient enrichment. The results of this investigation will be used to help establish nutrient endpoints for the protection of recreation in NYS streams and rivers.

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Table 1 – Median water chemical values and benthic macroinvertebrate community metrics of samples categorized by field crew responses to a use perception survey. Chemical variables presented are total phosphorus (TP), total nitrogen (TN), suspended chlorophyll-a (SChl-a), and turbidity (Tb). Benthic macroinvertebrate community metrics include NYS's multimetric, the Biological Assessment Profile (BAP) score and the eutrophication specific Nutrient Biotic Index (NBI).

Perception Category	Primary contact recreation						Secondary contact recreation					
	TP ug/L	TN ug/L	SChl-a ug/L	Tb NTU	BAP	NBI	TP ug/L	TN ug/L	SChl-a ug/L	Tb NTU	BAP	NBI
Beautiful	18	539	1.2	2.7	8.1	5.3	16	519	1.1	2.9	7.9	5.3
Minor	16	440	1.3	2.3	7.8	5.4	18	532	1.9	2.4	7.5	5.7
Slightly Impacted	26	709	1.8	4.0	6.5	6.4	29	714	2.1	4.3	5.9	6.6
Substantially Reduced	36	965	5.2	5.0	5.5	7.0	50	1042	3.4	4.7	5.3	7.2
Awful	50	1756	4.2	8.1	4.3	7.0	59	1756	16.0	8.5	4.1	7.0

Table 2 – Results of logistic regression models. Field crew responses to survey questions about ability to participate in primary and secondary contact recreation were transformed to a binomial response of "not impaired" or "impaired" based on results of analysis of variance. Individual predictors of the binomial response were identified that increase the odds of resulting in an impaired assessment of recreational ability.

Coefficient	Estimate	SE	Z-value	P-value	Odds ratio	% Change
Primary contact recreation						
Clarity	0.45971	0.11901	3.863	0.0001	1.6	60
Phytoplankton	−0.0729	0.37924	−0.192	0.8476		
Periphyton	0.39576	0.09859	4.014	0.0001	1.5	50
Macroalgae	0.04467	0.15139	0.295	0.7679		
Odor	0.63390	0.24270	2.612	0.0090	1.9	90
Trash	0.53173	0.17829	2.982	0.0029	1.7	70
Pipes	−0.1075	0.35989	−0.299	0.7652		
Null deviance	*245.8*	*df*	*201*			
Residual deviance	*121.3*	*df*	*194*			
Chi-square	*124.5*	*df*	*7*	*p-value*	*<0.0001*	
Secondary contact recreation						
Clarity	0.39744	0.11720	3.391	0.0007	1.5	50
Phytoplankton	−0.5261	0.28414	−1.852	0.0641		
Periphyton	0.39904	0.10987	3.632	0.0003	1.5	50
Macroalgae	−0.0466	0.18621	−0.250	0.8023		
Odor	0.40131	0.16153	2.485	0.0129	1.5	50
Trash	0.31216	0.15915	1.961	0.0500		
Pipes	0.69048	0.34535	1.999	0.0500		
Null deviance	*203.8*	*df*	*201*			
Residual deviance	*108.1*	*df*	*194*			
Chi-square	*95.8*	*df*	*7*	*p-value*	*<0.0001*	

measured by the NBI, moving on average from mesotrophic to eutrophic benthic macroinvertebrate communities (NBI $\geq$ 6.0) (Fig. 5).

4. Discussion

Effective environmental policy is usually arrived at through the inclusion of some form of public participation. Substantial effort has been invested in developing measures that gage the public's concern for environmental issues (Arcury and Johnson, 1987). Often, participation by the public includes the consultation of selected representatives in the form of a committee or some specially formed interest group. However, their input typically reflects personal concerns and not necessarily that of the general public. Therefore, it has been suggested that the integration of public attitudes into environmental management decisions should include their direct contact, for example through the use of public opinion surveys (House and Fordham, 1997). Public opinion surveys have been used to assess the status of environmental knowledge on a range of topics (Arcury, 1990; Arcury and Johnson, 1987; Dunlap, 1991; Lowe et al., 1980) from general environmental awareness and attitude (Scott and Willits, 1994) to the public's position on global warming (Bord et al., 1998) to the value of specific landscapes (Kellomäki and Savolainen, 1984).

In lake and reservoir management public opinion has become an important component of ensuring the needs and

Fig. 3 – Box and whisker plots of selected water chemistry variables (total phosphorus, total nitrogen, suspended chlorophyll-a, and turbidity) for each sampling location, categorized by user perception ranking of each site. Chemistry data are presented in log10 transformation for presentation purposes only. Overall there is a consistent trend of increasing nutrients, chlorophyll-a, and decreasing water clarity (turbidity) with worsening user perceptions of recreational ability.

DEVELOPMENT OF USE-BASED CHLOROPHYLL CRITERIA FOR RECREATIONAL USES OF RESERVOIRS

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ABSTRACT

This investigation was sponsored by the Texas Water Conservation Association (TWCA) with support from the Association of Metropolitan Sewerage Agencies (AMSA) and the Texas Association of Metropolitan Sewerage Agencies (TAMSA). The study was conducted by seven Texas river authorities in association with Dr. William W. Walker, Jr., Ph.D., and Alan Plummer Associates, Inc. (APAI). Its purpose is to provide data to assist in the development of surface water quality standards for nutrients in reservoirs. This investigation focuses on the identification of use-based criteria to support recreational uses. These results can be compared to criteria to support other types of uses of reservoirs (water supply, aquatic life use, fisheries, etc.) to derive appropriate water quality standards for nutrients.

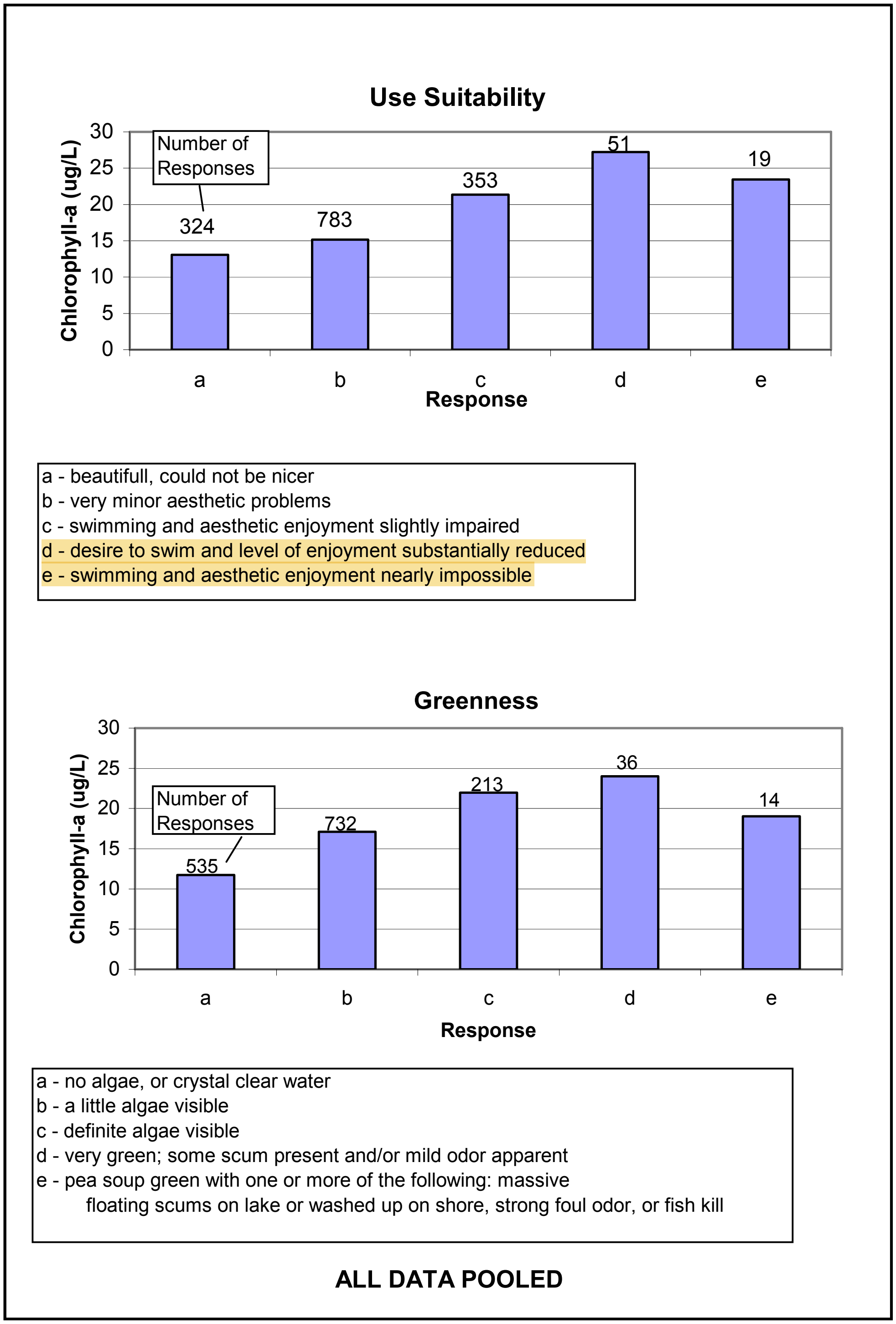
The study method was to collect simultaneous data on user perception of whether recreational use was impaired (and, if so, the extent of the impairment) and water quality data. The water quality parameters measured included water clarity, nutrient concentrations, chlorophyll concentrations, dissolved oxygen, and pH. Data were collected twice each month during the summer in eight reservoirs. Two stations were sampled in each reservoir: one station was in the main body of the lake, and one station was in either a cove or a headwaters area. The study was conducted over two summers. The eight reservoirs studied represent a wide range of sizes, ecoregions, nutrient loadings, and natural (inorganic) turbidity levels.

Over the two-year period, approximately 310 sampling events were conducted, and over 1,800 survey forms were completed. Approximately 96% of the survey records could be paired with chlorophyll measurements. Chlorophyll was concluded to be the most appropriate parameter for a water quality standard.

KEY WORDS

Nutrients, Nutrient Criteria, Recreational Uses, Chlorophyll Criteria, Reservoirs.

Figure 5 – Average Chlorophyll Concentration for Each Category of Use Suitability and Algal Growth



a - beautifull, could not be nicer
b - very minor aesthetic problems
c - swimming and aesthetic enjoyment slightly impaired
d - desire to swim and level of enjoyment substantially reduced
e - swimming and aesthetic enjoyment nearly impossible

a - no algae, or crystal clear water
b - a little algae visible
c - definite algae visible
d - very green; some scum present and/or mild odor apparent
e - pea soup green with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill

ALL DATA POOLED

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AQUATIC TASTE AND ODOR: A PRIMARY SIGNAL OF DRINKING-WATER INTEGRITY

Susan B. Watson

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AQUATIC TASTE AND ODOR: A PRIMARY SIGNAL OF DRINKING-WATER INTEGRITY

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Aquatic taste and odor (T/O) is rarely produced by toxic contaminants or pathogens; nevertheless, it has major negative impacts on the public and the drinking-water industry. Consumers use T/O as a primary measure of drinking water safety, yet this criterion is poorly understood, and its origins and triggers often go untraced. Much surface-water T/O is produced by the increased production of volatile organic compounds (VOCs) by algae. These chemicals can be symptomatic of short-term problems with source, treatment, or distribution systems. At a broader level, they can signify fundamental changes in aquatic ecosystems induced by human activity. T/O varies in chemistry, intensity, and production patterns among different algal taxa, and is often linked with excessive algal growth and/or the invasion of noxious species. Some VOCs may signal the presence of potentially toxic algae and/or other associated water quality issues. Traditionally, T/O has been linked with the widespread eutrophication of many surface waters; however, there has been a recent growth in the number of T/O events reported in oligo-mesotrophic systems, for example, the Glenmore Reservoir (Calgary AB) and the Laurentian Great Lakes. From a management and public perspective, therefore, it is vitally important to monitor T/O, and to continue to work toward a better understanding of the proximal and the ultimate causes—which VOCs and algae species are involved. In the short term, odor events could be anticipated and water treatment optimized. In the long term, this approach would contribute toward more a robust management of this resource through remedial or preventative measures.

In the aftermath of several recent outbreaks of serious water-borne disease in Canada, there is a growing recognition of the need for a "source-to-tap" or multibarrier approach to the prevention and removal of hazardous contaminants and pathogens from drinking water (O'Connor, 2002; Hrudey, 2003; Park & Huck, 2003; Watson & Lawrence, 2003). In comparison to such serious health threats, some policymakers might regard drinking water taste–odor (T/O) as secondary. On the contrary, T/O monitoring is essential to the proactive management

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TABLE **1.** Survey of Aquatic Odor Threshold Concentrations (OTC; μg/L) Reported for Selected Odorous Algal Metabolites

Compound	OTC μg/L	Odor
Sulfurous		
Dimethyl trisulfide	0.01	Septic, garlic, putrid, swampy
Dimethyl disulfide	<4.0	Septic, garlic, putrid
Methanethiol	2.1	
Ethanethiol	1	
Propanethiol	0.74	
t-Butythiol	0.09	
Dimethyl sulfide	1	
Hydrogen sulfide	7.2	
PUFA derivatives		
n-Heptanal	3	Fishy, oily
n-Hexanal	4.5	Grassy, fatty
3-Methylbutyrate	20	Rotten, rancid
n-Pentanal	60	Fishy
trans-2-Nonenal	0.8	Cucumber
1-Penten-3-one	1.25	Pungent; rancid; fishy
trans-2-Hexenal	17	
cis-3-Hexen-1-ol	70	Grassy
2-Methylpent-2-enal	290	Rum, marzipan
trans-2,*cis*-6-Nonadienal	0.08	Grassy; cucumber
1,3-Octadiene	5600	Earthy/mushroom
trans,*cis*-2,4-Heptadienal	5	Fishy, oily
trans,*cis*,*cis*-2,4,7-Decatrienal	1.5	Fishy, oily
Amines		
Ethanolamine	6.5	Mild ammonia –fish[y]
Isopropylamine	210	Ammonical, amine
Butylamine	80	Sour, ammonical, amine
Propylamine	90,000	Ammonia
Methylamine	21	Ammonia
Trimethylamine	0.21	Pungent, fishy, ammonia
Dimethylamine	47	
Terpenoids		
α-Ionone	0.007	Violets
β-Ionone	0.007	Violets
Epoxy-α-ionone	0.007	
Geosmin	0.004	Earthy/musty
3-Methylbut-2-enal	0.15	Rancid, putrid
3-Methyl butanal	0.15	Rancid, putrid
2-Methylisoborneol	0.015	Earthy, musty
Limonene	4	Citrus
Linalool	6	Grassy, floral
Cieneole (1,8)	12	Camphor, spicy, cool
6-Methyl-5-hepten-2-one	50	Fruity, esterlike
β-Cyclocitral	19.3	Tobacco, smoky, moldy
Styrene	65	Sweet, balsamic
Pyrazines		
2,6-Dimethyl pyrazine	6	Cocoa, roasted nuts, coffee
3-Methoxy-2-isopropyl pyrazine	0.0002	Earthy/potato bin
2-Isobutyl-3-methoxy pyrazine	0.001	Earthy/potato bin

Note. From Mallevialle and Suffet (1987), Young et al., (1996), and Watson and Ridal (2002).

TABLE 2. Survey of Major Odor Compounds Identified From Algal Cultures or Field Samples

a-Campholene
γ-Cadinene
Camphor
Chlorophene
Cieneol
Trimethyl
Cyclohex-1-ene
β-Cyclocitral
Hydroxy-β-cylocitral
Cyclohexanone
Dihydrotrimethylnapthalene
Dihydroactinidiolide
α-Ionone
β-Ionone
Geosmin
Geranyl acetone
Geraniol
Germacrene-D
Limonene
Linalool
Menthone
Methyl gerianate
Myrcene
2-Methylisoborneol
6-Methyl-5-hepten-2-one
6-Methyl-5-hepten-2-ol
3-Methylbut-2en-1-ol
4-Methylpent-3-en-2-one
Nerol
Phytol
Squalene
Skatol
Styrene
Trimethylcyclohex-2-en-1-one
γ-Terpinene
Isopropyl disulfide
Dimethyl sulfide
Dimethyl trisulfide
Dimethyl tetrasulfide
Isopropyl thiol
Isopropyl trisulfide
Isopropyl methyl disulfide
Methyl 2-methyl propanethiolate
Methyl 3-disulfide
Methyl mercaptan
Methylbutane
Methylethane thiolate
2,4-Heptadienal
2,4-Decadienal
2,4 –Nonadienal
2,6 –Nonadienal
2-Octene
Oct-1-en-3-ol
1,3,5-Octatriene
2,4 –Octadienal
2-Furfural
Propenal
Hexan-1-ol
n-Hexanal
3-Hexen-1-ol
Pent-1-en-3-one
1-Pentanol
n-Heptane
2,4,7-Decatrienal
Undecan-2-one
Heptan-1-ol
Pent-1-en-3-ol
Octene
Actetaldehyde
Heptadec-5-ene
Heptan-2-ol
n-Hexanol
Octan-3-ol
Octan-3-one
Octadecene
n-Octadecane
n-Hexanol
2-Octenal
1,3-Octadiene
Methyl *n*-valerate
Octan-3-ol
n-Heptanal
Octa-1,5-dien-3-ol
Oct-1-ene
n-Heptanal
Octene
Octane
Oct-1-en-3-one
Ectocarpene
Dictyopterene A'
Dictyopterene C'
n-Nonadecane
n-Heptadecane
Heptadec-5-ene
2-Pentenal
Octan-1-ol
Oct-2-en-1-ol
Isobutyrate
Methyl acetate
Methyl butanoate
2-Methyl propan-1-ol
3-Methyl butanal
2-Methyl but-2-en-1-ol
2-Pentylfuran
2-Methylpent-2-enal
3-Methyl -1-butanol
3-Methylbut-2-enal
3-Methylbutan-2-one
Butanone
Isobutyl alcohol
Ethyl propionate
Isobutyl acetate
Isopropyl alcohol
Methyl 2-methyl formate
Methylbutanoate
2,4,6-Trichloroanisole

Note. Adapted from Watson (1999,2003).

of the more than 35,000 algal species identified to date have been implicated in aquatic T/O, although many species have yet to be characterized for AVOC production (Watson, 2000). Third, AVOCs fall under two broad (although overlapping) biosynthesis patterns, which generate different odor chemistry and production dynamics, those compounds produced throughout growth, and those released mainly following cell senescence, death, or mechanical damage (Jüttner, 1995; Watson, 2003). Active growth tends to produce secondary water can be significant (Watson et al., 1999). These compounds have no known adverse human health effects, and their role in algal chemical ecology (as allelogens) is debated (Watson, 2003). But because some toxic cyanobacteria species also produce G-MIB (Figure 2), the presence of these AVOCs can act as a vital chemical marker—particularly where these potentially harmful taxa are hidden, for example, as with benthic growth (Baker et al., 2001).

Cyanobacteria are associated with surface-water total phosphorus (TP) (Watson et al., 1999). At moderate TP, these taxa often appear as late summer or fall outbreaks, which become more extended and dramatic with eutrophication (Figure 3) (Downing et al., 2001). Thus, G-MIB are typically problematic in eutrophic waters, where they can reach many times their OTCs (Persson, 1980; Watson et al., 2000). However, G-MIB can provide important early warning signals in less eutrophic waters. For example, the widespread eutrophication of the Laurentian Great Lakes in the latter part of the last century initiated a joint international remedial effort in the late 1970s. This led to a significant drop in nutrient levels, accompanied by an initial decrease in the extent and severity of cyanobacteria blooms (Munawar & Munawar, 1996, 2000). More recently, there have been signs of a reversal in this response, with an apparent increase in the frequency and severity of outbreaks of these taxa, cyanotoxins, and G-MIB events (Brittain et al., 2001; Budd et al., 2002).

In Lake Ontario, a recent onset of two major G-MIB T/O patterns was identified, which differ in interannual frequency and chemistry (Watson & Ridal, 2002). These T/O events have had major impacts on drinking water provided

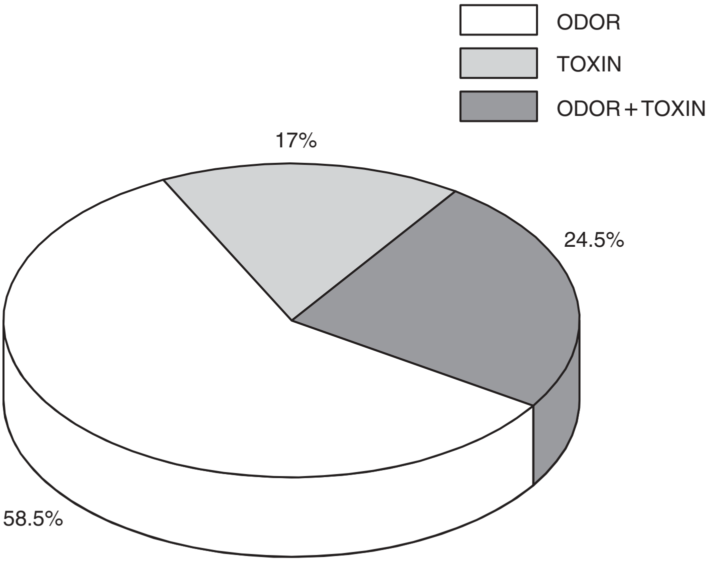

FIGURE 2. Survey of 45 odor-producing cyanobacteria (producing geosmin, 2-methylisoborneol or β-cyclocitral) characterized for toxin production (microcystin and/or neurotoxins); data from Watson (2003).

Lake and Reservoir Management 18(4):319-323, 2002

Managing Taste and Odor Problems in a Eutrophic Drinking Water Reservoir

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ABSTRACT

Smith, V. H., J. Sieber-Denlinger, F. deNoyelles, Jr., S. Campbell, S. Pan, S. J. Randtke, G. T. Blain and V. A. Strasser. 2002. Managing taste and odor problems in a eutrophic drinking water reservoir. Lake and Reserv. Manage. 18(4):319-323.

Drinking water for the City of Wichita, KS is provided by Cheney Reservoir, a eutrophic impoundment constructed by the U.S. Bureau of Reclamation in 1962. This large, shallow reservoir has a mean depth of 5.3 meters and a surface area of 40 km^2. Numerous reports of undesirable taste and odor in drinking water were received by the City of Wichita Water and Sewer Department in the early 1990's, and periodic episodes of objectionable tastes and odor have occurred up through fall 2001. An intensive limnological sampling program was carried out from August 1999-October 2000, and simultaneous measurements of two taste and odor-causing compounds (geosmin and methylisoborneol) in the lakewater were also performed. These data were used to construct empirical, phosphorus-based water quality management recommendations designed to help reduce the likelihood of objectionable taste and odor events in Cheney Reservoir. The general framework developed here should also be applicable to other waterbodies exhibiting taste and odor-related problems.

Key Words: blue-green algae, cyanobacteria, eutrophication, geosmin, reservoirs, taste and odor.

Taste and odor problems are a common symptom of eutrophication worldwide (Welch 1992; Smith 1998; Smith et al. 1999), and the costs of drinking water treatment to remove this problem can be very high (Wnorowski 1992; Blain 2001). Objectionable, volatile organic compounds such as geosmin (trans-1,

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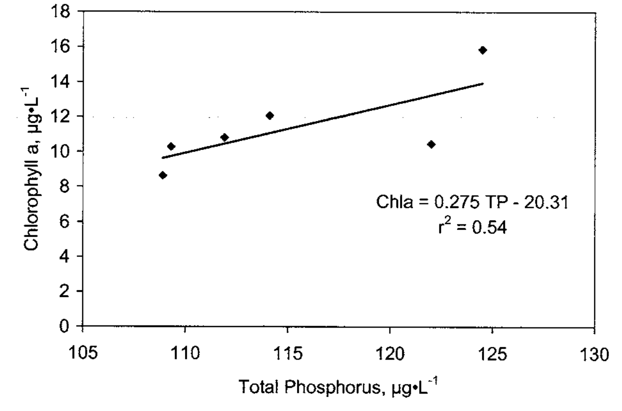


Figure 1.–Relationship between station mean concentrations of chlorophyll a and TP in Cheney Reservoir, USA.

complaints received by the City of Wichita's Water and Sewer Department during June-July 2001 (Fig. 3). These data suggest that telephone complaints are most likely to occur when blooms of *Anabaena* plus *Aphanizomenon* exceed ca. 300,000 $\mu^3 \cdot mL^{-1}$ in the lakewater, and confirm the likely role of cyanobacteria as the agents causing taste and odor problems in Cheney Reservoir. We thus examined our dataset for potential relationships between water quality and geosmin production in Cheney Reservoir, and a strong predictive relationship was found between the mean concentrations of geosmin and chlorophyll *a* in the water column (Fig. 4).

Based upon these results, we provisionally suggest that the intensity and frequency of taste and odor events in drinking water drawn from Cheney Reservoir would consistently be reduced if mean concentrations of chlorophyll *a* throughout the reservoir are maintained below ca. 10 $\mu g \cdot L^{-1}$. This goal potentially could be achieved by maintaining water column TP concentrations less than 110 $\mu g \cdot L^{-1}$ throughout the entire lake.

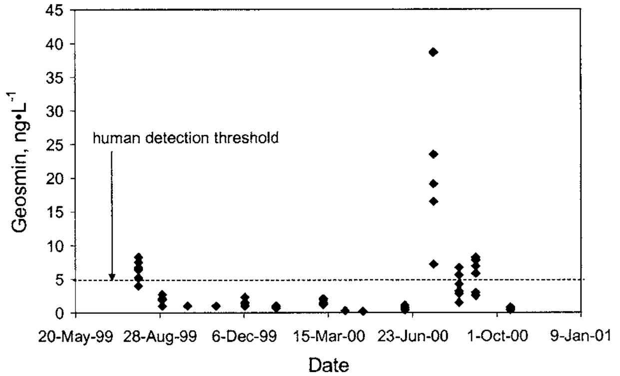


Figure 2.–Trends in geosmin at all six sampling stations in Cheney Reservoir, USA.

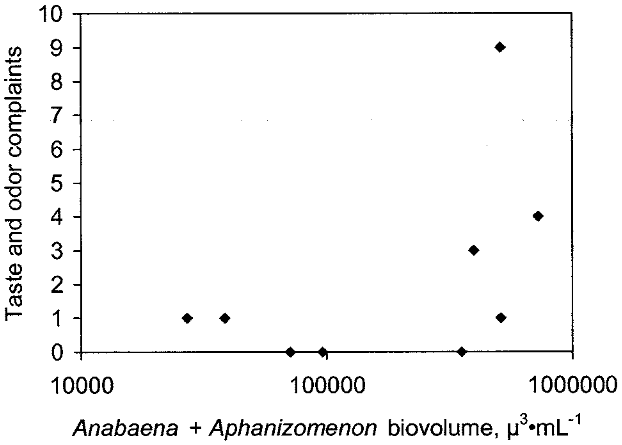


Figure 3.–Relationship between instantaneous concentrations of two nuisance taste and odor-producing cyanobacteria, *Anabaena* and *Aphanizomenon*, and telephone drinking water quality complaints received by the City of Wichita, Kansas.

Conclusions

The data summarized in this report suggest that taste and odor problems (as measured here by concentrations of geosmin in the water column) are strongly linked to algal growth in Cheney Reservoir, and in particular to the growth of nuisance species of cyanobacteria, or blue-green algae. We suggest that phosphorus control measures designed to reduce total algal biomass at all sites in Cheney Reservoir will be most effective management tool to limit the frequency and likelihood of taste and odor events in Cheney Reservoir, because the biomass of all potential taste and odor-forming species within the phytoplankton (including cyanobacteria) will be maintained at the lowest possible

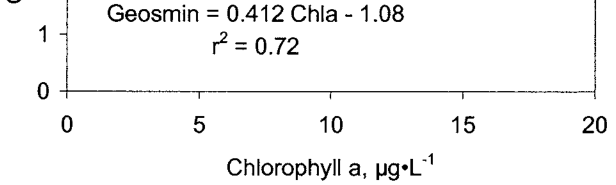
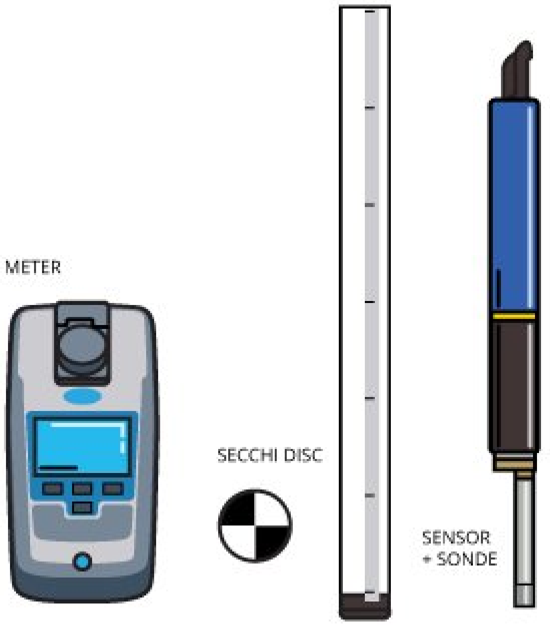


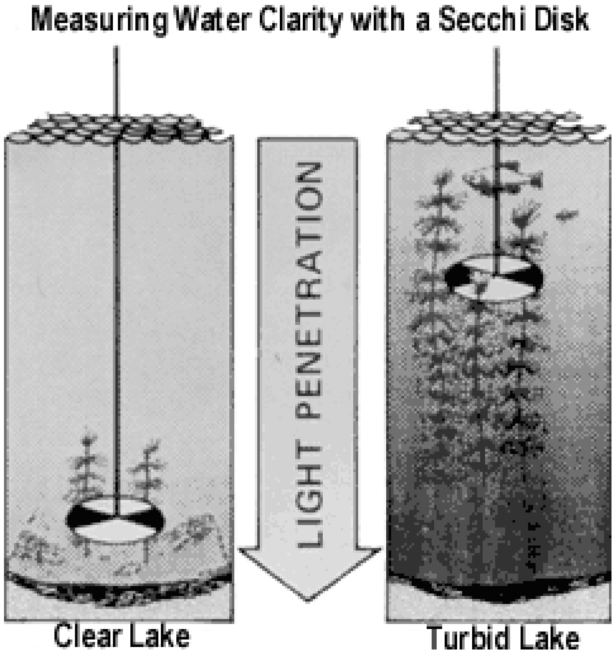
Figure 4.–Relationship between station mean concentrations of geosmin and chlorophyll a in Cheney Reservoir, USA. The horizontal dotted line indicates an approximate threshold concentration of geosmin for human detection of 5 $ng \cdot L^{-1}$.

Water Clarity Indicators

- Turbidity (Inversely related to water clarity)
- Secchi depth (Directly related)
- Total suspended sediments



http://www.fondriest.com/



http://www.pca.state.mn.us/

Potential ranges – Secchi Depth

(more lake data available for this indicator)

Parameter Secchi Depth (m)	Notes	Source	Location
0.81-1.29	excellent to good; good to acceptable range	Burden and Malone, 1987	Louisiana
> 1	clear, no blooms	Barica 1975, Walker et al. 2007	Canadian Prairie
1.5-2; >2	Fair to Good	Lillie and Mason 1983, Walker et al. 2007	Wisconsin
1.5	Water suitable for swimming	Smith et al. 1995, Walker et al. 2007	New Zealand
0.3-1.35	nuisance to severe nuisance, no swimming	Smeltzer et al. 1990, Walker et al. 2007	Minnesota
1; 1.4	greater likelihood of water clarity classified as "good"; median secchi depth ranked "swimmable" from survey of 2003 lake visitors	Burkart et al. 2008	Iowa

Zipper et al. 2005

“undesirable”

0.8-1.7 FL
1-1.7 MN, VT
0.4-0.6 MN
0.5-1 MN
<1.5 NZ
<1.38 NZ

“undesirable”
can range from 0.4-1.7 m
depending on region

Lower end of swimmable~ 0.6 m

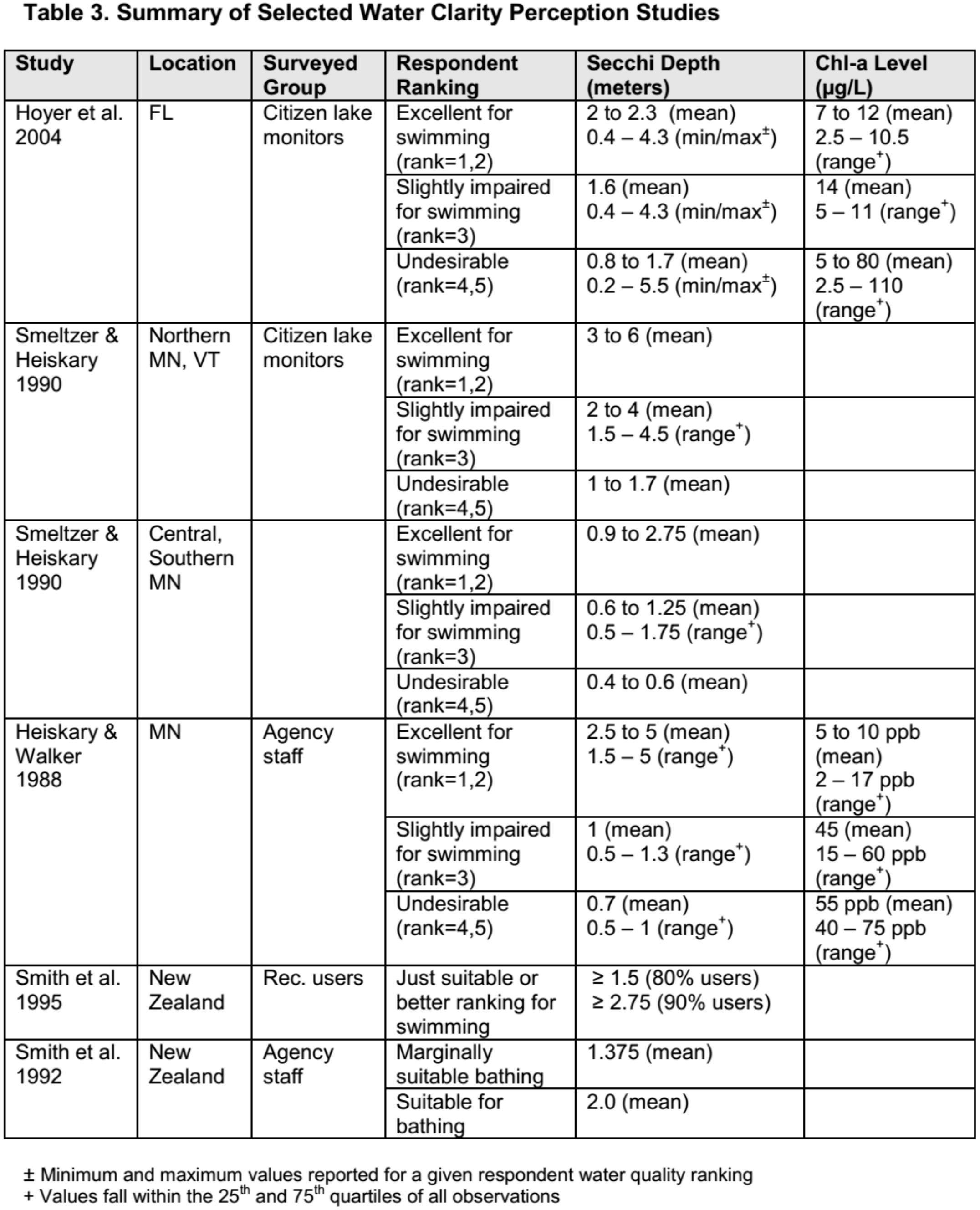


Table 3. Summary of Selected Water Clarity Perception Studies

Study	Location	Surveyed Group	Respondent Ranking	Secchi Depth (meters)	Chl-a Level (µg/L)
Hoyer et al. 2004	FL	Citizen lake monitors	Excellent for swimming (rank=1,2)	2 to 2.3 (mean) 0.4 – 4.3 (min/max$^{\pm}$)	7 to 12 (mean) 2.5 – 10.5 (range^{+})
			Slightly impaired for swimming (rank=3)	1.6 (mean) 0.4 – 4.3 (min/max$^{\pm}$)	14 (mean) 5 – 11 (range^{+})
			Undesirable (rank=4,5)	0.8 to 1.7 (mean) 0.2 – 5.5 (min/max$^{\pm}$)	5 to 80 (mean) 2.5 – 110 (range^{+})
Smeltzer & Heiskary 1990	Northern MN, VT	Citizen lake monitors	Excellent for swimming (rank=1,2)	3 to 6 (mean)	
			Slightly impaired for swimming (rank=3)	2 to 4 (mean) 1.5 – 4.5 (range^{+})	
			Undesirable (rank=4,5)	1 to 1.7 (mean)	
Smeltzer & Heiskary 1990	Central, Southern MN		Excellent for swimming (rank=1,2)	0.9 to 2.75 (mean)	
			Slightly impaired for swimming (rank=3)	0.6 to 1.25 (mean) 0.5 – 1.75 (range^{+})	
			Undesirable (rank=4,5)	0.4 to 0.6 (mean)	
Heiskary & Walker 1988	MN	Agency staff	Excellent for swimming (rank=1,2)	2.5 to 5 (mean) 1.5 – 5 (range^{+})	5 to 10 ppb (mean) 2 – 17 ppb (range^{+})
			Slightly impaired for swimming (rank=3)	1 (mean) 0.5 – 1.3 (range^{+})	45 (mean) 15 – 60 ppb (range^{+})
			Undesirable (rank=4,5)	0.7 (mean) 0.5 – 1 (range^{+})	55 ppb (mean) 40 – 75 ppb (range^{+})
Smith et al. 1995	New Zealand	Rec. users	Just suitable or better ranking for swimming	≥ 1.5 (80% users) ≥ 2.75 (90% users)	
Smith et al. 1992	New Zealand	Agency staff	Marginally suitable bathing	1.375 (mean)	
			Suitable for bathing	2.0 (mean)	

± Minimum and maximum values reported for a given respondent water quality ranking
+ Values fall within the 25th and 75th quartiles of all observations

Not much data for Piedmont Reservoirs

- Literature from other regions suggests for swimming – 0.8 m or greater is good

- BUT perceptions may vary regionally and there is not much literature on Piedmont reservoirs (that I could find in published journals)

- WANTED:

A study that evaluates water clarity and user perception for Piedmont Reservoirs, esp. High Rock Lake

WRRI Water Resources Research Institute
of The University of North Carolina

Report No. 385

EVALUATING EUTROPHICATION-RELATED WATER QUALITY PARAMETERS IN NORTH CAROLINA LAKES AND RESERVOIRS

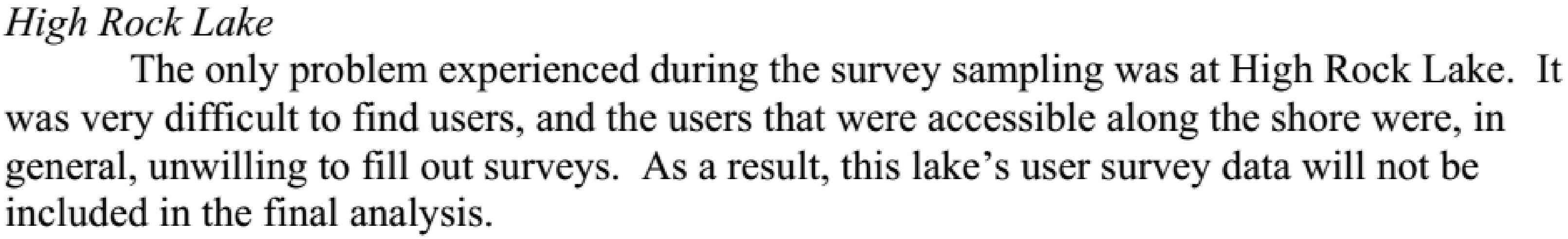
By

Melissa A. Kenney[1] ,Kenneth H. Reckhow, Ph.D[1], George B. Arhonditsis, Ph.D[2]

[1]Duke University
Durham, North Carolina

[2]University of Toronto
Toronto, Canada

January 2007



High Rock Lake

The only problem experienced during the survey sampling was at High Rock Lake. It was very difficult to find users, and the users that were accessible along the shore were, in general, unwilling to fill out surveys. As a result, this lake's user survey data will not be included in the final analysis.

Reference Condition for NC Piedmont Reservoirs

- EPA (2000). Piedmont Lakes-> Reference Condition Secchi Depth-1.66 meters

- Maximum Secchi Depth (m) for High Rock Lake from 2008-2010 was 1.4 m (YAD 169F, 6/4/08)

- What is a potential reference condition for NC Piedmont Reservoirs?

Analysis Report

For

Classification and Exploratory Analysis of North Carolina Lakes Data for the Nutrient Scientific Technical Exchange Partnership and Support (N-STEPS)

Prepared for:

U.S. Environmental Protection Agency
Office of Science and Technology,
Health Ecological Criteria Division
1200 Pennsylvania Avenue, NW
Washington, DC 20460

Prepared by:

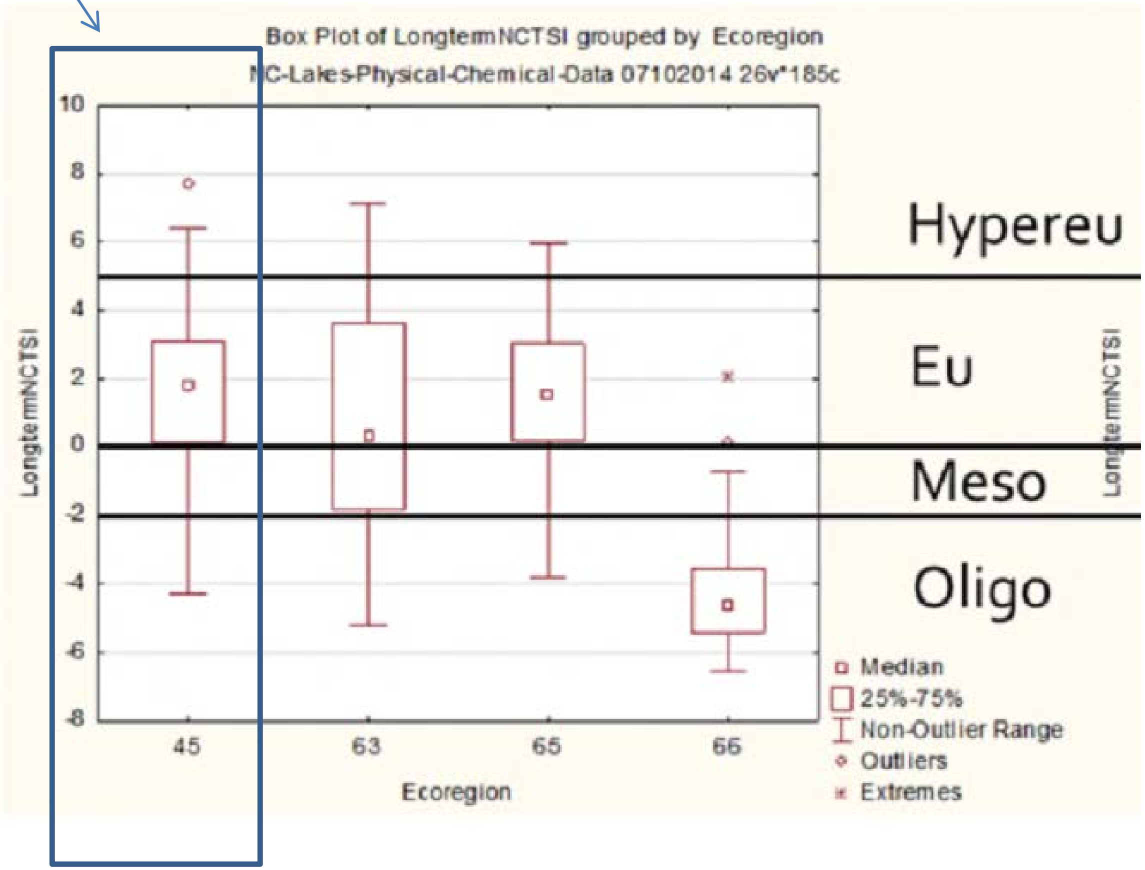
Tetra Tech, Inc.
1 Park Drive, Suite 200
Research Triangle Park, NC 27709

June 25, 2015

TETRA TECH, INC.

NC Piedmont Reservoirs- commonly eutrophic

NC Trophic State Index

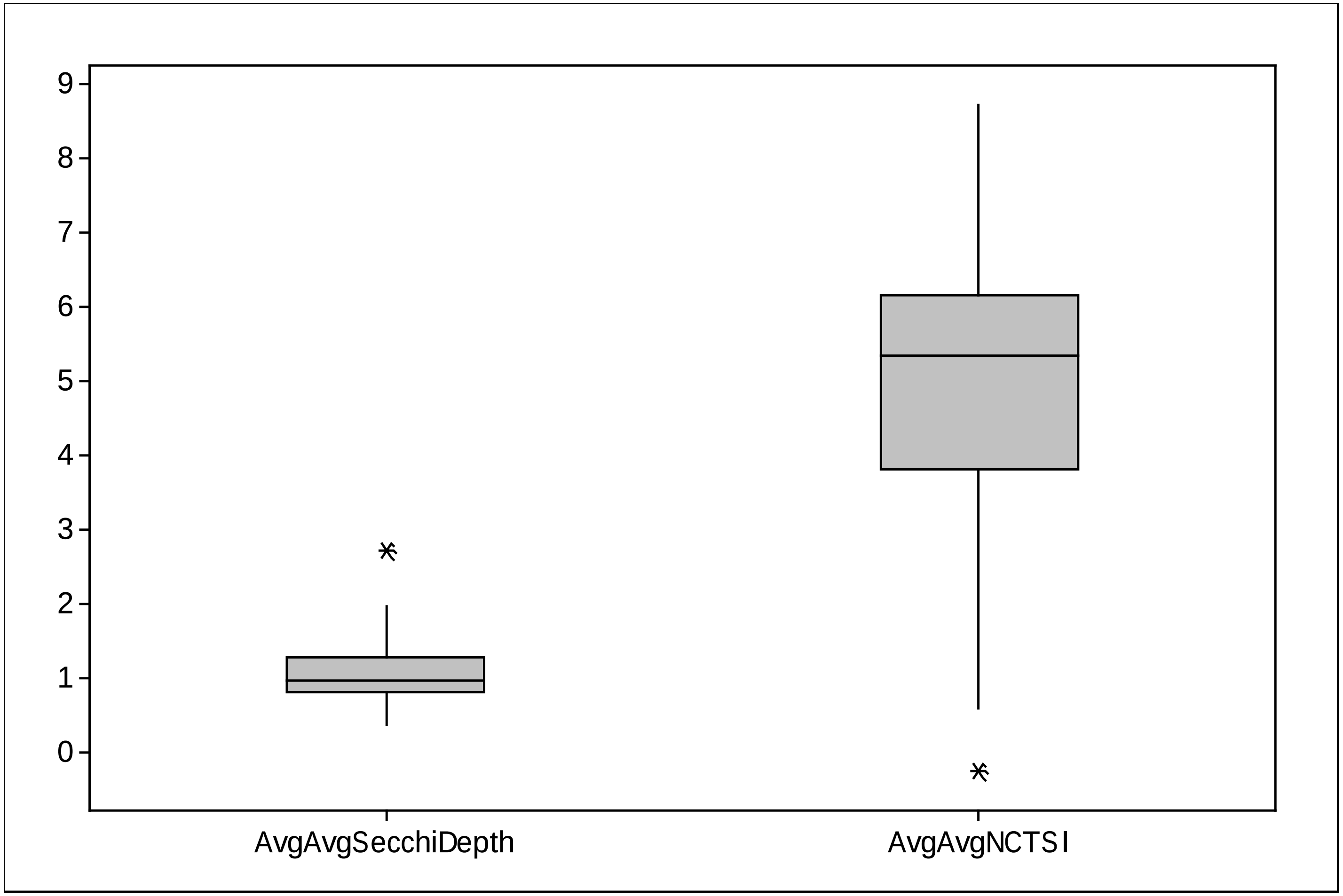


To get a better idea of how HRL clarity compares to “similar” reservoirs in NC

- Filtered long term average data provided by DEQ
- Piedmont only
- Lakes <10 m
- Lakes >100ha

- Total lakes with data in these categories: 41
- Based on DEQ NC Lakes Physical-Chemical Data spreadsheet – HRL had 1007 samples from 1981-2011

NC Piedmont Reservoirs



Median=0.97 m
75th percentile= 1.28 m (n=41, NC Piedmont Lakes > 100ha and <10 m deep)

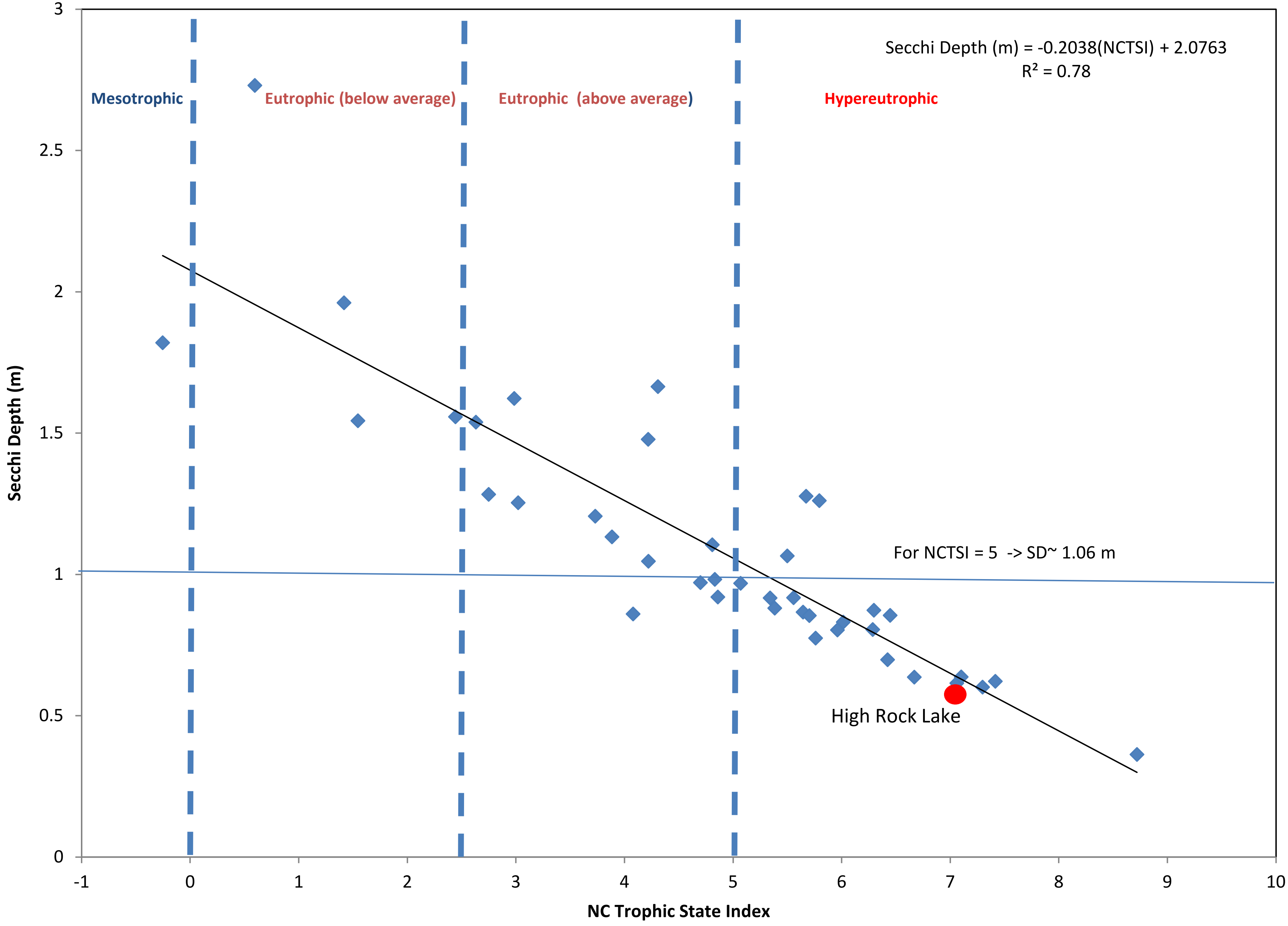
Median NCTSI =5.34 (hypereutrophic)
25th percentile= 3.8 (eutrophic)

EPA- reference for Piedmont- 1.66 m ; NC 75th percentile for NC Piedmont Reservoirs =1.28 m

Potential Reference Lakes

Filtered out those lakes with secchi depth > 75th percentile (> 1.28 m)

Lake	AvgAvgTP	AvgAvgTN	AvgAvgChla	AvgAvgSecchiDepth	AvgAvgChla	AvgAvgNCTSI	AvgAvgSecchiDepth	Area	MeanDepth
HARRIS LAKE	0.030689	0.515694	15.89501425	1.664506173	15.89501425	4.308597563	1.664506173	1680	6
HYCO LAKE	0.025896	0.322153	4.593472222	1.961388889	4.593472222	1.416106482	1.961388889	1518	6.1
LAKE ADGER	0.011167	0.181667	6.256666667	1.82	6.256666667	-0.252638017	1.82	186	8
LAKE BUTNER	0.024311	0.415489	10.14755556	1.622888889	10.14755556	2.983819764	1.622888889	151	9
LAKE GASTON	0.024067	0.662108	7.279	1.538333333	7.279	2.6306778	1.538333333	8215	6
MAYO RESERVOIR	0.017333	0.251247	4.751604938	2.730123457	4.751604938	0.596879542	2.730123457	1133	9
MOUNTAIN ISLAND LAKE	0.014984	0.407048	6.626031746	1.543968254	6.626031746	1.545254197	1.543968254	1309	5
REIDSVILLE LAKE	0.027929	0.457976	18.36190476	1.47797619	18.36190476	4.217837397	1.47797619	304	6
RICHLAND LAKE	0.021667	0.326667	9.416666667	1.283333333	9.416666667	2.748857349	1.283333333	105	3.5
ROANOKE RAPIDS LAKE	0.0362	0.501078	7.075555556	1.557333333	7.075555556	2.442567193	1.557333333	1980	5
HIGH ROCK LAKE	0.099804	0.870285	29.20513699	0.615043251	29.20513699	7.061069328	0.615043251	6374	5


Secchi Depth (m) = -0.2038(NCTSI) + 2.0763
R² = 0.78
Mesotrophic
Eutrophic (below average)
Eutrophic (above average)
Hypereutrophic
For NCTSI = 5 -> SD~ 1.06 m
High Rock Lake
Secchi Depth (m)
NC Trophic State Index
0
0.5
1
1.5
2
2.5
3
-1
0
1
2
3
4
5
6
7
8
9
10

Chl a vs secchi depth (m)

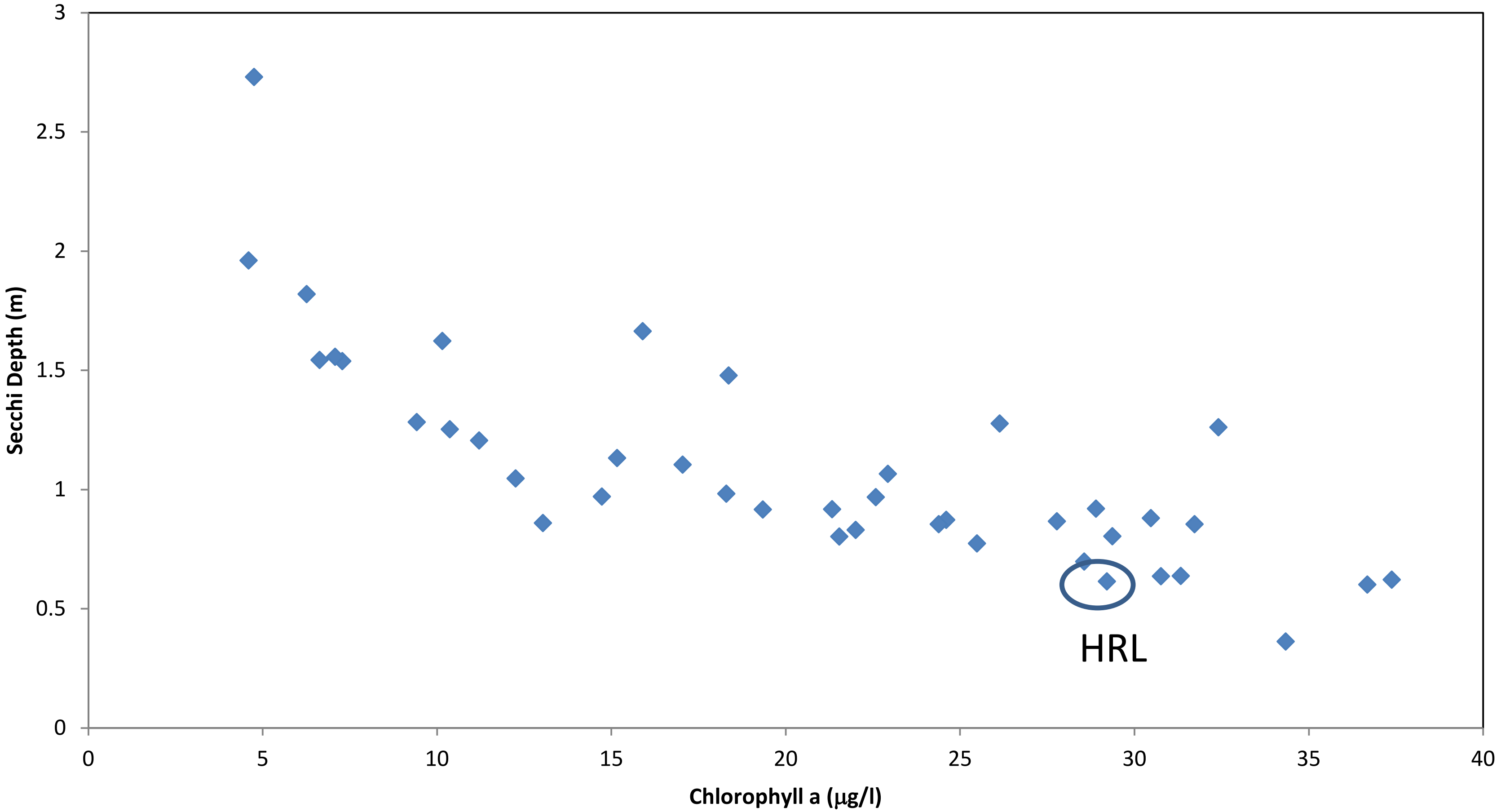
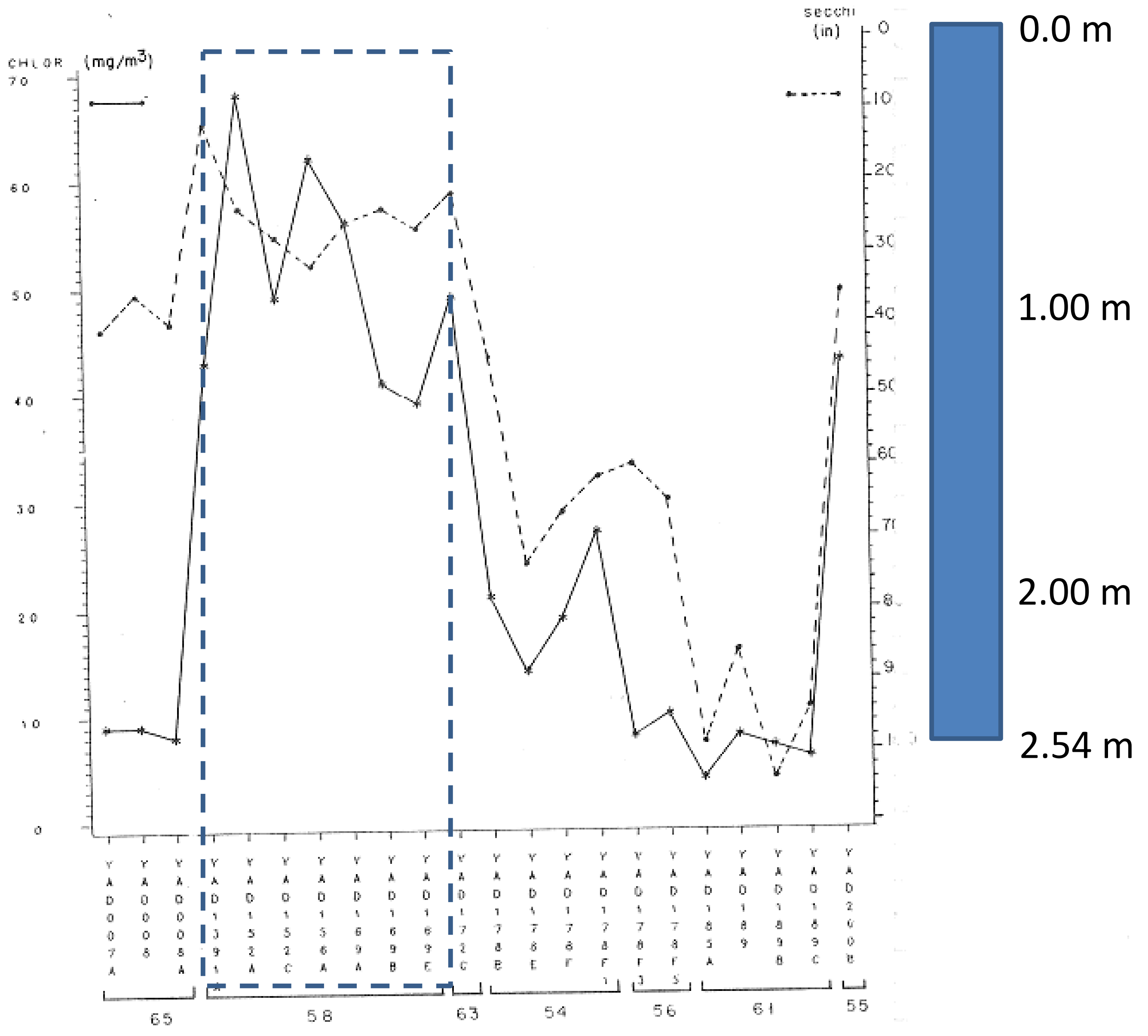


FIGURE 2. Longitudinal Changes in Chlorophyll a and Secchi Depth in the Yadkin Reservoirs.



Lake Stations and Lake Identification Numbers (see Table 2).

NORTH CAROLINA

CLEAN LAKES

CLASSIFICATION SURVEY

1982

NORTH CAROLINA DEPARTMENT OF

NATURAL RESOURCES AND COMMUNITY DEVELOPMENT

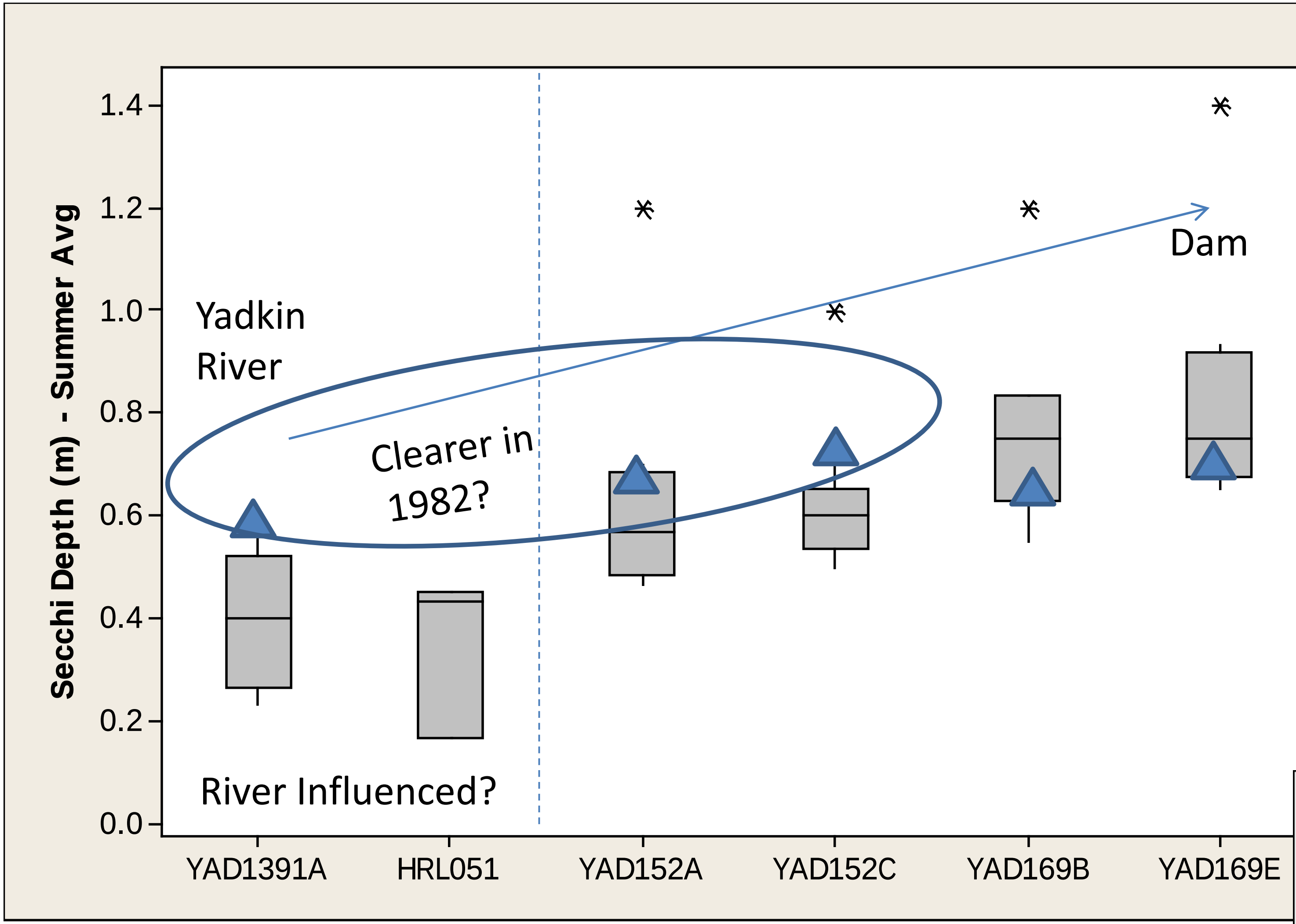
DIVISION OF ENVIRONMENTAL MANAGEMENT

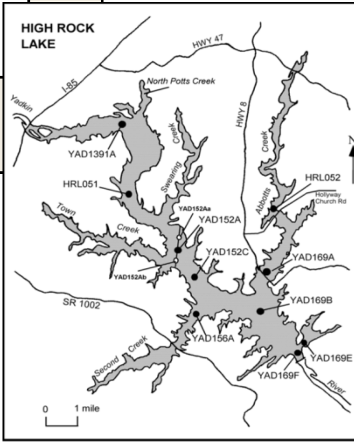
WATER QUALITY SECTION

RALEIGH, NORTH CAROLINA

FEBRUARY 1983

Spatial and Temporal Variability in HRL Clarity





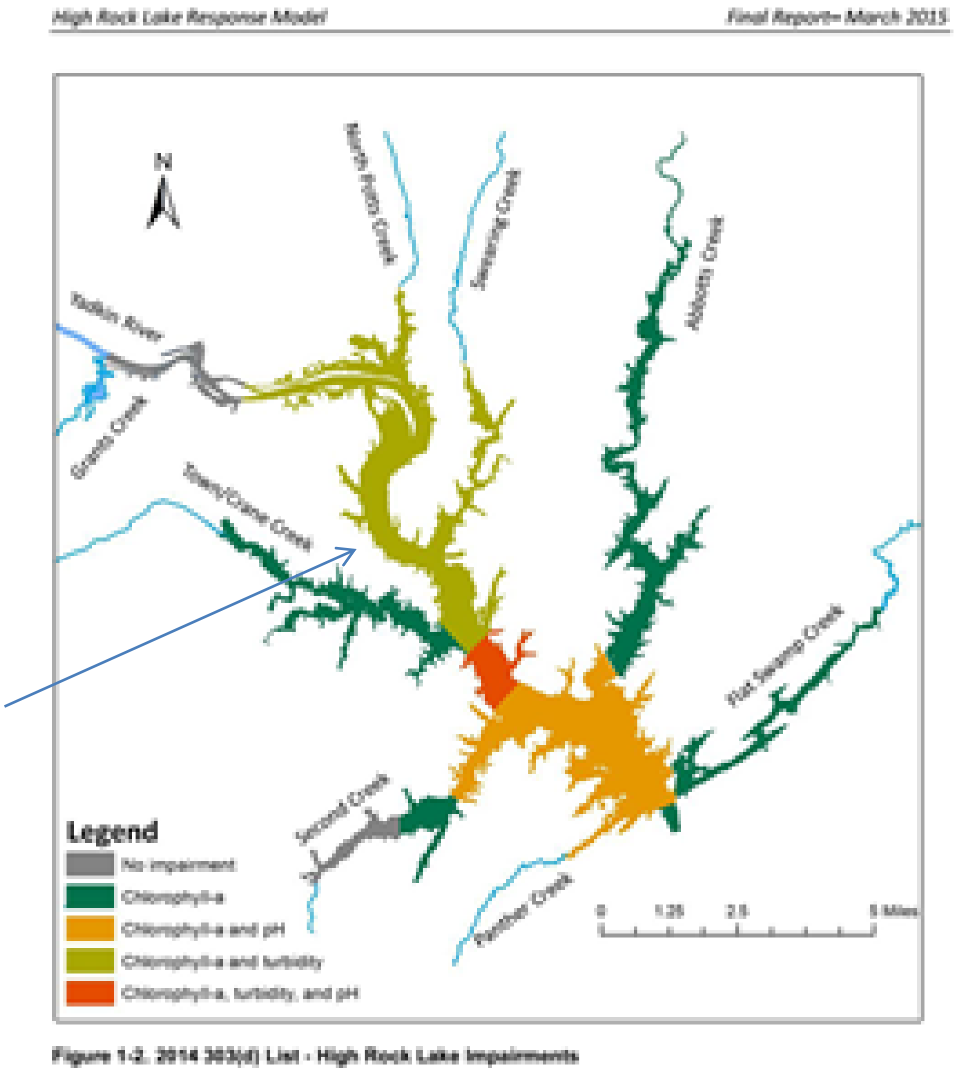
▲ 1982 Lake Survey (mean Secchi Depth=0.61 m)

1986 -2011 data (not all sites /all years covered)

Impaired sections

Is turbidity impairment dominated by riverine mineral inputs during high flows?

Or more related to algal growth?



High Rock Lake Response Model *Final Report– March 2015*

Figure 1-2. 2014 303(d) List - High Rock Lake Impairments

Potential Ranges

- Aquatic Life: ? Need more info (literature available on turbidity influence on fisheries)

- Recreation (full-body contact): 0.8m (low)
- Recreation (infrequent contact): 0.5m (low)
-
- 1m generally can be aesthetically pleasing (can see your toes). 2m appears to be the high end of all ranges (from regions with much clearer lakes).

- 75th percentile Secchi Depth for NC Piedmont – Reservoirs < 10m deep - 1.28 m

- For comparisons with NC Trophic State Index- < 1.06 m would correspond with lakes that fall in the hypereutrophic category.

- Split the difference? – 0.75 m

- Need more info on users and perceptions and fisheries and what component of clarity impairment is due to riverine turbidity increase during and after runoff events.

Referenced Materials

Summerkill Risk in Prairie Ponds and Possibilities of its Prediction

JAN BARICA

Department of the Environment, Fisheries and Marine Service, Freshwater Institute, Winnipeg, Man. R3T 2N6

BARICA, J. 1975. Summerkill risk in prairie ponds and possibilities of its prediction. J. Fish. Res. Board Can. 32: 1283–1288.

Summer fish kills in shallow, landlocked ponds of the Erickson–Elphinstone area, southwestern Manitoba, were caused by collapses of heavy algal blooms, mostly *Alphanizomenon flos-aquae*, and subsequent oxygen depletion. Kills occurred only in ponds that were in the specific conductance range of 800–2000 μmho/cm and where chlorophyll *a* concentrations exceeded 100 μg/liter. A practical rating system for assessment of summerkill risk was suggested. Correlations between various parameters from 51 ponds were computed; the best correlation (r = 0.866; P = >0.99) was found between the late-winter concentration of ammonia nitrogen and the maximum concentration of chlorophyll *a* in the following summer. Two summerkill prediction systems were proposed, based on ammonia, dissolved oxygen, and Secchi disc transparency, enabling the prediction of summerkill risk 9 or 3 mo prior to stocking of the fish.

BARICA, J. 1975. Summerkill risk in prairie ponds and possibilities of its prediction. J. Fish. Res. Board Can. 32: 1283–1288.

TABLE 1. Frequency distribution of different chlorophyll *a* ranges (summer maxima) in aquaculture experimental lakes and summerkill risk rating.

Chlorophyll *a* range (µg/liter)	No. of lakes	% of total	Predominant algae species (midsummer)[a]	Secchi disc. transp. (*m*)	Appearance	Summerkill risk[b]	
0–25	13	25.5	*Microcystis* *Merismopedia* *Ceratium*	>1.0	clear, no blooms frequent macrophytes	low	LOW
25–100	21	41.2	*Anabaena* *Microcystis*	0.4–1.0	moderate blooms	medium	
100–200	10	19.6	*Aphanizomenon* *flos-aquae*	<0.4	dense colonies, clumping, scums	high	HIGH
>200	7	13.7				very high	

[a] (Kling 1975).

[b] Arbitrary limits and categories based on data published separately (Barica 1975).

A CLASSIFICATION OF FRESHWATER LOUISIANA LAKES BASED ON WATER QUALITY AND USER PERCEPTION DATA

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(Received August 1985; in revised form April 1987)

Abstract. An index system developed for Louisiana lakes was based on correlations between measurable water quality parameters and perceived lake quality. Support data was provided by an extensive monitoring program of 30 lakes coordinated with opinion surveys undertaken during summer 1984. Lakes included in the survey ranged from 4 to 735 km^2 in surface area with mean depths ranging from 0.5 to 8.0 m. Water quality data indicated most of these lakes are eutrophic, although many have productive fisheries and are considered recreational assets. Perception ratings of fishing quality and its associated water quality were obtained by distributing approximately 1200 surveys to Louisiana Bass Club Associaton members. The ability of Secchi disc transparency, total organic carbon, total Kjeldahl nitrogen, total phosphorus, and chlorophyll *a* to discriminate between perception classes was examined using probability distributions and multivariate analyses. Secchi disc and total organic carbon best reflected perceived lake conditions; however, these parameters did not provide the discrimination necessary for developing a quantitative risk assessment of lake trophic state. Consequently, an interim lakes index system was developed based on total organic carbon and perceived lake conditions. The developed index system will aid State officials in interpretating and evaluating regularly collected lake quality data, recognizing potential problem areas, and identifying proper management policies for protecting fisheries usage within the State.

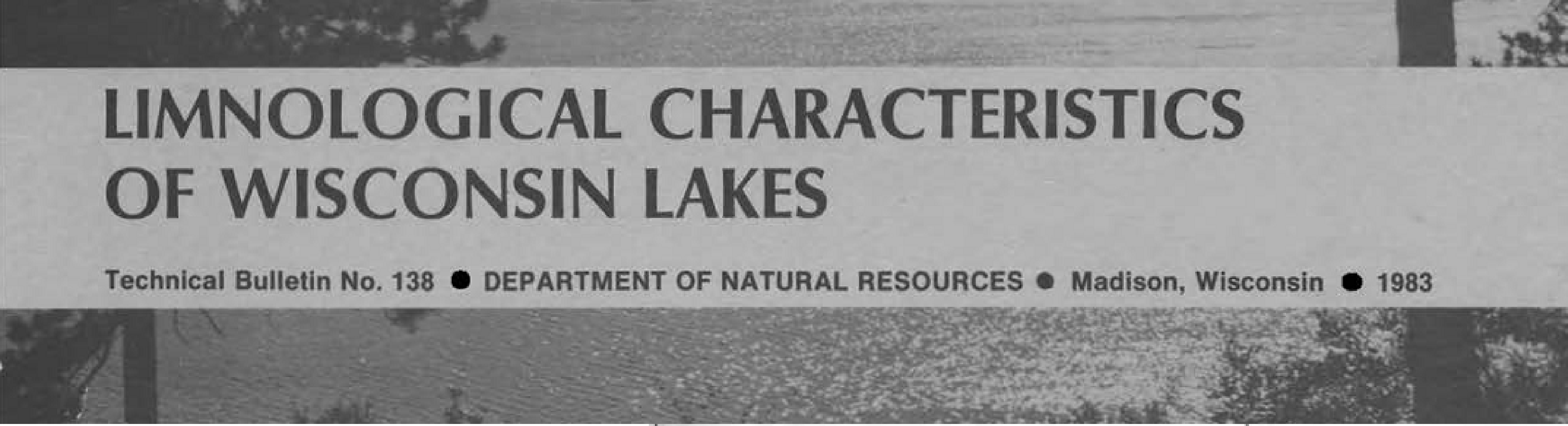
TABLE II

Summary of individual parameter observations by perception class

	Water quality perception class (n = number of lakes in each class)					
Parameter	Excellent/good ($n=7$)		Good/acceptable ($n=16$)		Acceptable/marginal ($n=7$)	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
TOC (mg L^{-1})	6.02	1.58	7.38	2.18	9.27	2.58
CHLA (μg L^{-1})	8.71	11.0	22.8	21.3	25.0	22.6
NO2-NO3 (mg L^{-1})	0.03	0.04	0.04	0.08	0.04	0.04
TKN (mg L^{-1})	0.69	0.41	0.93	0.65	1.05	0.55
TP (mg L^{-1})	0.08	0.12	0.10	0.11	0.14	0.13
SS (mg L^{-1})	6.80	6.08	11.9	11.1	17.3	23.9
VSS (mg L^{-1})	3.90	4.72	6.20	7.91	8.46	14.6
SECCHI (m)	1.29	0.45	0.81	0.40	0.56	0.18

LIMNOLOGICAL CHARACTERISTICS OF WISCONSIN LAKES

Technical Bulletin No. 138 ● DEPARTMENT OF NATURAL RESOURCES ● Madison, Wisconsin ● 1983



LIMNOLOGICAL CHARACTERISTICS OF WISCONSIN LAKES

By
Richard A. Lillie and John W. Mason

Technical Bulletin No. 138
DEPARTMENT OF NATURAL RESOURCES
P.O. Box 7921, Madison, WI 53707

1983

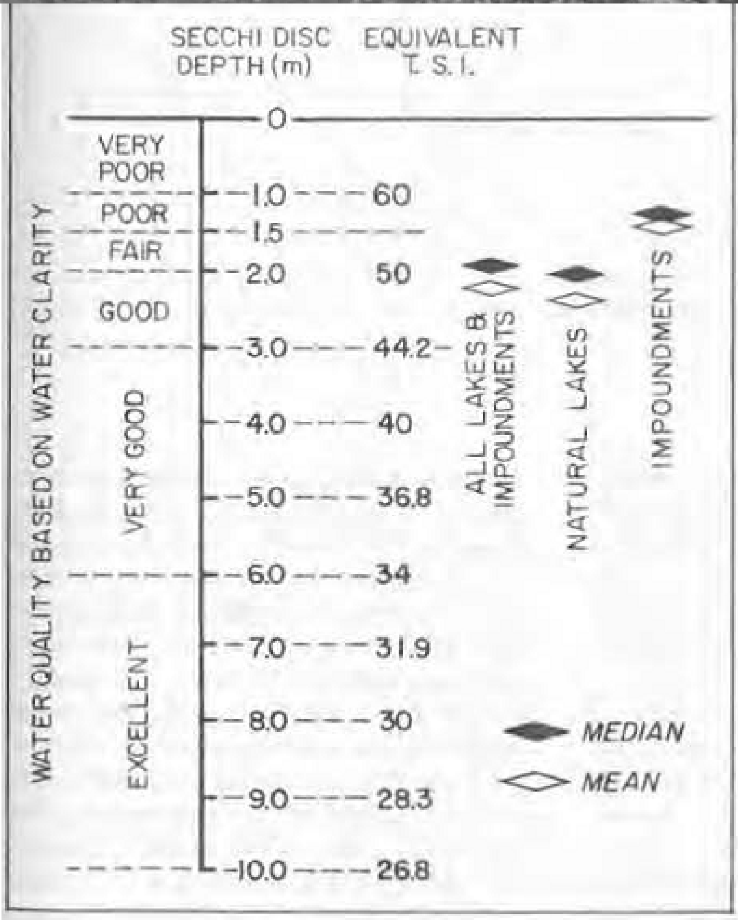


FIGURE 26. *Water clarity for 595 randomly sampled Wisconsin lakes and its relationship to Carlson's (1977) Trophic State Index (TSI).*

LAKE AND RESERVOIR MANAGEMENT, 1990 6(1): 109-118

Analysis and Applications of Lake User Survey Data

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ABSTRACT

Lake management often requires assessment of water quality impacts on lake users. Lake user surveys provide a means for linking sampling parameters such as total phosphorus, chlorophyll *a*, or transparency and user impacts such as nuisance algae levels and recreational impairment. A lake user survey was conducted on nearly 500 lakes in Minnesota and Vermont concurrently with citizens' water quality sampling programs. The results showed that quantifiable and statistically significant relationships existed between eutrophication-related water quality measurements and user perceptions of nuisance algal conditions. However, strong differences existed in these relationships between the two states and among lake regions within each state, indicating that specific regional relationships should be developed whenever possible. This report describes applications of lake user survey results, including statewide lake assessments, wastewater discharge impact evaluations, lake management goal setting, and water quality standards development.

Table 1.—Lake user survey form.

A. Please circle the one number that best describes the *physical condition* of the lake water today.
   1. Crystal clear water.
   2. Not quite crystal clear, a little algae visible.
   3. Definite algal greenness, yellowness, or brownness apparent.
   4. High algal levels with limited clarity and/or mild odor apparent.
   5. Severely high algae levels with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill.

B. Please circle the one number that best describes your *opinion* on how suitable the lake water is for recreation and aesthetic enjoyment today.
   1. Beautiful, could not be any nicer.
   2. Very minor aesthetic problems; excellent for swimming, boating, enjoyment.
   3. Swimming and aesthetic enjoyment slightly impaired because of algae levels.
   4. Desire to swim and level of enjoyment of the lake substantially reduced because of algae levels.
   5. Swimming and aesthetic enjoyment of the lake nearly impossible because of algae levels.

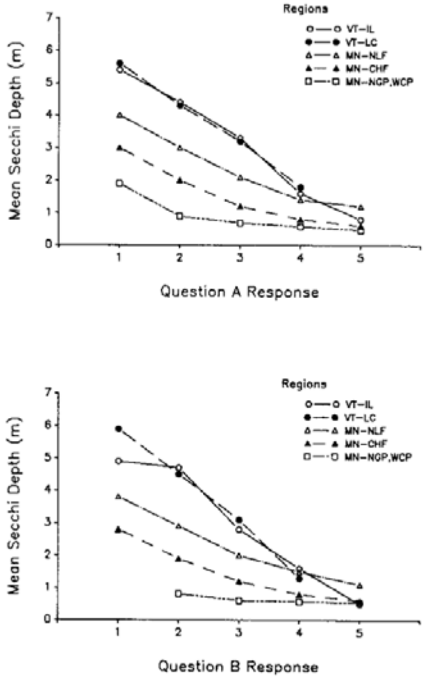

Figure 2.—Geometric mean Secchi depth plotted vs. user survey response category for lake regions in Vermont and Minnesota. See Table 2 for region definitions.

NUTRIENTS IN LAKES AND RESERVOIRS – A LITERATURE REVIEW FOR USE IN NUTRIENT CRITERIA DEVELOPMENT

Grant No. 06HQGR0021

Submitted to:
Ms. Tiffany Crawford
U.S. EPA Region III

Submitted by:
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August 24, 2007

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VWRRC Special Report SR34-2007

Nutrient Criteria for Iowa Lakes

Recommended Criteria for Class “A” Recreational Uses

Report of the Nutrient Science Advisors

February 14, 2008

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Tom Wilton, Lake Restoration, Iowa Department of Natural Resources

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Recognizing natural variability in the quality of water of Iowa’s lakes, Secchi depth may occasionally fail to meet 1.0 m even in lakes with good water quality. This recommended criterion must be met 75% of the time for purposes of determining whether a lake supports its designated Class A uses (Table 1). This frequency was defined using data from three samples in each of seven consecutive summer recreation seasons. The NSA recommends that the frequency be determined using a minimum of nine samples; three samples taken during each summer recreation season (see definition above) over at least three consecutive years. Consequently, lakes designated as Class A are understood to meet these minimum sample conditions and meet

Year	June Samples		July Samples		August Samples		All Samples	
	Prob.	95% C.I	Prob.	95% C.I	Prob.	95% C.I	Prob.	95% C.I
Iowa Lakes classified as "Good" water quality systems								
2000	0.86	0.81-0.91	0.82	0.75-0.88	0.82	0.75-0.88	0.82	0.78-0.85
2001	0.86	0.81-0.91	0.95	0.94-0.97	0.95	0.94-0.97	0.94	0.93-0.95
2002	0.95	0.93-0.97	0.90	0.87-0.94	0.90	0.87-0.94	0.90	0.88-0.93
2003	1.00	1.00-1.00	0.95	0.93-0.97	0.95	0.93-0.97	0.94	0.92-0.95
2004	0.86	0.80-0.91	0.90	0.86-0.94	0.90	0.86-0.94	0.85	0.82-0.88
2005	0.96	0.94-0.97	0.92	0.89-0.95	0.92	0.89-0.95	0.86	0.83-0.89
2006	0.95	0.94-0.97	0.91	0.87-0.94	0.91	0.87-0.94	0.91	0.89-0.93
Totals	**0.92**	**0.91-0.93**	**0.91**	**0.89-0.92**	**0.91**	**0.89-0.92**	**0.89**	**0.88-0.90**
All Monitored Iowa lakes								
2000	0.34	0.30-0.38	0.29	0.25-0.33	0.29	0.25-0.33	0.31	0.29-0.33
2001	0.62	0.58-0.66	0.62	0.57-0.66	0.54	0.50-0.58	0.59	0.57-0.62
2002	0.60	0.56-0.64	0.38	0.34-0.43	0.28	0.24-0.31	0.42	0.39-0.44
2003	0.65	0.61-0.69	0.46	0.42-0.50	0.34	0.30-0.38	0.48	0.46-0.51
2004	0.43	0.39-0.48	0.42	0.38-0.46	0.32	0.28-0.36	0.39	0.37-0.42
2005	0.58	0.55-0.62	0.41	0.37-0.45	0.24	0.21-0.27	0.41	0.39-0.43
2006	0.50	0.46-0.54	0.39	0.35-0.43	0.31	0.27-0.35	0.40	0.38-0.43
Totals	**0.53**	**0.52-0.55**	**0.42**	**0.41-0.44**	**0.33**	**0.32-0.34**	**0.43**	**0.42-0.44**

Table 1. Probability of monitored Iowa lakes achieving a Secchi disk depth of at least 1.0 m.

Human perception of water appearance
1. Clarity and colour for bathing and aesthetics

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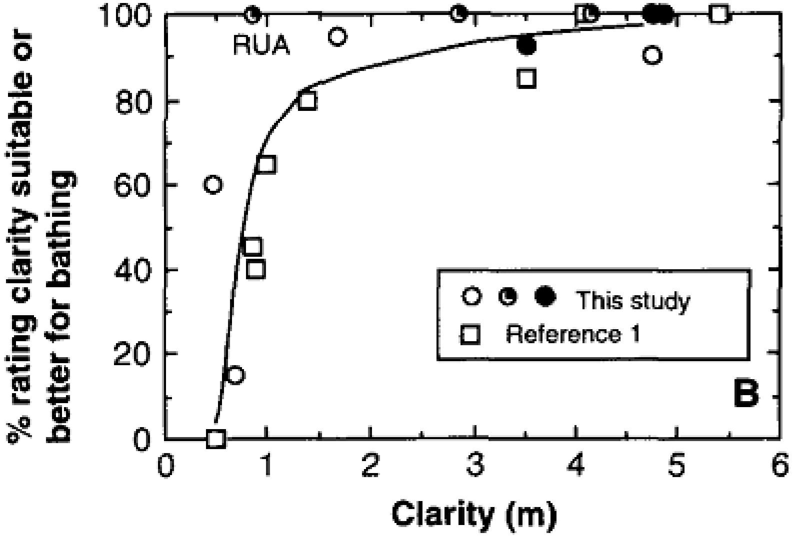
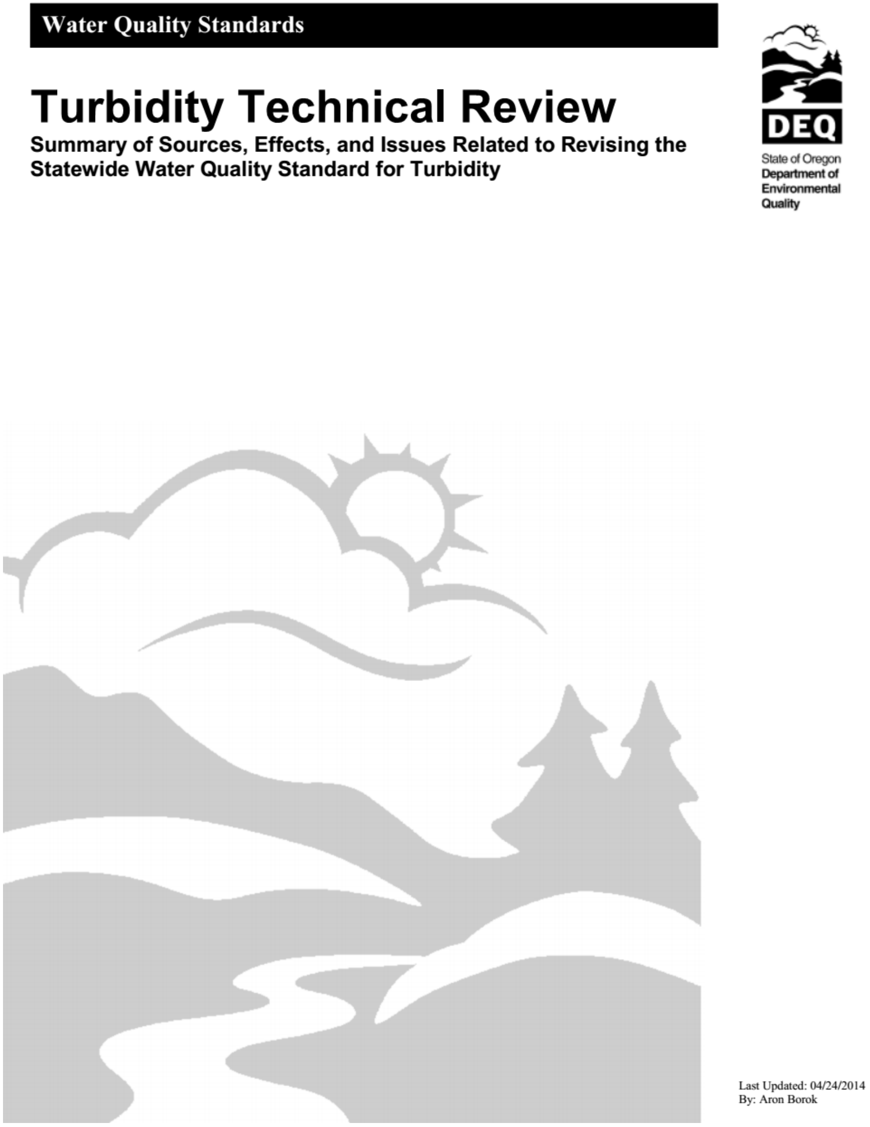
Abstract Human perception of two important visual aspects of the appearance of river and lake water, clarity and colour, was investigated from the perspective of bathing and aesthetics in New Zealand. Bankside interviews were conducted at the same time as measurements were made for clarity and colour. We found that water appearance, perceived suitability of the water for bathing, and bathing activity are closely linked, as is perception of water clarity and colour. Water is perceived as just suitable for bathing at a horizontal black disc visibility of 1.2 m (equivalent Secchi depth c. 1.5 m) with a 90 percentile of 2.2 m (equivalent Secchi depth c. 2.75 m), confirming earlier work. As might be expected, blue waters are preferred to yellow waters, and water is perceived as just suitable for bathing if the Munsell colour is greater than around 30 units (i.e., at the low end of the green-yellow range). For bathing waters, consideration of personal safety is very important; for aesthetics, surroundings are important. People's perception of visual aspects (i.e., clarity and colour) appears to have a strong influence on their rating of overall site suitability.



Turbidity



Water Quality Standards

Turbidity Technical Review

Summary of Sources, Effects, and Issues Related to Revising the Statewide Water Quality Standard for Turbidity

DEQ

State of Oregon
Department of Environmental Quality

Last Updated: 04/24/2014
By: Aron Borok

Effects of turbidity on fishing

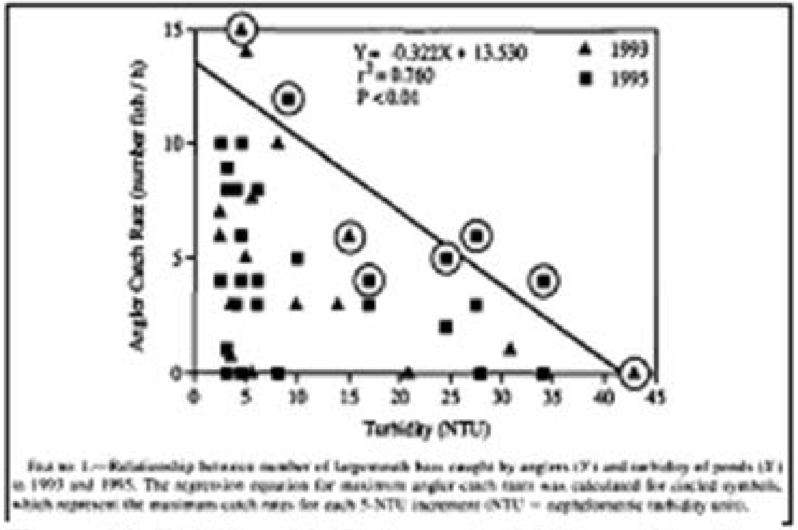


Figure 30. Relationship between turbidity and angler catch rate of largemouth bass in an experimental pond (Drenner, et al 1997).

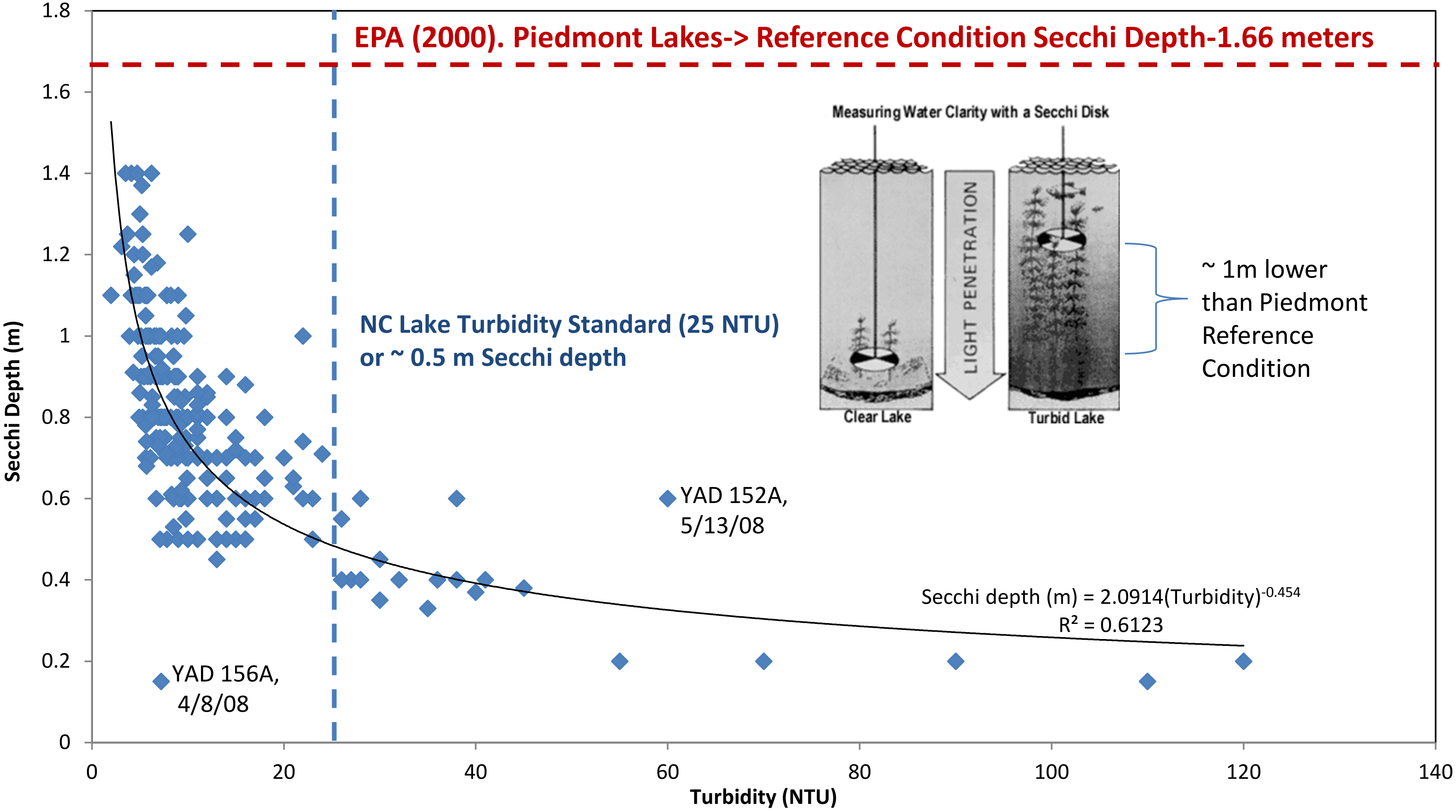
In locations where chronic turbidity results in decreased fish populations and diversity, a number of studies have noted an indirect effect on the quality of fishing in those locations. For example, Buck (1956), in a study of a clear and a turbid reservoir in Oklahoma, found that fish species grew faster in the clear reservoir. In addition, catch per unit effort in the clear reservoir was reported as 3-4 times higher in the clear reservoir than the turbid reservoir. Drenner, et al. (1997) found that catch rates of largemouth bass were significantly and linearly correlated with turbidity in an experimental pond (Figure 32). Ewing (1991) hypothesized that chronic turbidity (>100 NTU) was the culprit for the decline in fish populations in a bottomland hardwood backwater system. Lloyd, et al. (1987) reported a 55% decline in sport fishing downstream from mine discharges on the Chatainika River, Alaska, which was attributed to avoidance by fishers of increased turbidities of 8-50 NTU. The authors did not note whether this decline was due to a decrease in fish numbers or a preference to fish in clear waters due to safety or aesthetic concerns.

Table 5. Summary of effects of turbidity on aquatic life in lakes and reservoirs.

Turbidity Level	Duration	Effect	Source	Turbidity Measurement	Lab or Field
Effects at turbidity levels ≤10 turbidity units					
~1.2 JTU	chronic	50% decrease in reactive distance of bluegill trout to avoid largemouth bass	Miner and Stein 1996	Not reported	Laboratory
1.5 NTU	4 hours	Minimum turbidity to decrease reactive distance of lake, rainbow, and cutthroat trout	Mazur and Beauchamp 2003	LaMotte 2008	Laboratory
1.65 NTU	1 hour	Lowest effect level for turbidity to decrease reactive distance in yearling Chinook salmon	Hansen, et al. (2013)	LaMotte 2020e	Laboratory
3.18 NTU	4 hours	Decrease in reactive distance of lake trout to juvenile rainbow and cutthroat trout at optimum light intensity	Vogel and Beauchamp 1999	LaMotte 2008	Laboratory
5 NTU	n/a	80% reduction in compensation depth	Lloyd, et al. 1987	HF DRT-150 Turbidimeter	Field
5 NTU	3.5 – 42.6 hours	Significant decrease in consumption of prey by smallmouth bass	Carter, et al. 2010	LaMotte 2020	Laboratory
10 NTU	19-49 hour	Change in size selectivity of prey by largemouth bass	Shoup and Wahl 2009	Cole-Parmer Model 8391–40	Laboratory
Effects at turbidity levels from 11-20 turbidity units					
17-19 JTU	n/a	Decrease in reactive distance of largemouth bass to crayfish	Crowl 1989	Not reported (Jackson turbidimeter)	Laboratory
Effects at turbidity levels from 21-30 turbidity units					
25 NTU	2 hours	60-80% decrease in feeding rates of Lahontan redside shiner and cutthroat trout on daphnia	Vinyard and Yuan 1996	DRT-15 Turbidimeter	Laboratory
Effects at turbidity levels from 31-50 turbidity units					
30+ NTU	n/a	Limitation in compensation of photosynthetic efficiency for low-light conditions	Lloyd, et al. 1987	n/a	Field
33 NTU	n/a (mean turbidity over multiple	Reduction in chlorophyll *a* levels in glacial lakes	Koenings, et al. 1990	DRT-100	Field

Turbidity Level	Duration	Effect	Source	Turbidity Measurement	Lab or Field
	lakes and years)				
40 NTU	42-77 hours	Decrease in predation rate by largemouth bass	Shoup and Wahl 2009	Cole-Parmer Model 8391–40	Laboratory
Effects at turbidity levels >50 turbidity units					
60 NTU	3 minutes	Decrease in prey consumption by bluegill	Gardner 1981	DRT-100	Laboratory
70 NTU	one hour	Decrease in predation rates by largemouth bass	Reid, et al. 1999	DRT-15B	Laboratory
100 FTU	n/a	Population level declines of centrarchids in a Louisiana bottomwood backwater system	Ewing 1991	Hach DR-EL/1	Field
144 FTU	25 weeks	No effect on growth rate of adult crappie	Spier and Heidinger 2002	Hach DR-2000	Field
160 NTU	3 hours	No decrease in predation rate by rainbow trout; however, size selectivity was affected.	Rowe, et al. 2003	Hach 18910 Turbidimeter	Laboratory
174 FTU	25 weeks	No decrease in growth rates of juvenile white and black crappie	Spier and Heidinger 2002	Hach DR-2000	Field

High Rock Lake Data (2008-2010)



~ 1 m secchi depth difference between Piedmont Reference and NC Lake Turbidity Standard

North Carolina Trophic State Index

Trophic classification is a relative description of a lake's biological productivity. The productivity of a lake is determined by a number of chemical and physical characteristics of which the most important are the availability of essential plant nutrients (primarily nitrogen and phosphorus), algal density, and the depth of light penetration. Lakes are classified according to productivity: unproductive lakes are termed "oligotrophic"; moderately productive lakes are termed "mesotrophic"; and productive lakes are termed "eutrophic". Individuals wanting further information on the trophic classification of lakes are urged to read the section entitled "Ecological Concepts". In addition, the 1982 North Carolina Clean Lakes Classification Survey (NRCD 1982) and Wetzel (1975) also review this subject.

The productivity of a lake is also related to water quality. In general, oligotrophic lakes have good water quality. Mesotrophic lakes are moderately productive and show little, if any, signs of water quality degradation. Eutrophic lakes may be so productive that the potential for water quality degradation exists in these water bodies. Many of these lakes already show symptoms of water quality problems such as algal blooms, fish kills, or excessive sedimentation.

Numerical indices are often used to evaluate the trophic status of lakes. An index was developed specifically for North Carolina lakes as part of the state's original Clean Lakes Classification Survey (NRCD 1982). The North Carolina Trophic State Index (NCTSI) is based on total phosphorus (TP in mg/l), total organic nitrogen (TON in mg/l), Secchi depth (SD in inches), and chlorophyll-a (CHL in µg/l). Lakewide means for these parameters are manipulated to produce a NCTSI score for each lake, using the following equations:

$$\text{TON score} = \frac{\text{Log(TON)} + (0.45)}{0.24} \times 0.90$$

$$\text{TP score} = \frac{\text{Log(TP)} + (1.55)}{0.35} \times 0.92$$

$$\text{SD score} = \frac{\text{Log(SD)} - (1.73)}{0.35} \times -0.82$$

$$\text{CHL score} = \frac{\text{Log(CHL)} - (1.00)}{0.43} \times 0.83$$

$$\text{NCTSI} = \text{TON score} + \text{TP score} + \text{SD score} + \text{CHL score}$$

In general, NCTSI scores relate to trophic classifications as follows:

NCTSI	CLASSIFICATION
< -2.0	Oligotrophic
-2.0 to 0.0	Mesotrophic
0.0 to 5.0	Eutrophic
> 5.0	Hypereutrophic

When the NCTSI values border between different classes, best professional judgement is used to assign the most appropriate trophic classification. In some cases, such as in lakes dominated by macrophytes, the index tends to underestimate trophic status, and best professional judgement is again employed to assign a realistic trophic status.

Lakes that have been monitored in North Carolina exhibit a wide range of productivity (table 3). Oligotrophic lakes are characteristically found in the mountains or in undisturbed watersheds. Many eutrophic and mesotrophic lakes are found in the central piedmont. A few are hypereutrophic, usually because point or nonpoint sources of pollution contribute high levels of nutrients. TSI values for a lake normally vary somewhat from year to year, but major differences may signal a change in trophic status and water quality (table 4).

NCTSI scores are less meaningful for evaluating dystrophic lakes. These acidic, "blackwater" lakes are rich in organic matter, mainly in the form of suspended plant colloids and larger plant fragments, but usually have low productivity and few water quality problems. In North Carolina, dystrophic lakes are scattered throughout the coastal plain, often located in marshy areas or overlying peat deposits.

Water Quality Issues

Most water quality problems in North Carolina lakes arise from three sources: eutrophication, macrophytes, and sedimentation. Toxic metal contamination is a concern in a few lakes. In addition, there is growing concern for the safety of drinking water supplies. Some work has been done to survey contamination of drinking waters by pesticides and other organic compounds, but more testing is needed across the state. Lake concerns and management options are discussed below.

Nutrient enrichment of North Carolina's lakes is a primary concern. Many of the lakes which have been monitored are eutrophic, and a few are hypereutrophic. When algal blooms, weed infestations, and fish kills occur, these waters may not fully support their designated uses. One should note that eutrophication, or the gradual progression toward increased lake nutrient status and productivity, is a natural process. However, human activity in a watershed can accelerate this process. Especially in the piedmont region of North Carolina, nutrient inputs from point source discharges and from nonpoint sources have contributed to "cultural" eutrophication of lakes.

Macrophytes are another source of lake problems. The greatest threat is from hydrilla,

NORTH CAROLINA LAKE ASSESSMENT REPORT

This report has been approved for release:

Steve W. Tedder 5/25/92

Steve W. Tedder, Chief
Date

Report 92-02

NORTH CAROLINA DEPARTMENT OF
ENVIRONMENT, HEALTH,
AND NATURAL RESOURCES
Division of Environmental Management
Water Quality Section

Table 4. Historical NCTSI Values, 1981-1990.

LAKE	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
High Rock Lake	3.8	4.0		4.6	3.8	2.5			3.5	3.3

HIGH ROCK LAKE

COUNTY:	Rowan/Davidson	**BASIN:**	Yadkin
SURFACE AREA:	6374 hectares (15750 acres)	**USGS TOPO:**	High Rock, N.C.
CLASS:	WS, B	**LAKE TYPE:**	Reservoir

LATEST NCTSI:	3.3	**TROPHIC STATE:**	Eutrophic
SAMPLING DATE:	August 14, 1990	**ADDITIONAL COVERAGE:**	Fecals, Water Supply Parameters
SECCHI DEPTH:	0.4 m	**CONDUCTIVITY:**	92-97 µmhos/cm^2
TOTAL PHOSPHORUS:	0.08 mg/l	**DISSOLVED OXYGEN:**	7.0 - 11.4 mg/l
TOTAL ORGANIC NITROGEN:	0.35 mg/l	**TEMPERATURE:**	28.2 - 29.1 °C
CHLOROPHYLL-A:	28 µg/l	**pH:**	7.5 - 9.6 s.u.

High Rock Lake is an impoundment of the Yadkin River situated downstream from W. Kerr Scott Reservoir. The dam that impounds High Rock Lake was originally built in 1927 by the Yadkin Corporation to provide hydroelectric power. With a maximum depth of 19 meters and a mean depth of five meters, High Rock Lake has a volume of 314 x 10^6 m^3. Because the water from the lake is used to generate hydroelectric power, the discharge rate from High Rock Lake remains fairly constant although the inflow varies. This variation causes considerable fluctuations in lake level and affects the hydraulic retention time. A two-year study conducted by the University of North Carolina (Weiss et. al. 1981) in 1977 and 1978 found residence times ranging from 3.6 days to 50.8 days depending on inflow to the impoundment.

The lake has a drainage area of 10,176 km^2 which is characterized by rolling hills. Half of the land is forested, over one quarter is agricultural, and the remainder is urbanized. The drainage basin includes several major urban areas of the Central Piedmont including Winston-Salem, Salisbury, Lexington and High Point. High Rock Lake is classified WS-III from its headwaters to and including Town and Swearing Creeks. From there to the dam, the lake is classified WS-III and B.

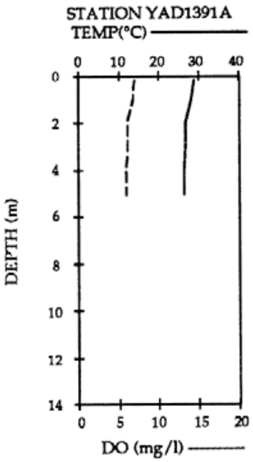
One major tributary is Abbotts Creek which gained the attention of DEM when mercury was discovered in the water and fish. Mercury entered the creek from a Duracell battery plant adjacent to the creek. Routine fish tissue analyses for mercury levels began in 1981. Although levels of mercury in fish tissue have declined overall, certain portions of the creek still contain high levels. Monitoring conducted in October of 1987 found that 18.5% of the fish collected had tissue concentrations of mercury above the FDA action level of 1.0 mg/kg. Largemouth bass is the species with the highest mercury levels. The State Health Director has issued an advisory limiting the consumption of fish taken from Abbotts Creek.

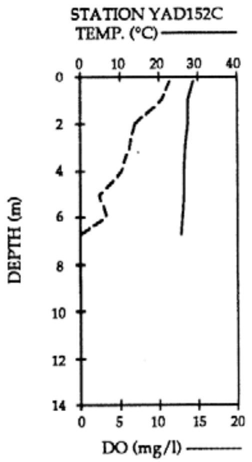
High Rock Lake was sampled by DEM on August 14, 1990. Oxygen levels were reduced towards the bottom of the water column except at YAD1391A where the lake is riverine. Nutrient and chlorophyll-a concentrations were elevated and water clarity was poor. A pronounced color gradation often exists near Potts Creek , a result of the incoming sediment load. Turbidity at the uppermost station (YAD1391A) was 32 NTU which is in violation of the state standard. Violations at this station are not unusual.

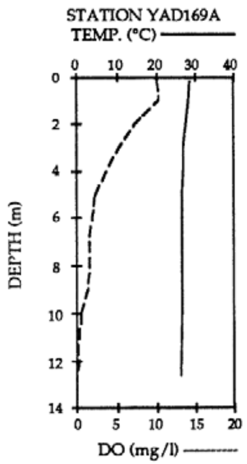
Populations of phytoplankton exceeding algal bloom levels were found at all stations sampled on High Rock Lake except YAD1391A, the station located furthest upstream. High flows and suspended solids inhibit the growth of phytoplankton at this station even in the presence of excessive levels of nutrients. The predominance of Anabaenopsis raciborskii and Oscillatoria geminata, small filamentous, blue-green algae, accounts for the particularly high estimates of phytoplanktonic density (85,596-110,053 units/ml) at three of the sampling stations. These species are commonly found in eutrophic waters throughout the state. Such elevated algal populations are cause for concern and could be reduced through watershed management.

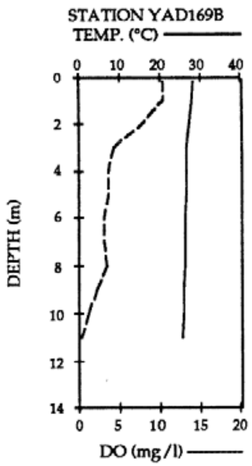
In 1990, the TSI was 3.3 which is indicative of a highly productive lake. This is similar to historical values.

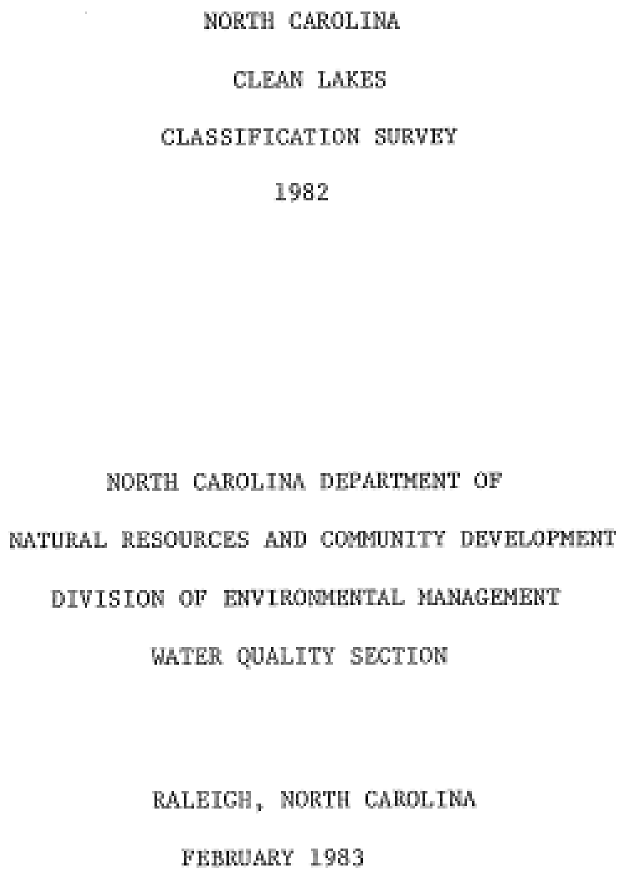
High Rock Lake remains one of the most eutrophic lakes in North Carolina. The mercury contamination in the Abbotts Creek arm of the lake has caused it to be classified as not supporting its designated use. Chlorophyll-a values have consistently exceeded the state water quality standard of 40 µg/l, and blue-green algal blooms are common. Clearly, the situation at High Rock Lake warrants ongoing monitoring and management strategies to improve water quality.











NORTH CAROLINA

CLEAN LAKES

CLASSIFICATION SURVEY

1982

NORTH CAROLINA DEPARTMENT OF

NATURAL RESOURCES AND COMMUNITY DEVELOPMENT

DIVISION OF ENVIRONMENTAL MANAGEMENT

WATER QUALITY SECTION

RALEIGH, NORTH CAROLINA

FEBRUARY 1983

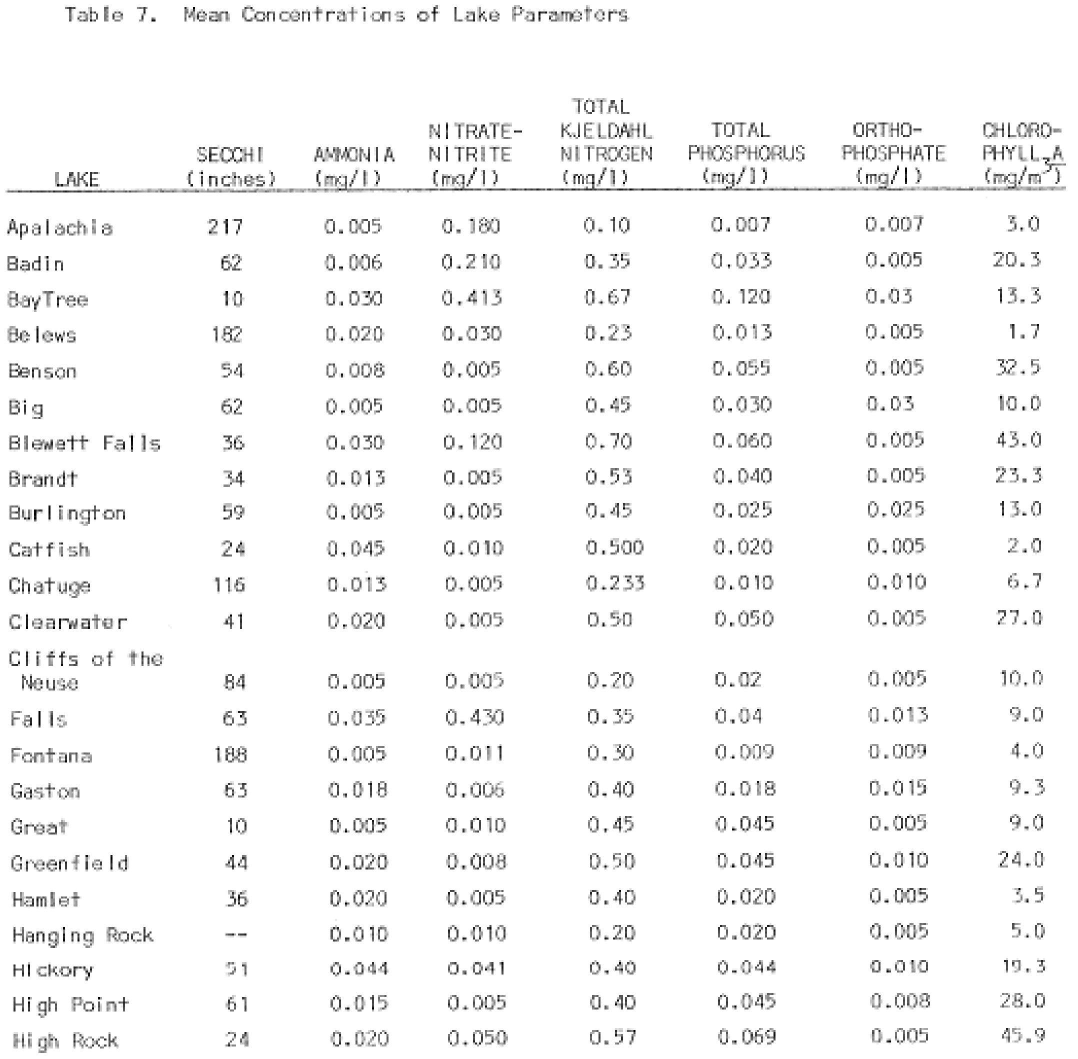


Table 7. Mean Concentrations of Lake Parameters

LAKE	SECCHI (inches)	AMMONIA (mg/l)	NITRATE-NITRITE (mg/l)	TOTAL KJELDAHL NITROGEN (mg/l)	TOTAL PHOSPHORUS (mg/l)	ORTHO-PHOSPHATE (mg/l)	CHLORO-PHYLL A (mg/m^3)
Apalachia	217	0.005	0.180	0.10	0.007	0.007	3.0
Badin	62	0.006	0.210	0.35	0.033	0.005	20.3
BayTree	10	0.030	0.413	0.67	0.120	0.03	13.3
Belews	182	0.020	0.030	0.23	0.013	0.005	1.7
Benson	54	0.008	0.005	0.60	0.055	0.005	32.5
Big	62	0.005	0.005	0.45	0.030	0.03	10.0
Blewett Falls	36	0.030	0.120	0.70	0.060	0.005	43.0
Brandt	34	0.013	0.005	0.53	0.040	0.005	23.3
Burlington	59	0.005	0.005	0.45	0.025	0.025	13.0
Catfish	24	0.045	0.010	0.500	0.020	0.005	2.0
Chatuge	116	0.013	0.005	0.233	0.010	0.010	6.7
Clearwater	41	0.020	0.005	0.50	0.050	0.005	27.0
Cliffs of the Neuse	84	0.005	0.005	0.20	0.02	0.005	10.0
Falls	63	0.035	0.430	0.35	0.04	0.013	9.0
Fontana	188	0.005	0.011	0.30	0.009	0.009	4.0
Gaston	63	0.018	0.006	0.40	0.018	0.015	9.3
Great	10	0.005	0.010	0.45	0.045	0.005	9.0
Greenfield	44	0.020	0.008	0.50	0.045	0.010	24.0
Hamlet	36	0.020	0.005	0.40	0.020	0.005	3.5
Hanging Rock	--	0.010	0.010	0.20	0.020	0.005	5.0
Hickory	51	0.044	0.041	0.40	0.044	0.010	19.3
High Point	61	0.015	0.005	0.40	0.045	0.008	28.0
High Rock	24	0.020	0.050	0.57	0.069	0.005	45.9

Table 21. Comparison of Weiss and Kuenzler (1976) Lake Trophic Classification with the Clean Lakes Survey Trophic Classification

LAKE TYPE AND NAME	WEISS AND KUENZLER TROPHIC CLASS	*CLEAN LAKES SURVEY TROPHIC CLASS
Natural Lakes		
Black	4 (α - Eutrophic)	5
Jones	2 (Oligo-Meso)	1
Mattamuskeet	4 (α - Eutrophic)	3
Phelps	3 (Mesotrophic)	1
Salters	2 (Oligo-Meso)	3
Singletary	3 (Mesotrophic)	3
Waccamaw	3 (Mesotrophic)	3
White	2 (Oligo-Meso)	1
Impoundments		
Belews	2 (Oligo-Meso)	1
High Point	4 (α - Eutrophic)	4
Wheeler	4 (α - Eutrophic)	
Brandt	4 (α - Eutrophic)	
Burlington	4 (α - Eutrophic)	
Lexington-Thomasville	5 (β - Eutrophic)	
Gaston	3 (Mesotrophic)	
Roanoke Rapids	2 (Oligo-Meso)	
W. Kerr Scott	2 (Oligo-Meso)	
High Rock	5 (β - Eutrophic)	
Badin	3 (Mesotrophic)	
Tillery	3 (Mesotrophic)	
Blewett Falls	3 (Mesotrophic)	
James	2 (Oligo-Meso)	
Rhodhiss	3 (Mesotrophic)	
Hickory	3 (Mesotrophic)	
Lookout Shoals	3 (Mesotrophic)	
Norman	2 (Oligo-Meso)	
Mountain Island	2 (Oligo-Meso)	
Wylie	3 (Mesotrophic)	
Lure	2 (Oligo-Meso)	
Chatuge	1 (Oligo-Meso)	[illegible]
Hiwasee	1 (Oligotrophic)	1
Nantahala	1 (Oligotrophic)	1
Santeetlah	1 (Oligotrophic)	1
Fontana	1 (Oligotrophic)	1
Old Mill Ponds		
John's Pond	6 (Hyper-Eutrophic)	6

*Clean Lakes Survey trophic groups range from 1 (least eutrophic) to 6 (most eutrophic).

Table 15. Trophic Classification of EPA National Eutrophication Survey Data from Discriminant Analysis.
(Lake classification is according to trophic groups defined by total phosphorus, total organic nitrogen, secchi depth, and chlorophyll a).

Lake Name	Present Clean Lakes Survey Classification *	Classification of 1973 NES Data
Badin	4	3
Blewett Falls	5	5
Fontana	1	2
Hickory	4	3
High Rock	5	4

Table 14. Trophic Classification of Sampling Stations
(Lake stations are ranked in downstream order.)

LAKE	STATION	TROPHIC GROUP*	
		1981	1982
Apalachia	HIW011A	1	-
	HIW011C	1	-
	HIW012	1	-
Badin	YAD178B	4	4
	YAD178E	3	4
	YAD178F	4	4
	YAD178F1	4	4
Bay Tree	CPF155G	5	-
	CPF155I	5	-
High Point	CPF089E2	4	5
	CPF089E4	4	4
High Rock	YAD1391A	5	5
	YAD152A	5	5
	YAD152C	5	5
	YAD156A	5	5
	YAD169A	5	5
	YAD169B	5	5
	YAD169E	5	5

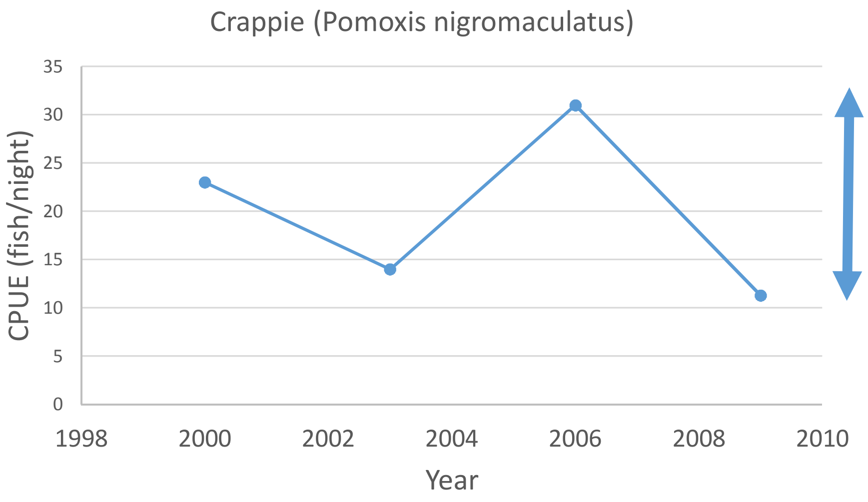
Fishery quality indicators
High Rock Lake

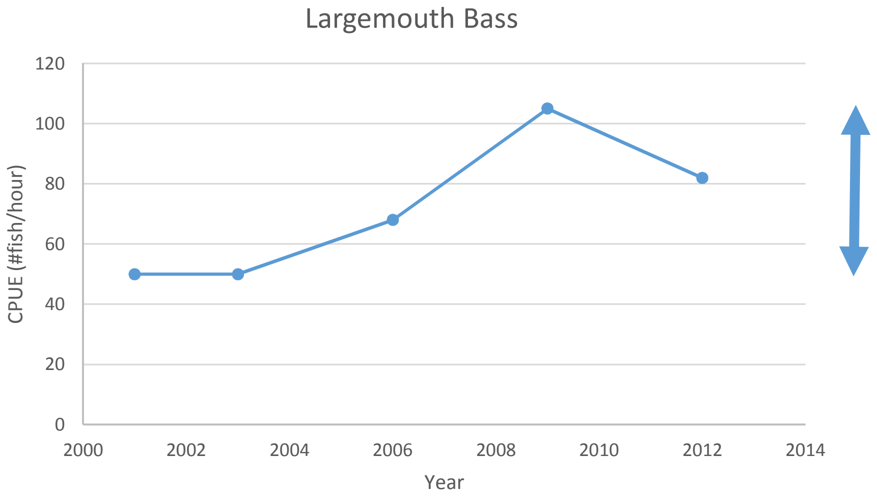
Marcelo Ardón

East Carolina University

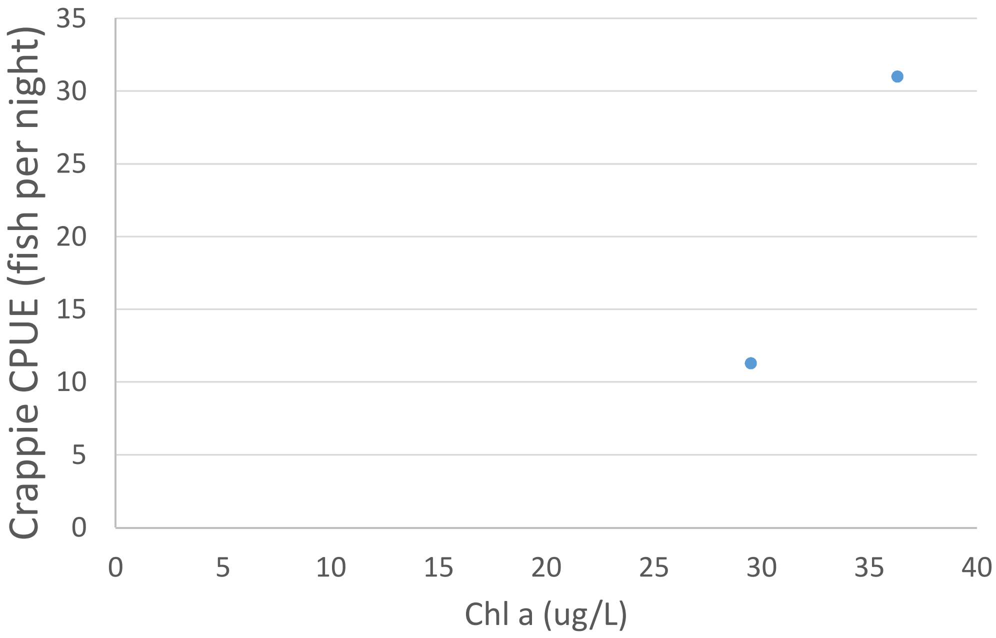
NC Wildlife Resources commission surveys

- Fisheries are healthy and some of the best in the state
- Use available data as baseline ranges





Is there a relationship between chl a and fisheries quality?



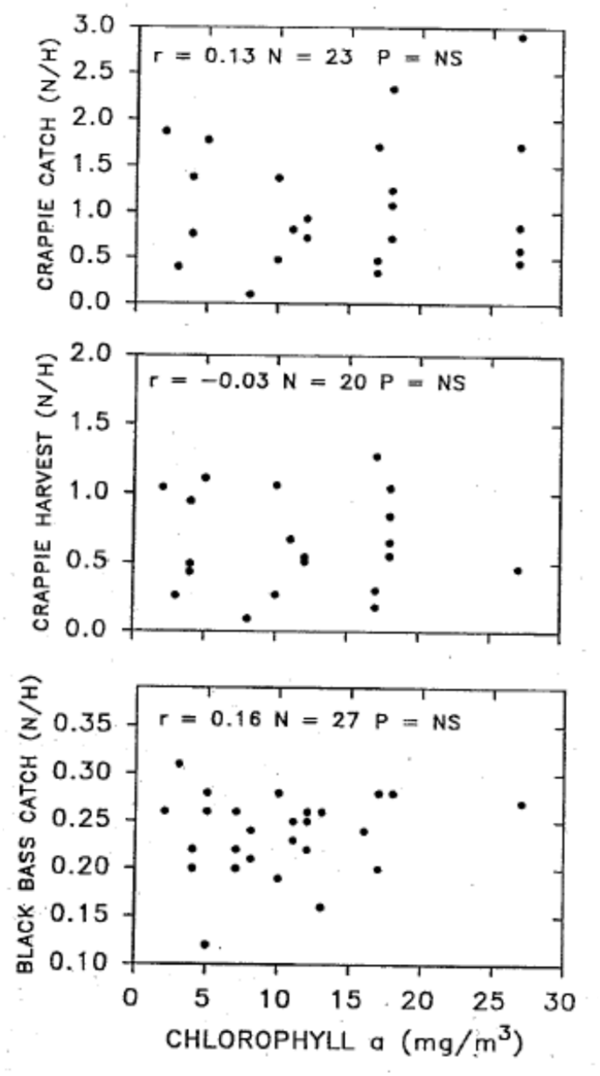
Better coordination between agencies

Alabama and Georgia

- 32 reservoirs
- Recommend chl a concentration 10-15 ug/L
- Balance between fish harvest and water clarity

- Bayne et al. 1994, Maceina et al. 1996

- HRL avg chl a = 17 to 45 ug/L



- Ney 1996
- Virginia, Arkansas, Nevada
- TP less than 40 ug/L fisheries decline
- Suggest that TP higher than 100 ug/L fisheries decline
- TP at HRL ranged from 60 to 180 ug/L

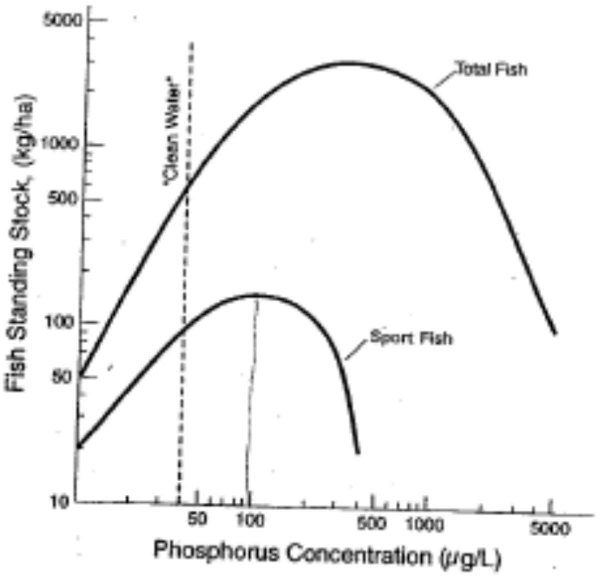
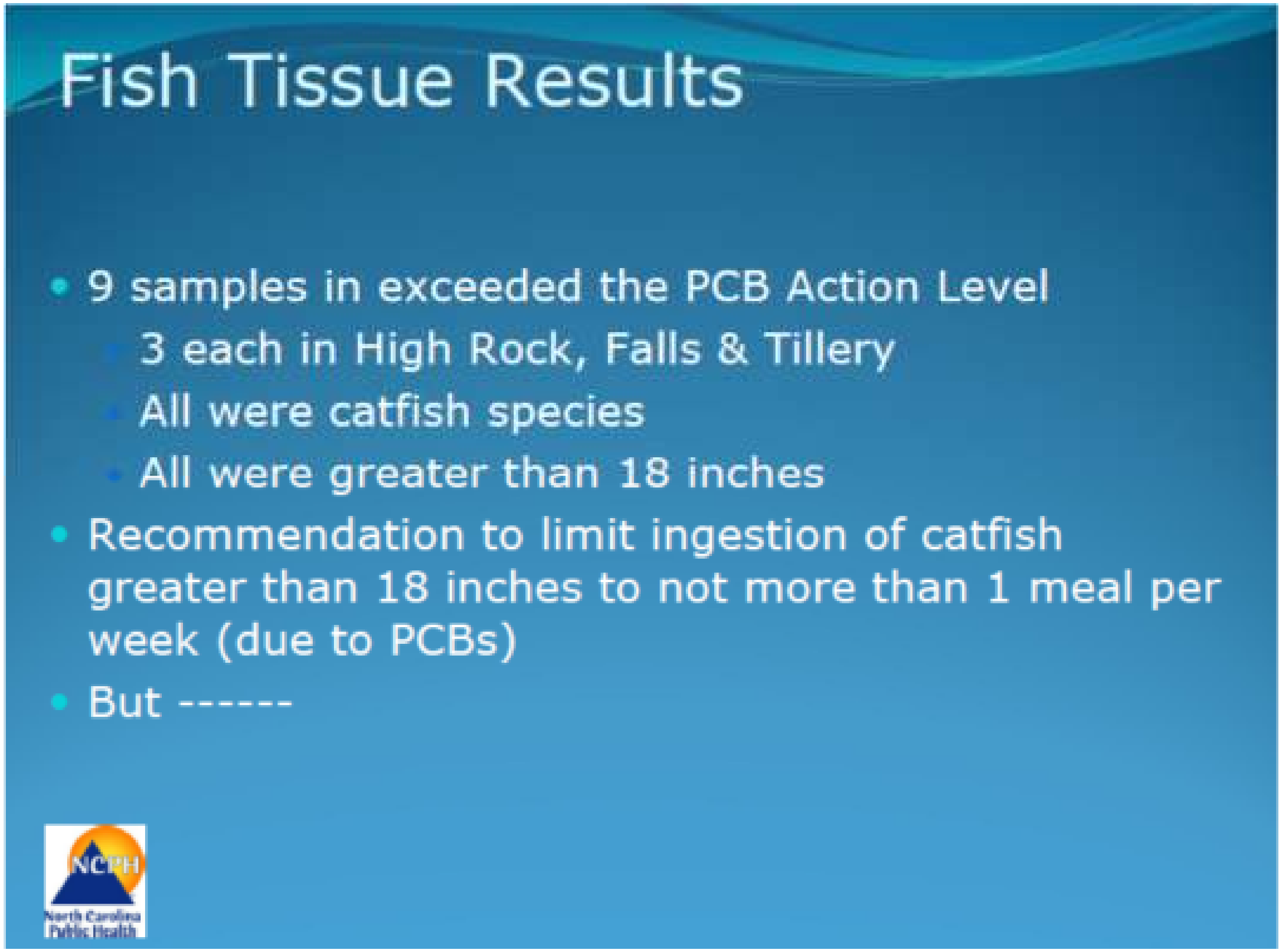


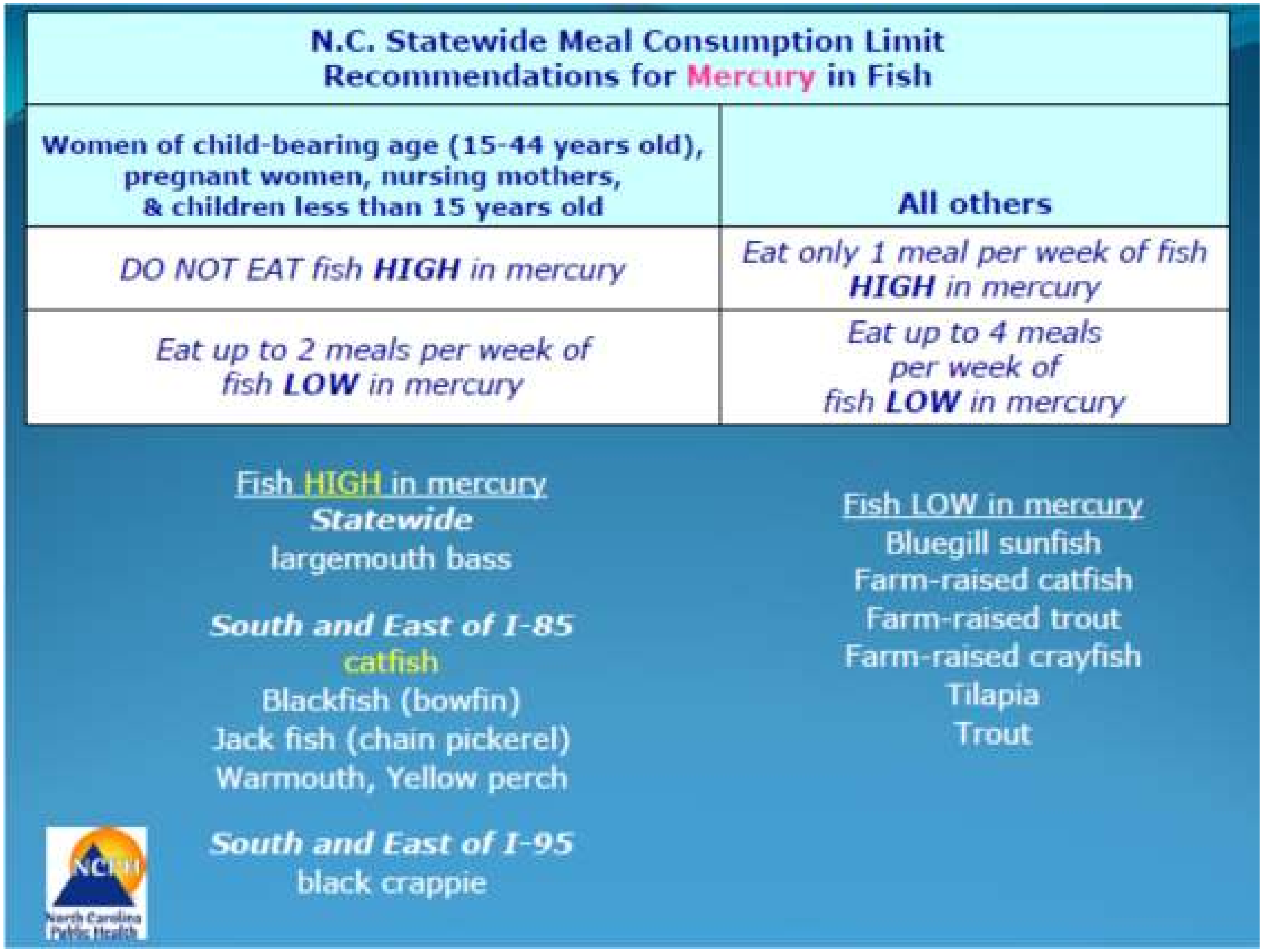
FIGURE 3.—Generalized relation of total and sport fish standing stock to total phosphorus concentration and trophic status in temperate-latitude reservoirs. Standing stock values are representative of southeastern U.S. reservoirs to 100 μg/L total phosphorus. Standing stocks at higher phosphorus concentrations are hypothetical.

- Fish kills only occurred once since Mr. Dorsey has been working there
- Refuges in the river (Thompson et al. 2007)
- Lack of fish kills is not necessary evidence of good conditions



Fish Tissue Results

- 9 samples in exceeded the PCB Action Level
  - 3 each in High Rock, Falls & Tillery
  - All were catfish species
  - All were greater than 18 inches
- Recommendation to limit ingestion of catfish greater than 18 inches to not more than 1 meal per week (due to PCBs)
- But ------



N.C. Statewide Meal Consumption Limit Recommendations for Mercury in Fish

Women of child-bearing age (15-44 years old), pregnant women, nursing mothers, & children less than 15 years old	All others
*DO NOT EAT fish **HIGH** in mercury*	*Eat only 1 meal per week of fish **HIGH** in mercury*
*Eat up to 2 meals per week of fish **LOW** in mercury*	*Eat up to 4 meals per week of fish **LOW** in mercury*

Fish HIGH in mercury

Statewide

largemouth bass

South and East of I-85

catfish

Blackfish (bowfin)

Jack fish (chain pickerel)

Warmouth, Yellow perch

South and East of I-95

black crappie

Fish LOW in mercury

Bluegill sunfish

Farm-raised catfish

Farm-raised trout

Farm-raised crayfish

Tilapia

Trout

Department of Environmental Quality

Division of Water Resources - Basin Planning Branch

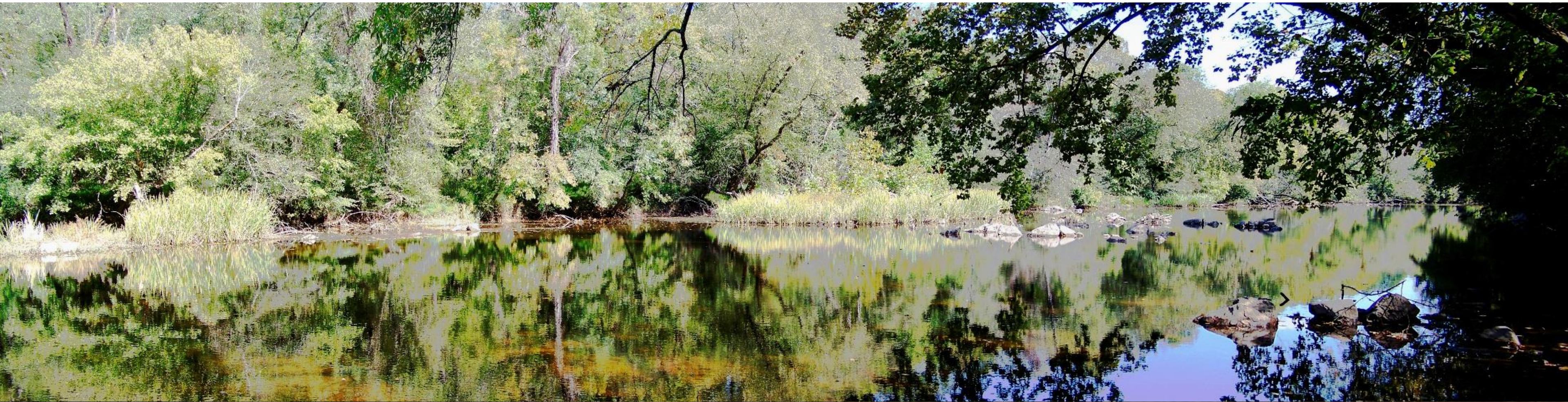
Nora Deamer - Cape Fear River Planner

Nutrient Criteria Development Plan
River/Stream Water Body Type

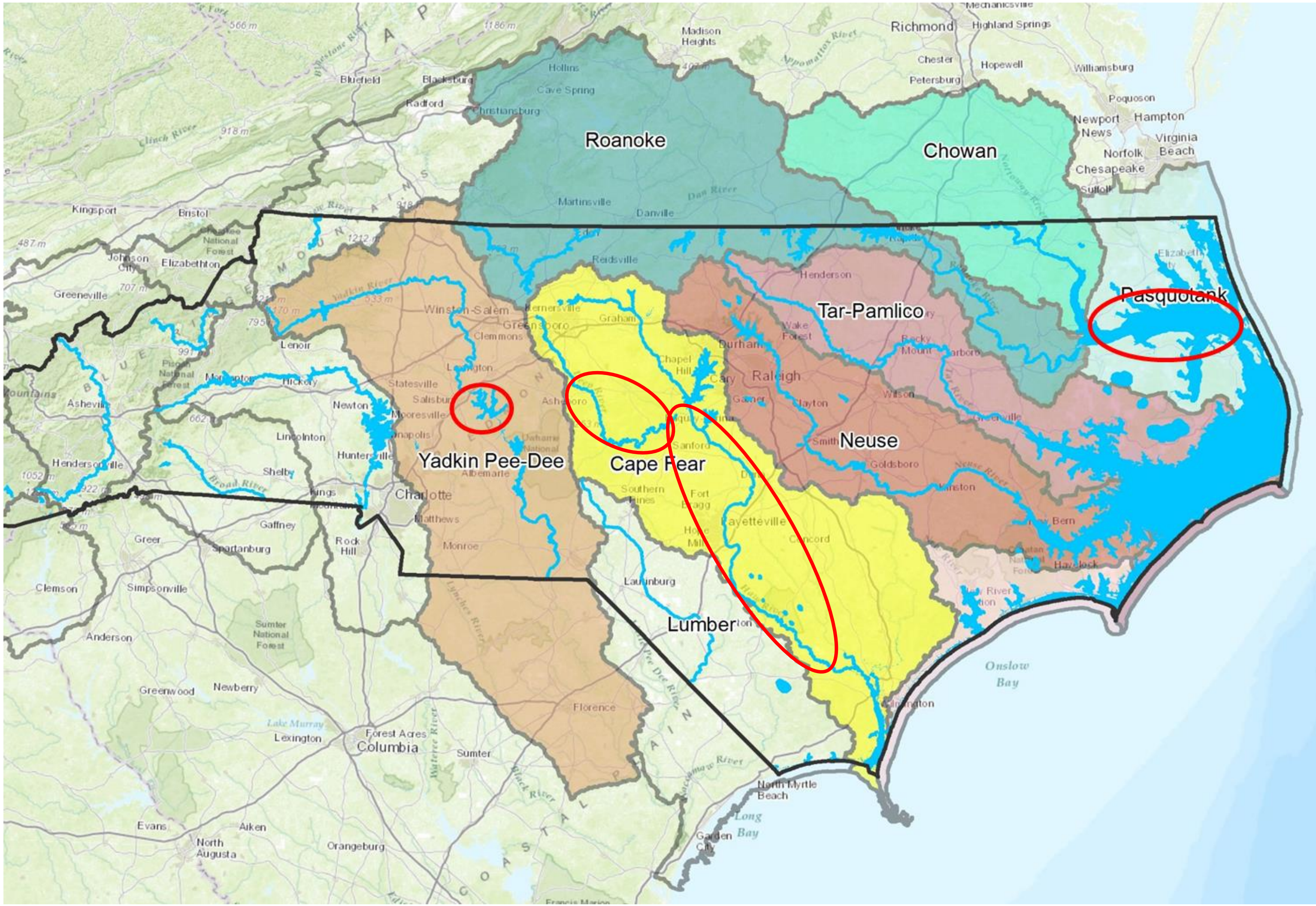
~

Central Cape Fear River

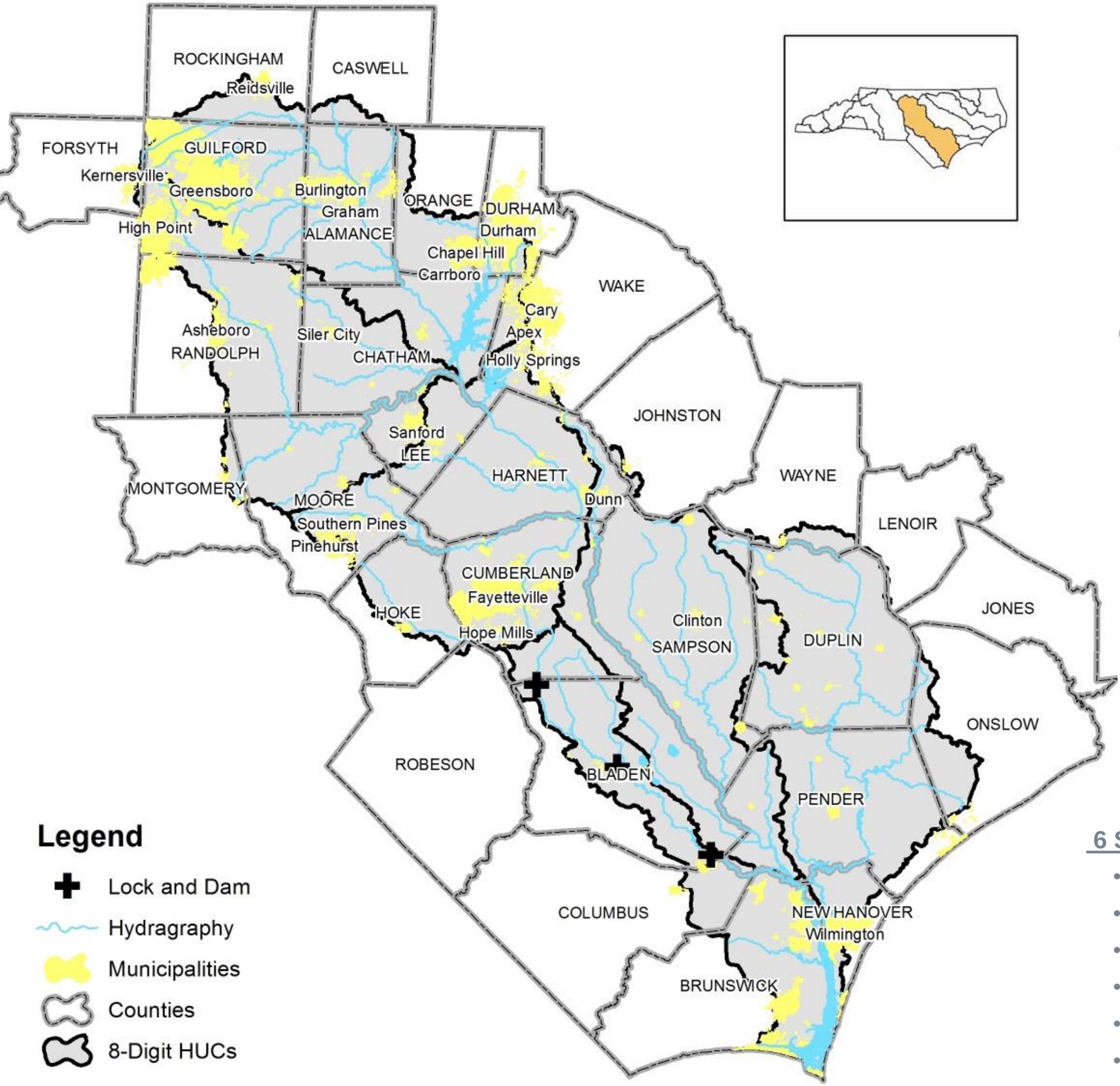
April 20, 2016

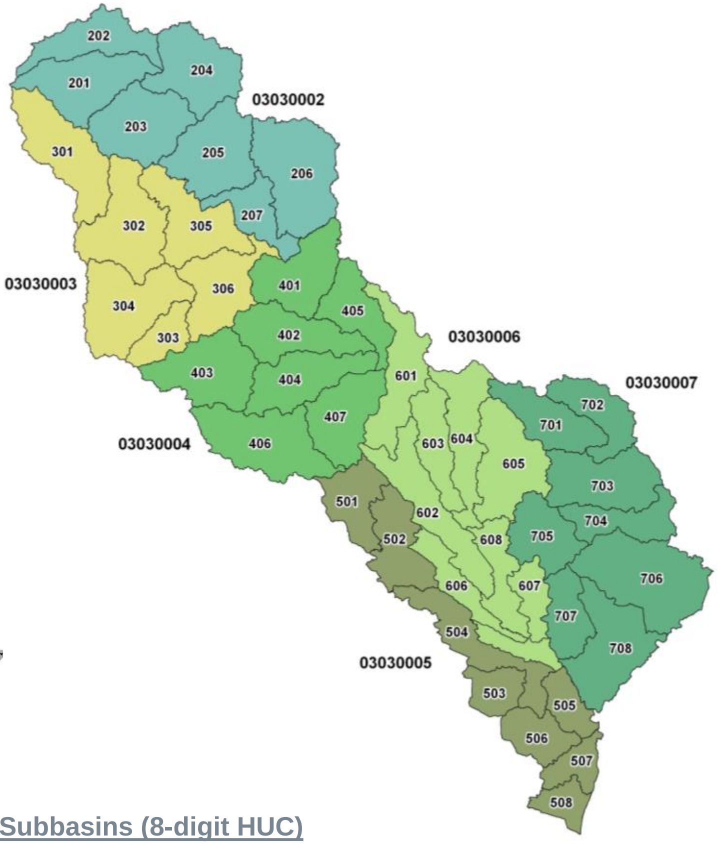


Nutrient Criteria Development Planning Process



Cape Fear River Basin





6 Subbasins (8-digit HUC)

- 03030002 – Haw River
- 03030003 – Deep River
- 03030004 – Upper Cape Fear
- 03030005 – Lower Cape Fear
- 03030006 – Black River
- 03030007 – Northeast Cape Fear

Existing Cape Fear Basin Management Strategies

- Jordan Lake Watershed
- Randleman Lake Watershed
- Water Supply Watersheds
- Proposed Swamp Waters Reclassification in CFR Estuary.
- Shellfish Waters
- Primary Nursery Area

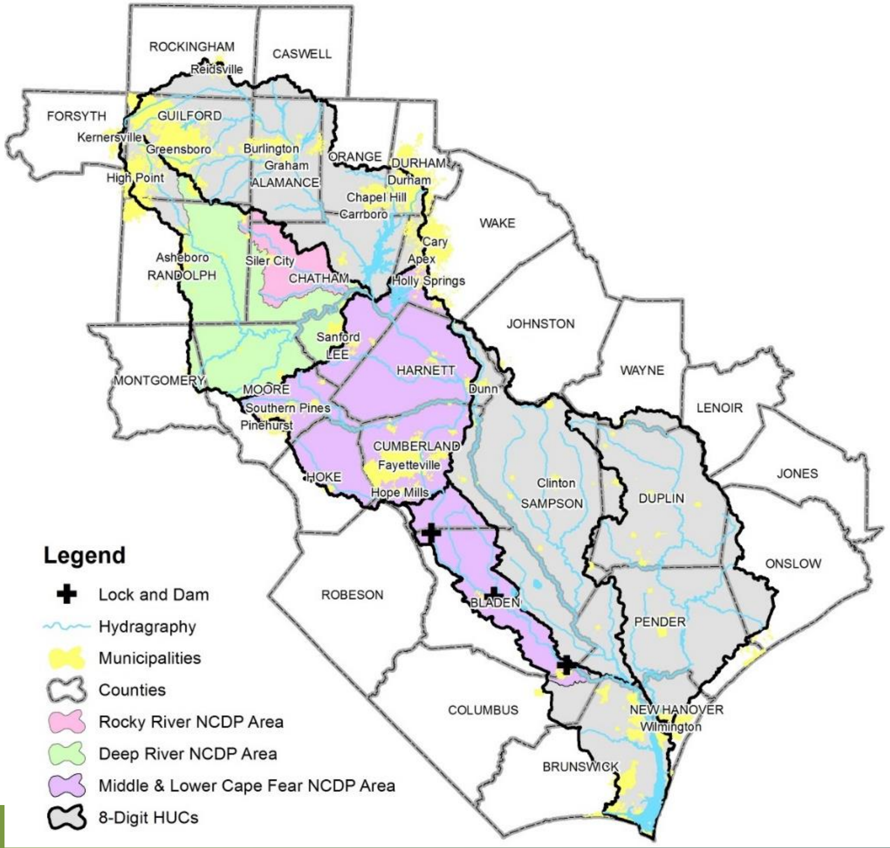
Central Cape Fear River NCDP Area

NCDP Area covers part of

- 03030002 – Haw River
- 03030003 – Deep River
- 03030004 – Upper Cape Fear
- 03030005 – Lower Cape Fear

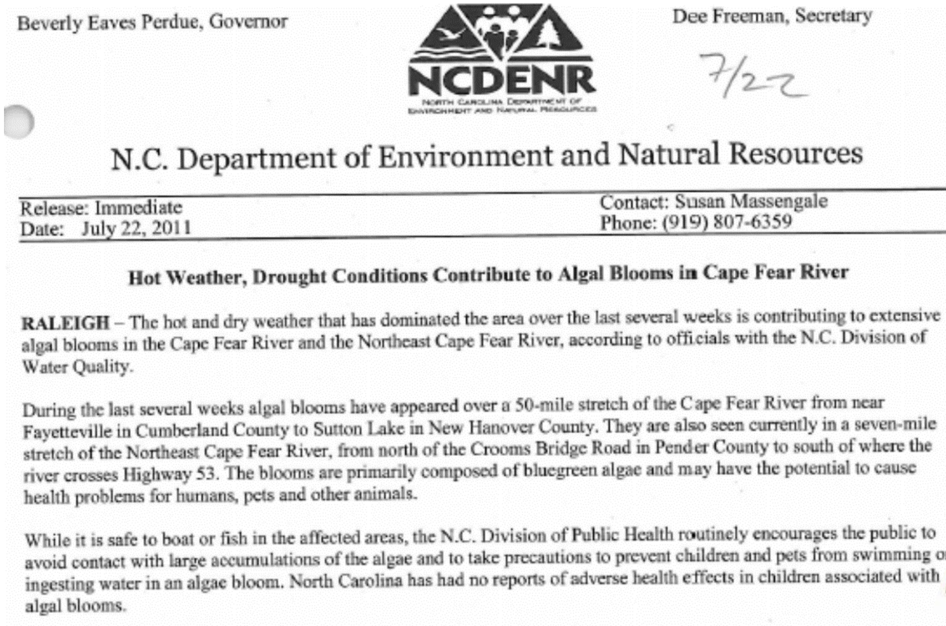
Why Central Cape Fear River was chosen?

- The central portion of the Cape Fear River was chose as the riverine/stream system to focus on for the development of nutrient criteria for this waterbody type.



- ❖ The central portion of the Cape Fear River basin contains approximately 6,050 miles of rivers and streams and is defined from below the B Everett Jordan Reservoir dam along the Haw River, and below the Randleman Lake dam along the Deep River to Lock and Dam #1.

Why the Central Cape Fear River????



Beverly Eaves Perdue, Governor

NCDENR
North Carolina Department of Environment and Natural Resources

Dee Freeman, Secretary

7/22

N.C. Department of Environment and Natural Resources

Release: Immediate
Date: July 22, 2011

Contact: Susan Massengale
Phone: (919) 807-6359

Hot Weather, Drought Conditions Contribute to Algal Blooms in Cape Fear River

RALEIGH – The hot and dry weather that has dominated the area over the last several weeks is contributing to extensive algal blooms in the Cape Fear River and the Northeast Cape Fear River, according to officials with the N.C. Division of Water Quality.

During the last several weeks algal blooms have appeared over a 50-mile stretch of the Cape Fear River from near Fayetteville in Cumberland County to Sutton Lake in New Hanover County. They are also seen currently in a seven-mile stretch of the Northeast Cape Fear River, from north of the Crooms Bridge Road in Pender County to south of where the river crosses Highway 53. The blooms are primarily composed of bluegreen algae and may have the potential to cause health problems for humans, pets and other animals.

While it is safe to boat or fish in the affected areas, the N.C. Division of Public Health routinely encourages the public to avoid contact with large accumulations of the algae and to take precautions to prevent children and pets from swimming or ingesting water in an algae bloom. North Carolina has had no reports of adverse health effects in children associated with algal blooms.

Toxic blue-green algae found in Cape Fear River

Posted: Aug 05, 2014 11:37 PM EDT
Updated: Aug 09, 2014 11:37 PM EDT

Looking north from Lock and Dam #1. (Source: WECT)

Looking south Lock and Dam #1. (Source: WECT)

City of Toledo releases preliminary report on water crisis

BLADEN COUNTY, NC (WECT) - The same type of toxic algae that caused the City of Toledo, Ohio to ban residents from using its water has been found in the Cape Fear River, north of New Hanover and Brunswick County water intake sites.

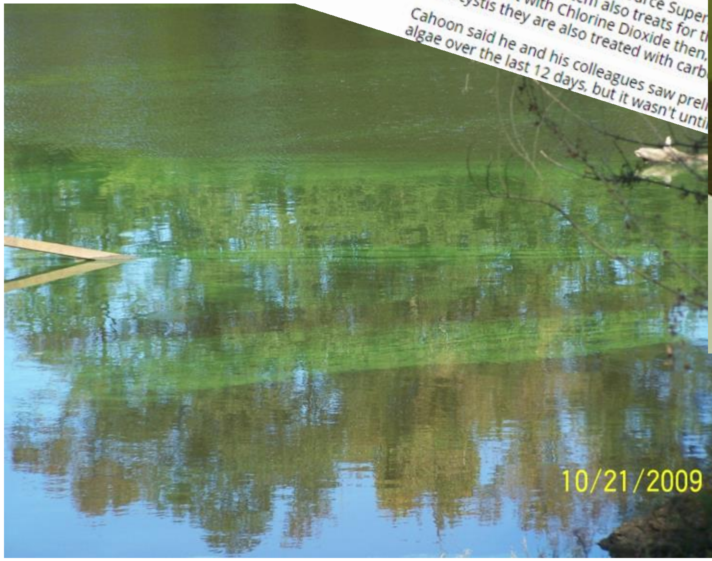
UNC Wilmington Biology Professor Larry Cahoon was alerted of a bloom of microcystis, the same blue-green algae that polluted Toledo's water supply, north of the Lock and Dam #1 on the Cape Fear River.

Both New Hanover and northern Brunswick Counties have water intake systems in the affected area, but CFPUA spokesperson Mike McGill said their water supply is not at risk because of their advanced water treatment system.

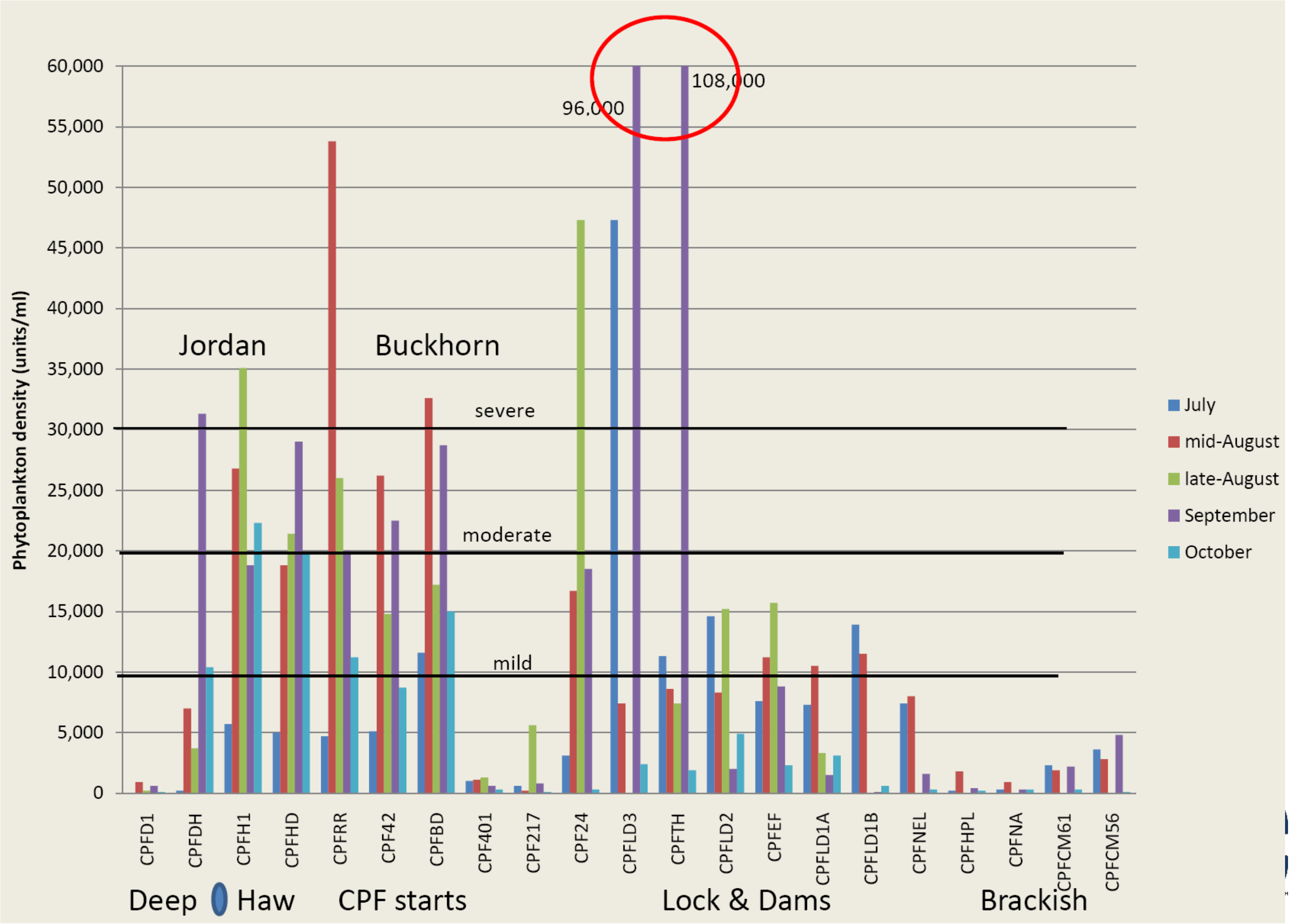
"We have an advanced filtration system that includes o-zo
biologically active carbon filters that actually kill th
remove it from our system," McGill explain

Glenn Walker the Water Resource Super
County said their system also treats for t
are initially hit with Chlorine Dioxide then,
microcystis they are also treated with carb

Cahoon said he and his colleagues saw prel
algae over the last 12 days, but it wasn't unti



WSS Cape Fear Special Study – 2010 Algal Densities

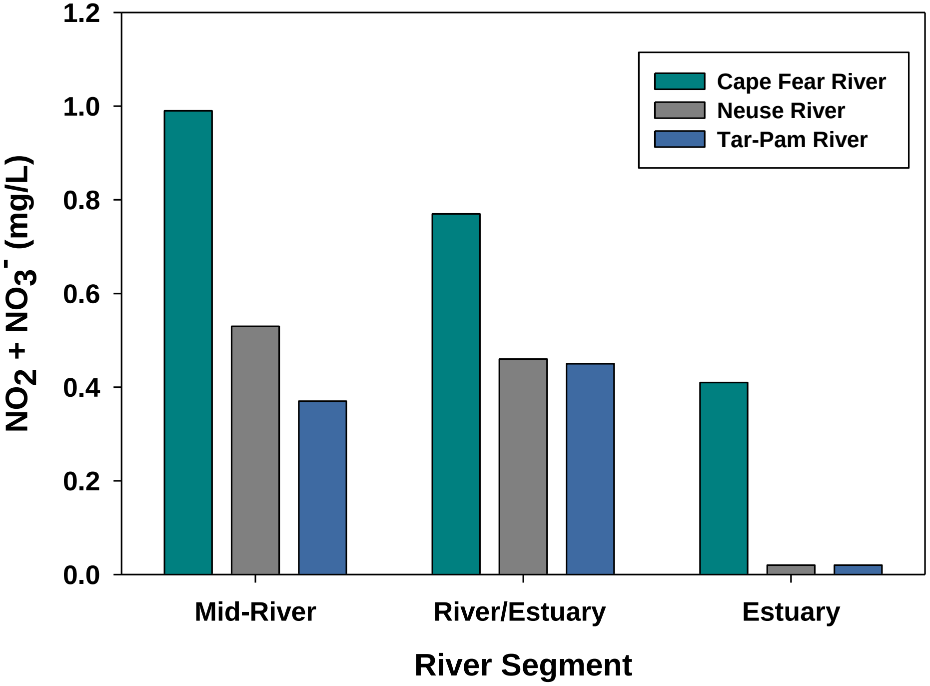


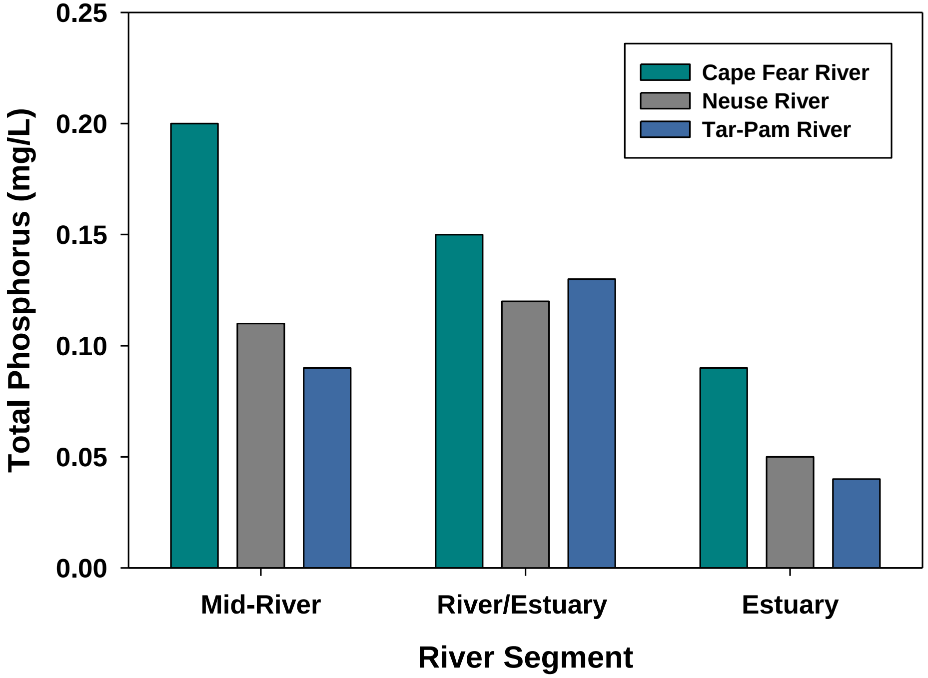
High Cape Fear River Basin Instream Nutrient Concentrations

50th Percentile for 5 yr assessment period

Cape Fear -2008-2012
Neuse - 2008-2012
Tar-Pam - 2008-2012

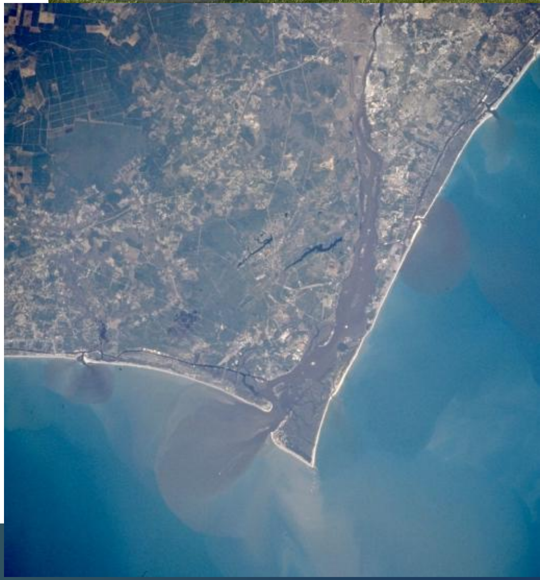
Station #	**Station Location**
Mid-River	
B8320000	CFR at Elizabethtown (above L&D #2)
J6150000	NR at Kinston
O6240000	Tar R. at Greenville
River/Estuary	
B8360000	CFR at East Arcadia (below L&D #1)
J7930000	NR at Streets Ferry
O6500000	Tar-R. at Grimesland
Estuary (SC waters)	
B9800000	CRF Estuary at Wilmington
J9530000	NR Estuary at Minnesott Beach
O865000N	Pamlico R. at Gum Point N. shore





Cape Fear River Basin Issues

- Nutrient over enrichment
- Algal blooms (some toxic)
- Taste and odor problems in drinking water due to algal blooms
- NPDES permits with minimal nutrient limitations
- Agriculture – CAFO’s (Swine & Poultry) and Cropland
- Increasing BOD loading to the Estuary
- Low DO in the Estuary
- High turbidity/light limited system

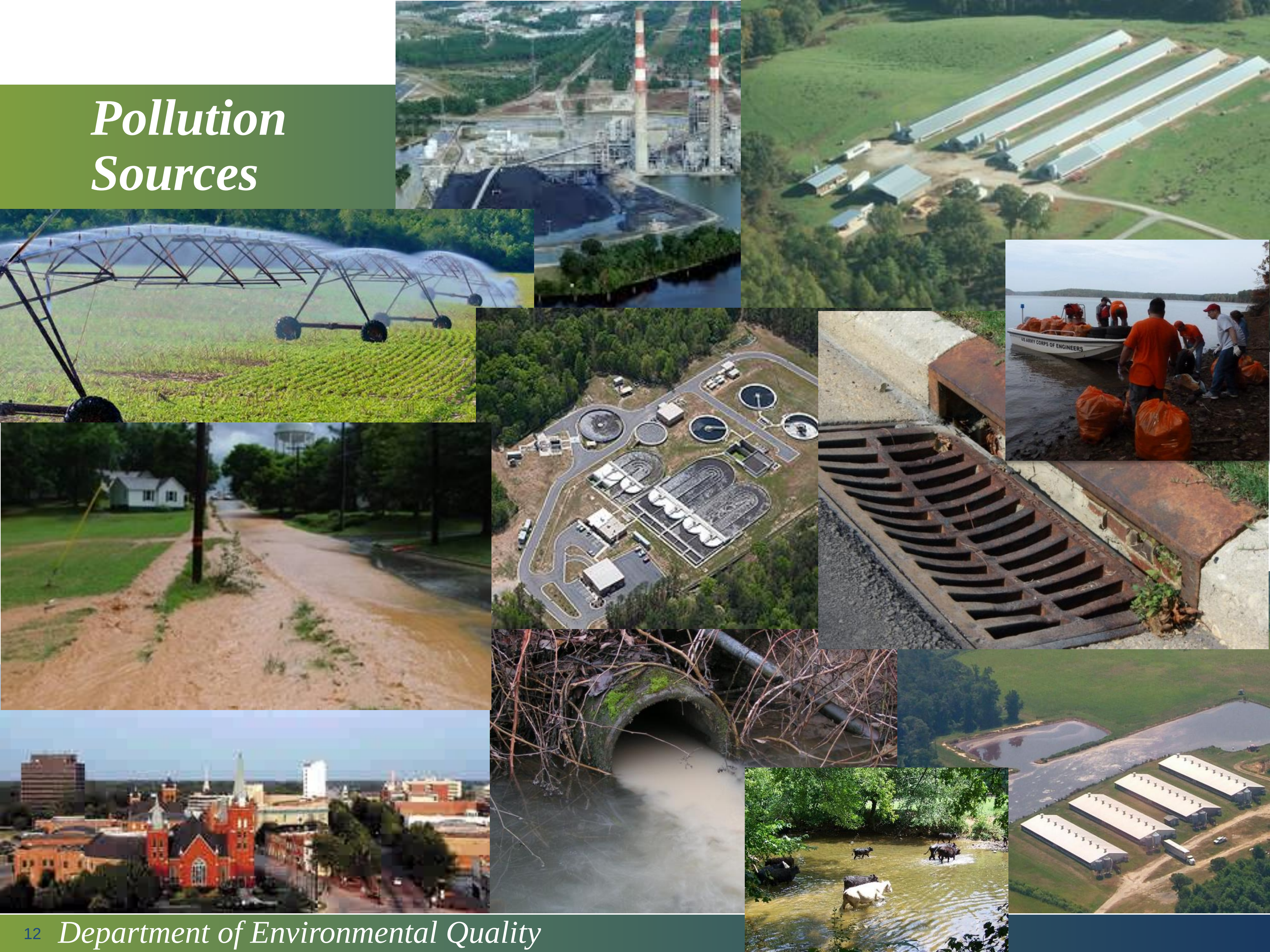


Cape Fear River Basin Issues

- Complex/dynamic hydrologic system
- Increasing water withdrawal demands due to growing populations projections and agricultural needs

- Decreasing 7Q10 flows
- Minimal buffer requirements
- State and Federal threatened and endangered species
- Fish passage issues due to dams throughout the riverine system

Pollution Sources



Central Cape Fear River NCDP Steps

Goal is to adopt appropriate nutrient criteria by December 2021

- Collect additional ambient data to support modeling efforts
- Select appropriate nutrient responses models
- Develop and run models
- Review model results
- Develop final nutrient criteria for Central Cape Fear River segment

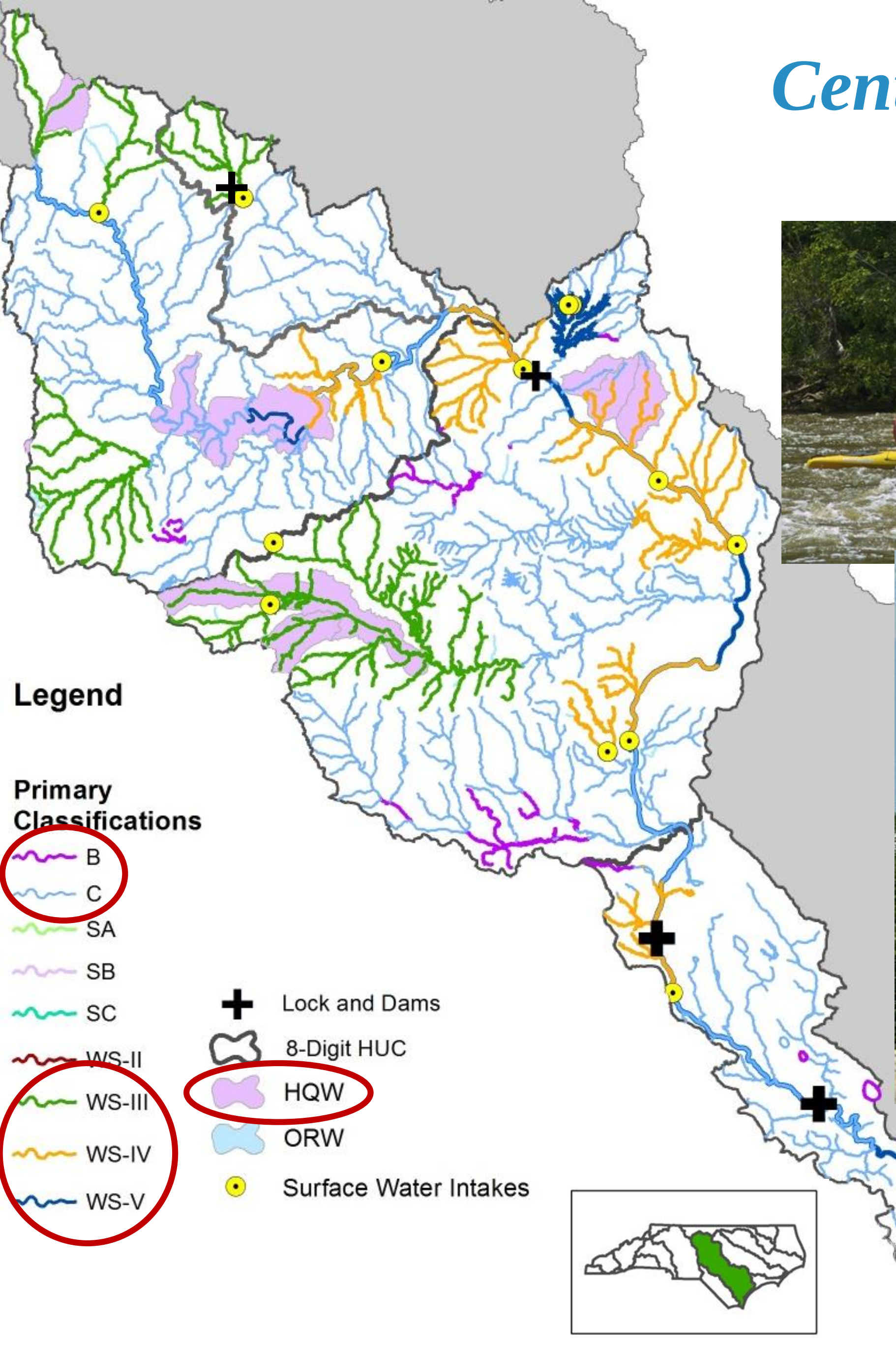
Stream Classifications and Use Protections

Designated uses are bases on stream classifications

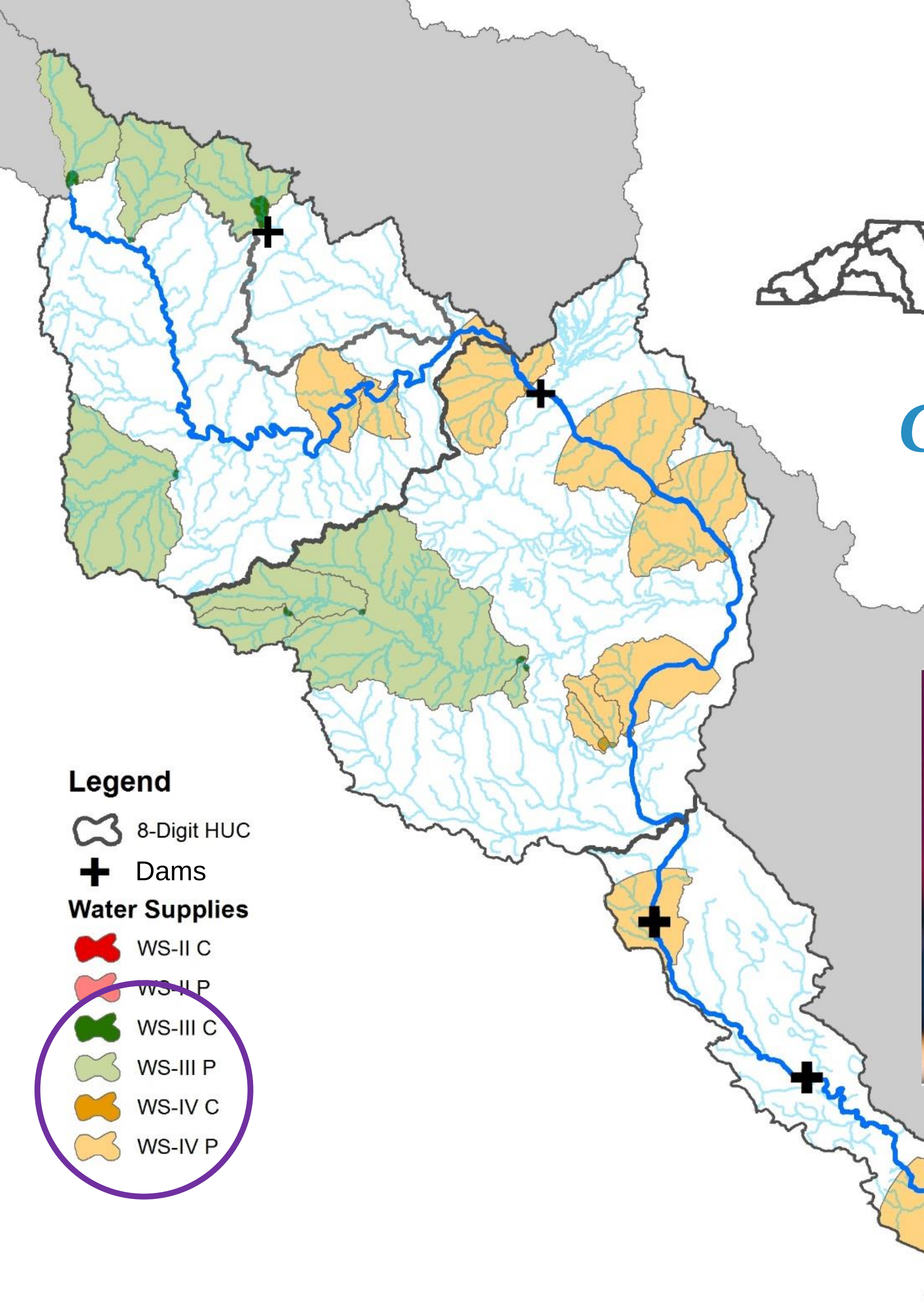
- Class **C** – Protection and propagation of aquatic life; Fish consumption; Secondary recreation (fishing and boating)
- Class **B** – Protection for primary recreation (swimming)
- Class **WS** – Water Supply (I, II, **III**, **IV**, **V**)
- Supplemental (NSW, ORW, **HQW**, TR, SA, PNA)

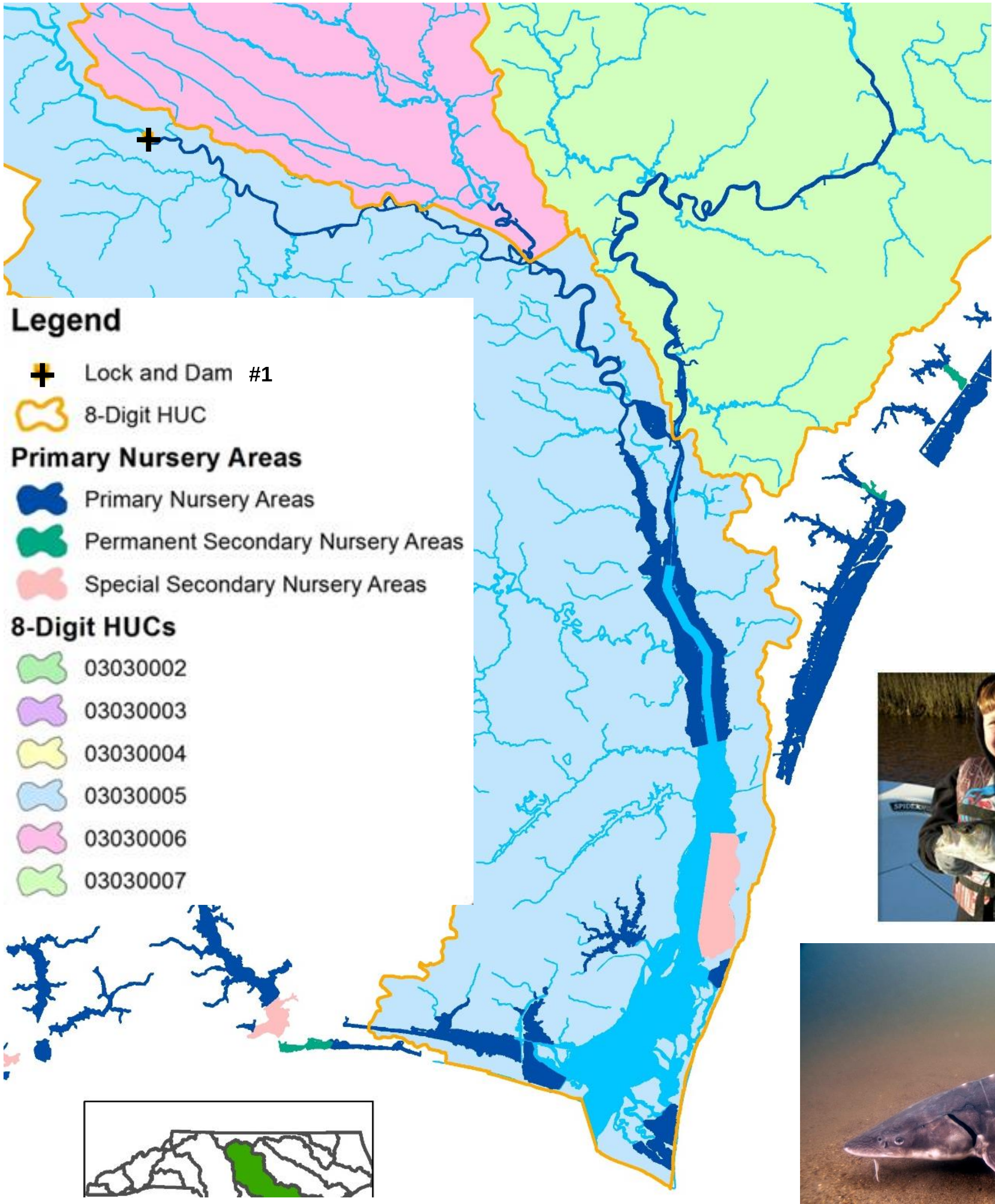
Stream classifications in blue are in the central portion of the Cape Fear River.

Central Cape Fear River Basin Stream Classifications

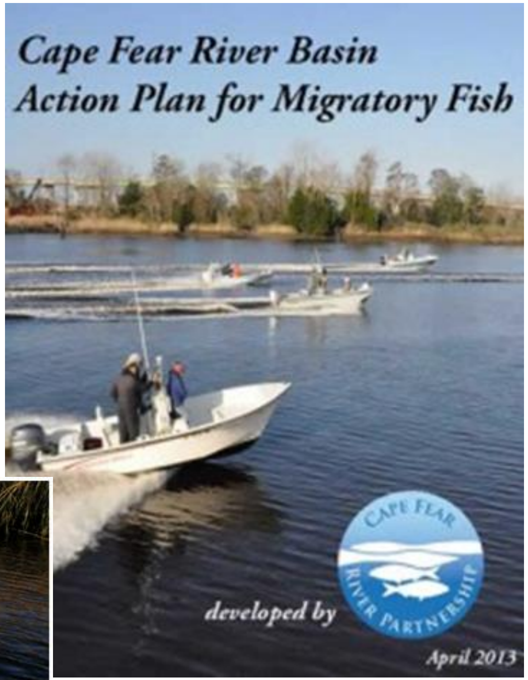


Central Cape Fear River Basin Water Supply Watersheds





Cape Fear River Basin Primary Nursery Area



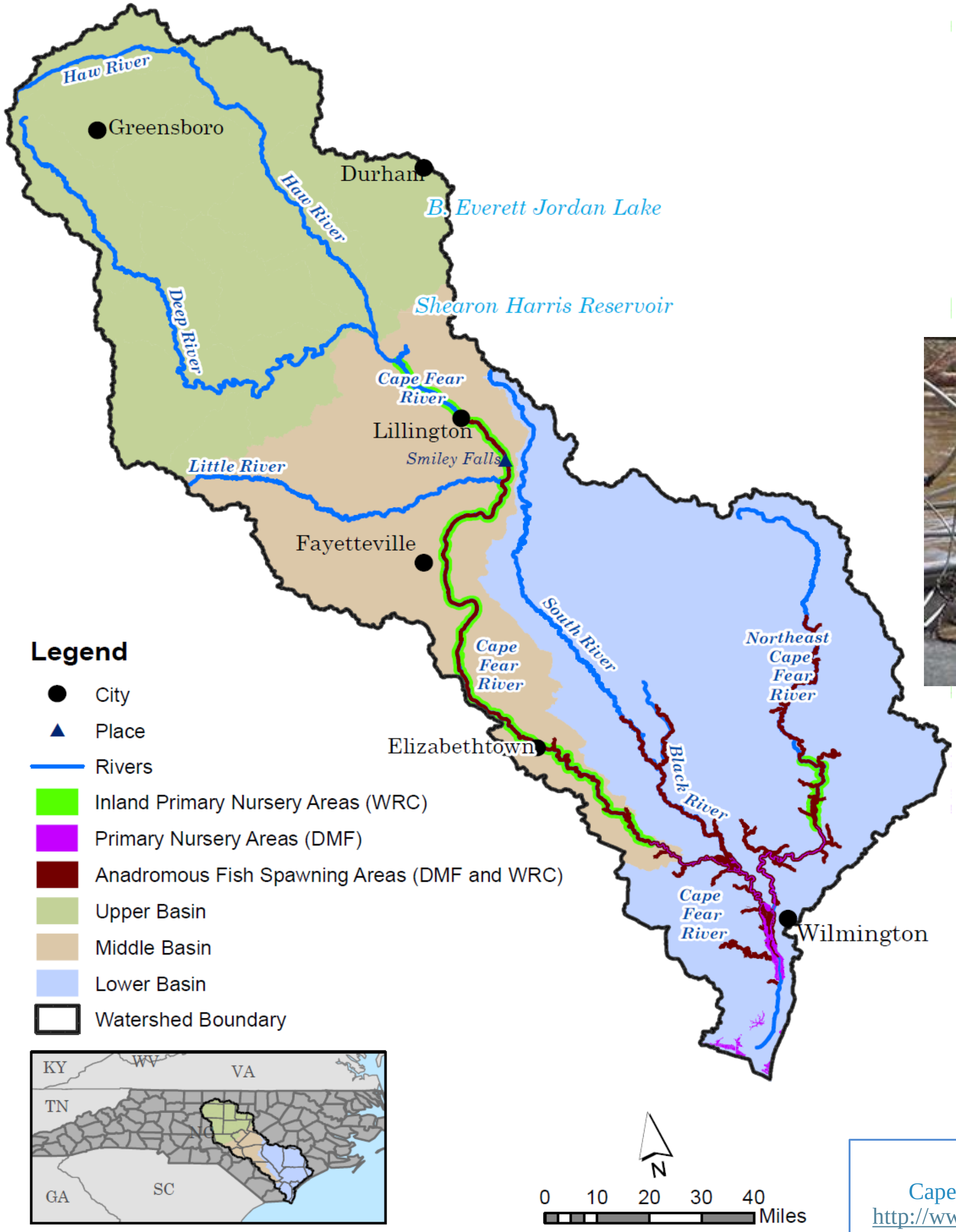
Cape Fear River Basin
Action Plan for Migratory Fish

developed by

CAPE FEAR RIVER PARTNERSHIP

April 2013

Cape Fear River Basin Anadromous Fish Spawning Areas and Primary Nursery Area

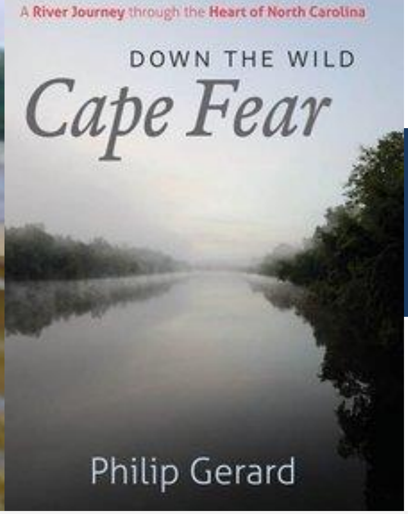


Map from Cape Fear River Partnership
Cape Fear River Basin Action Plan for Migratory Fish.
http://www.habitat.noaa.gov/protection/capefear/pdf/CapeFearActionPlan.pdf

Cape Fear River Lock & Dam # 1 ~ Fish Passage

Completed in 2013

Instream Uses –
Primary and Secondary Recreation



A River Journey through the Heart of North Carolina

DOWN THE WILD

Cape Fear

Philip Gerard

CAPE FEAR TACKLE

Aquatic Life Protections - Including propagation and survival

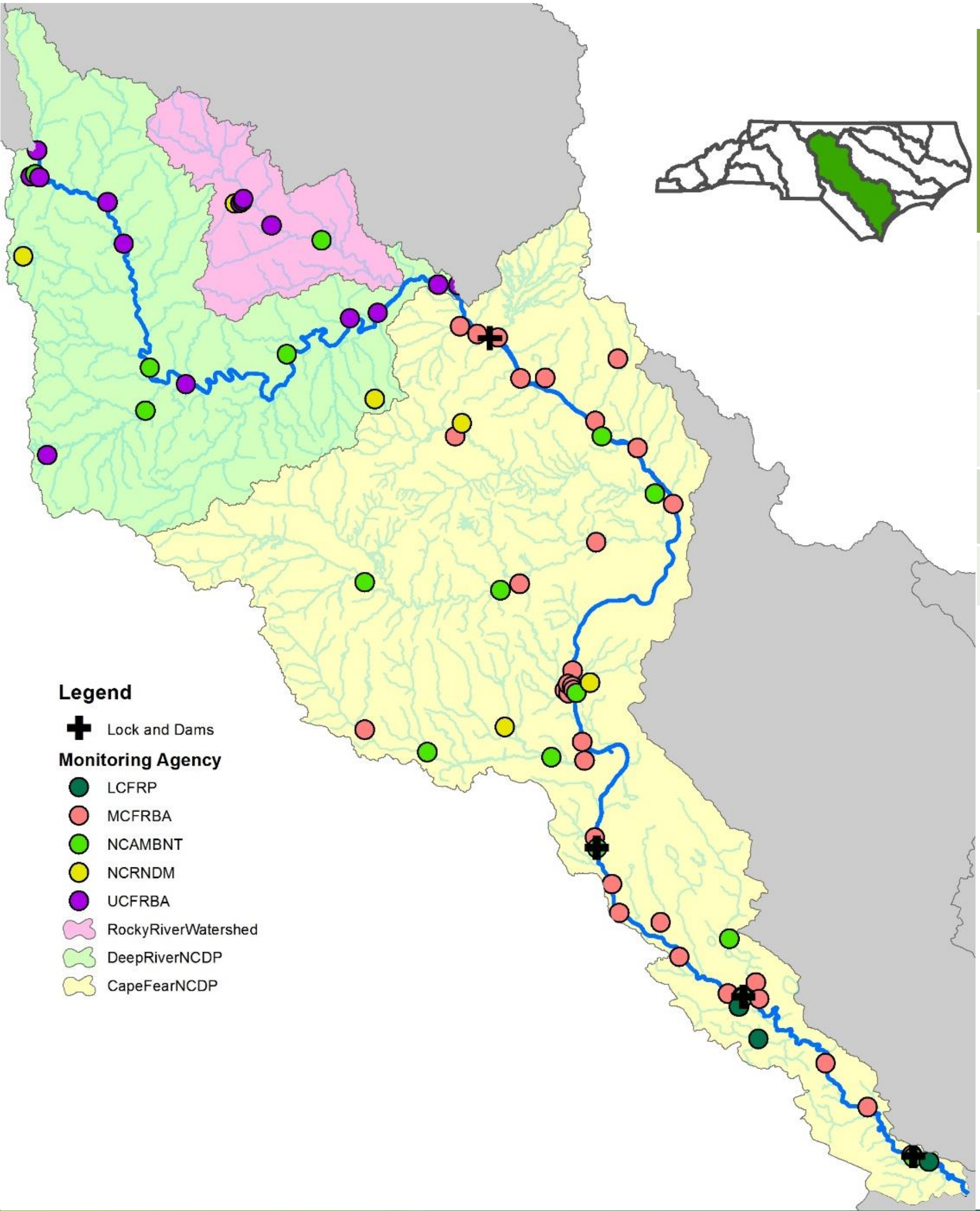
Instream Uses – Water Supply

Cape Fear
Public Utility Authority

Instream Uses

Data Collected/Available

Cape Fear River Basin
Ambient Monitoring Programs



Collection Program	Number of Stations	
	Whole Basin	NCDP Area
Division of Water Resources	59	**18**
Voluntary Monitoring Coalitions		
Upper CFR Basin Association	40	**13**
Middle CF Basin Association	32	**32**
Lower CFR Program	31	**2**

NCDP Segment	Number of Stations
Deep and Rocky	**19**
Cape Fear River	**46**
Total	**65**

Ambient Monitoring System Station Summaries

NCDENR, Division of Water Resources
Basinwide Assessment Report

Location: CAPE FEAR RIV ABOVE LOCK AND DAM 1 NR EAST ARCADIA

Station #: B8349000 **Hydrologic Unit Code:** 03030005

Latitude: 34.40693 **Longitude:** -78.29508 **Stream class:** WS-IV CA

Agency: MCFRBA **NC stream index:** 18-(58.5)

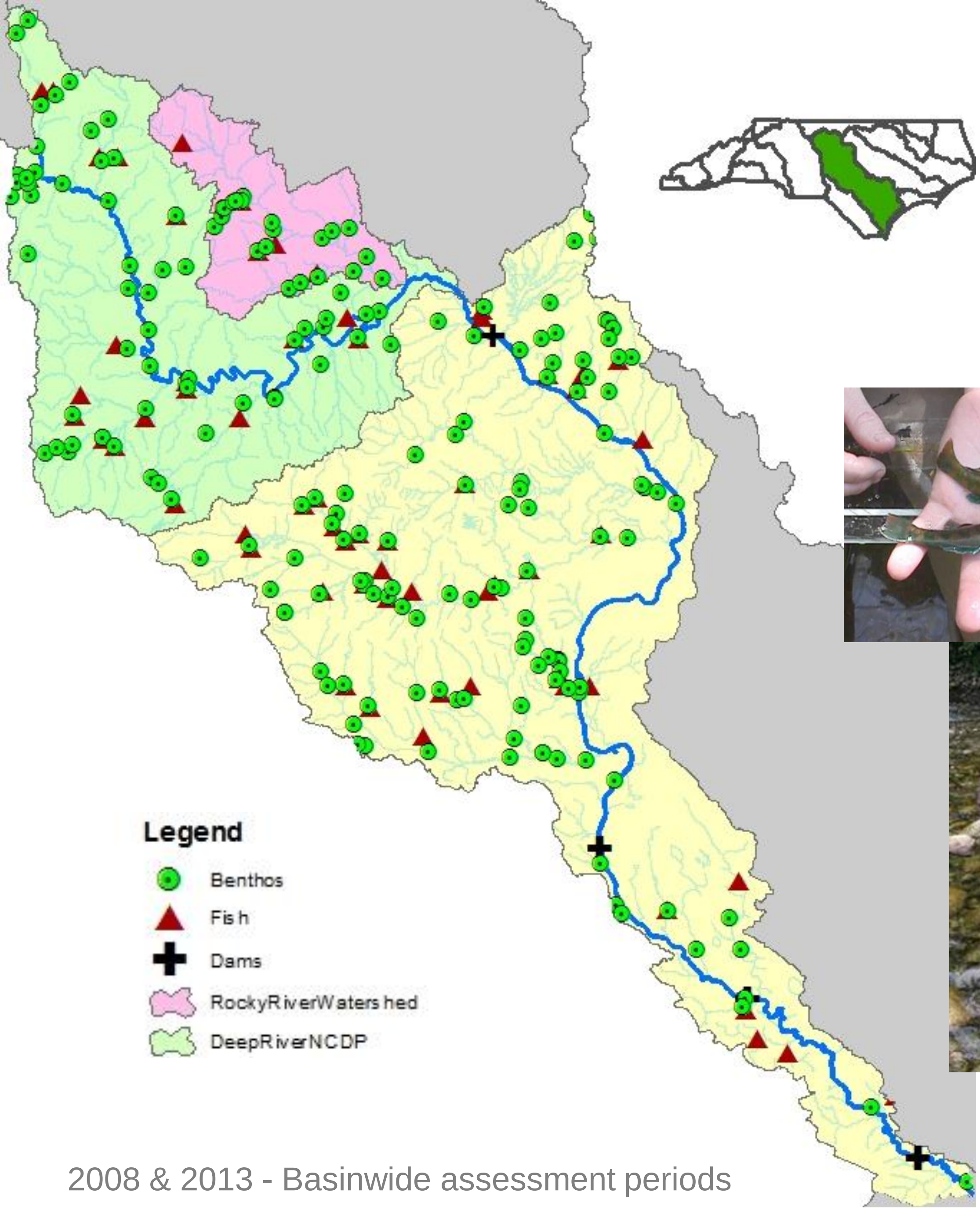
Time period: 01/14/2008 to 12/10/2012

	# results	# ND	EL	Results not meeting EL			Percentiles						
				#	%	%Conf	Min	10th	25th	50th	75th	90th	Max
Field													
D.O. (mg/L)	85	0	<4	1	1.2		3.2	5.1	6.1	7.1	9.1	11	15.8
	85	0	<5	7	8.2		3.2	5.1	6.1	7.1	9.1	11	15.8
pH (SU)	85	0	<6	6	7.1		5.7	6	6.3	6.7	6.9	7	9.2
	85	0	>9	1	1.2		5.7	6	6.3	6.7	6.9	7	9.2
Spec. conductance (umhos/cm at 25°C)	85	0	N/A				55	92	113	136	150	171	213
Water Temperature (°C)	85	0	>32	2	2.4		3.6	9.1	14	23.7	29	30.6	33.6
Other													
Chlorophyll a (ug/L)	60	2	>40	1	1.7		1	2	2	5	12	31	44
TSS (mg/L)	60	0	N/A				3	5	6	8	13	23.6	137
Turbidity (NTU)	60	0	>50	1	1.7		3.4	5.8	7	9.9	14.9	27.8	60.6
Nutrients (mg/L)													
NH3 as N	60	22	N/A				0.02	0.02	0.02	0.03	0.06	0.1	0.14
NO2 + NO3 as N	60	2	>10	0	0		0.02	0.48	0.63	0.81	1	1.33	1.85
TKN as N	60	3	N/A				0.2	0.34	0.51	0.67	0.9	1.04	3.27
Total Phosphorus	54	0	N/A				0.04	0.09	0.11	0.14	0.2	0.27	0.37

Fecal Coliform Screening(#/100mL)

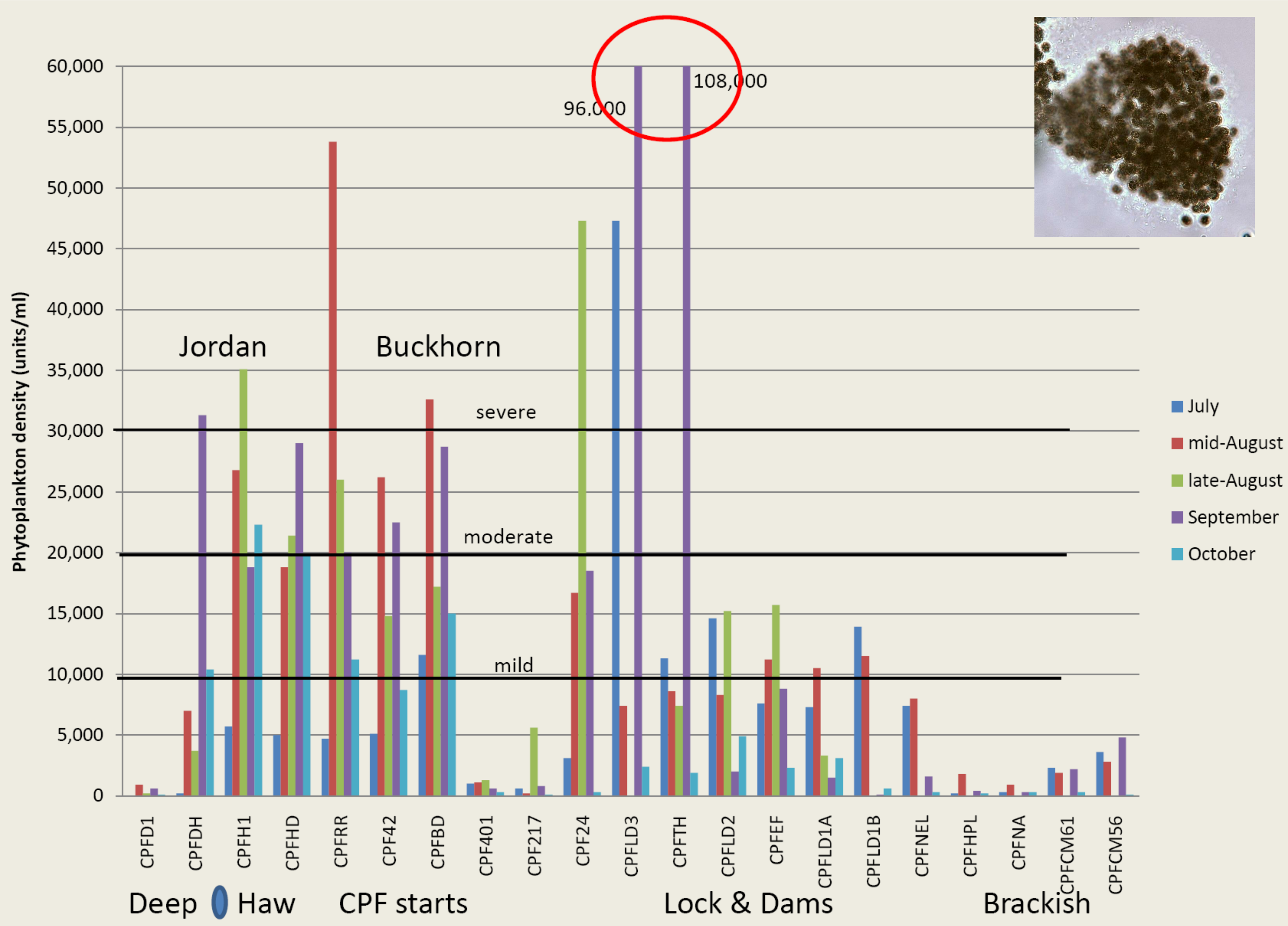
# results:	Geomean:	# > 400:	% > 400:	%Conf:
60	33.1	2	3.3	

Central Cape Fear River Basin Biological Monitoring

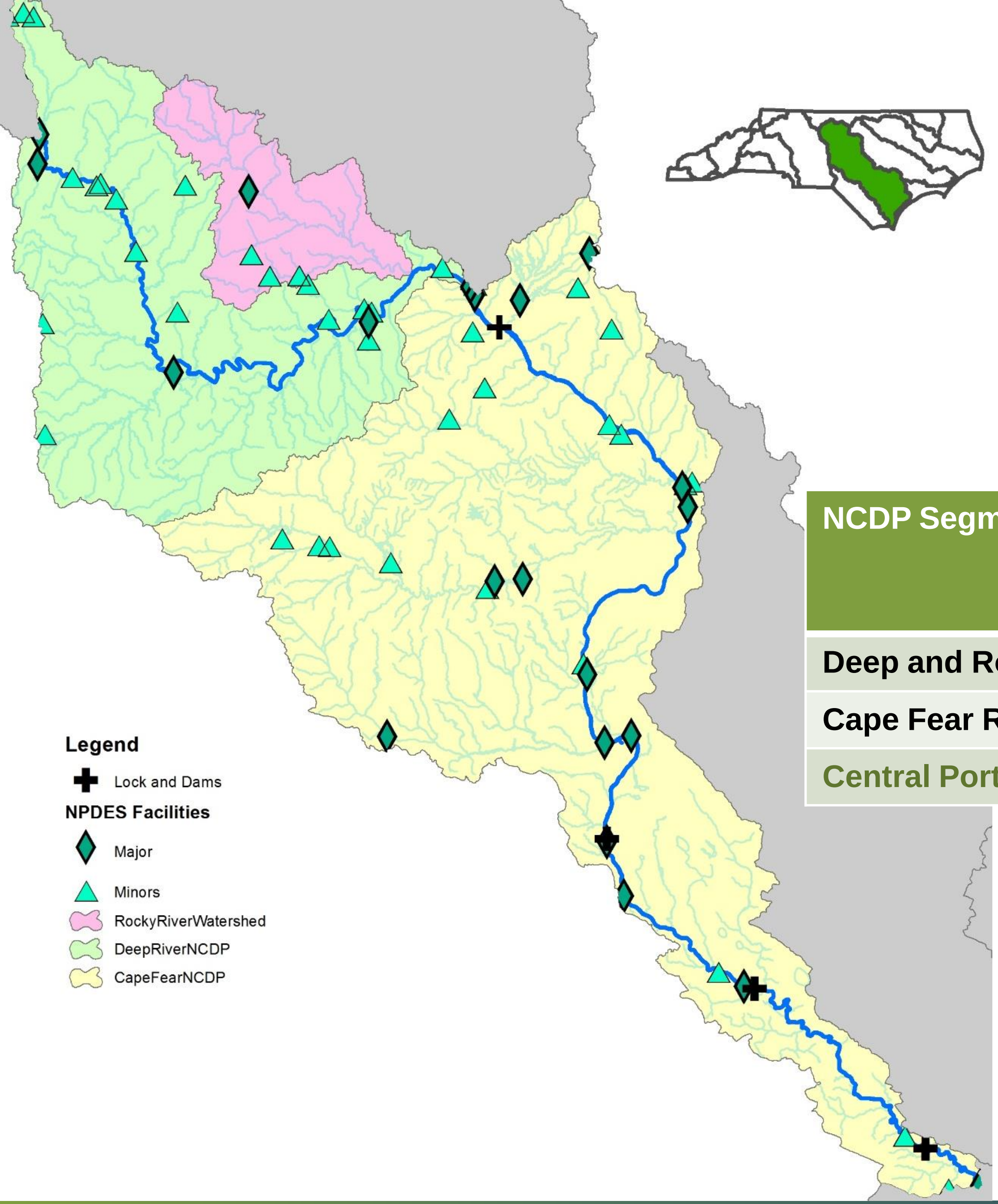


2008 & 2013 - Basinwide assessment periods

WSS Cape Fear Special Study – 2010 Algal Densities



Dischargers



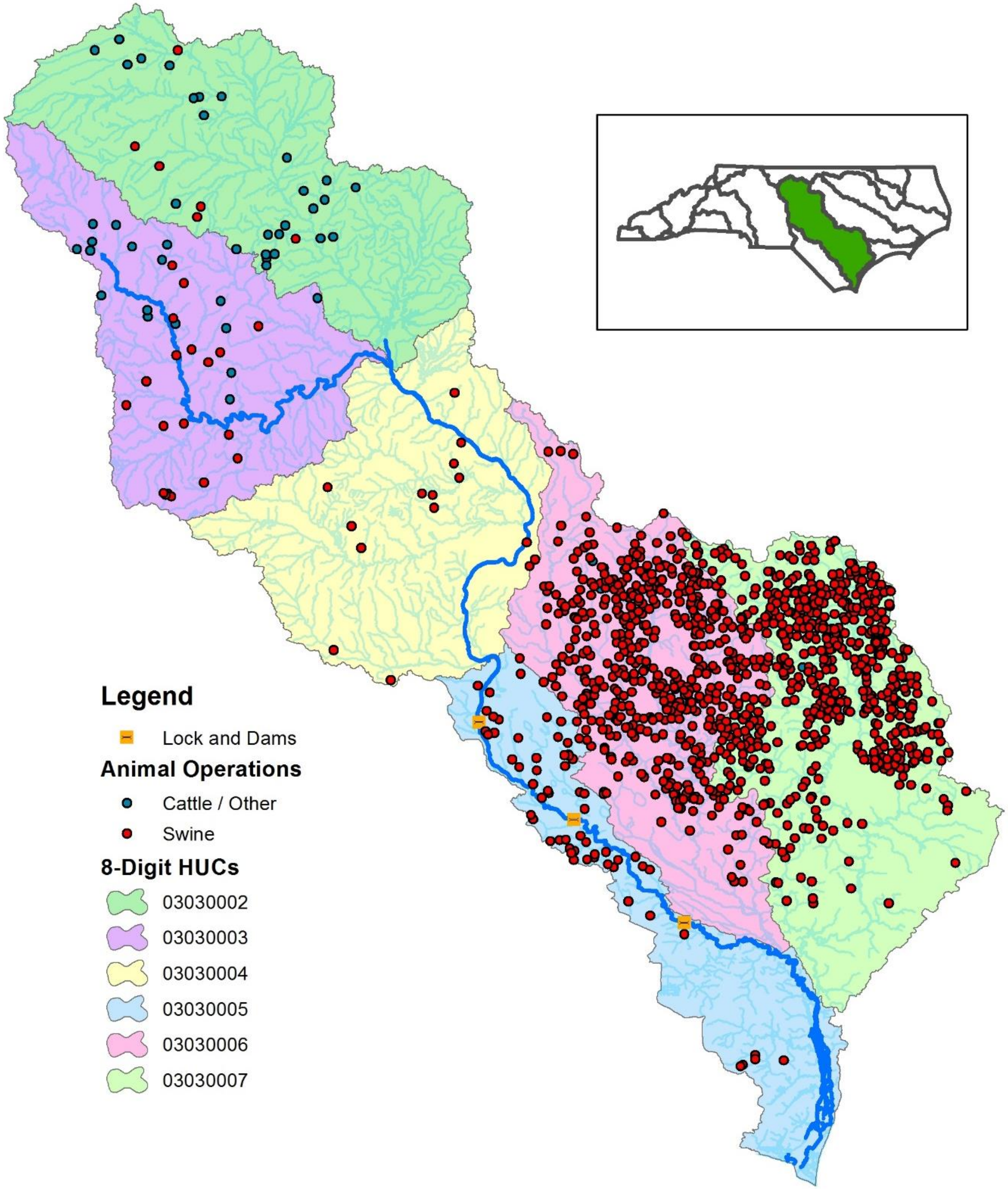
Central Cape Fear River Basin NPDES

NCDP Segment	Majors Dischargers > 1 mgd	Minor Dischargers < 1 mgd
Deep and Rocky	**5**	**21**
Cape Fear River	**14**	**17**
Central Portion Totals	**19**	**38**

Central Cape Fear River Basin Permitted CAFO’s

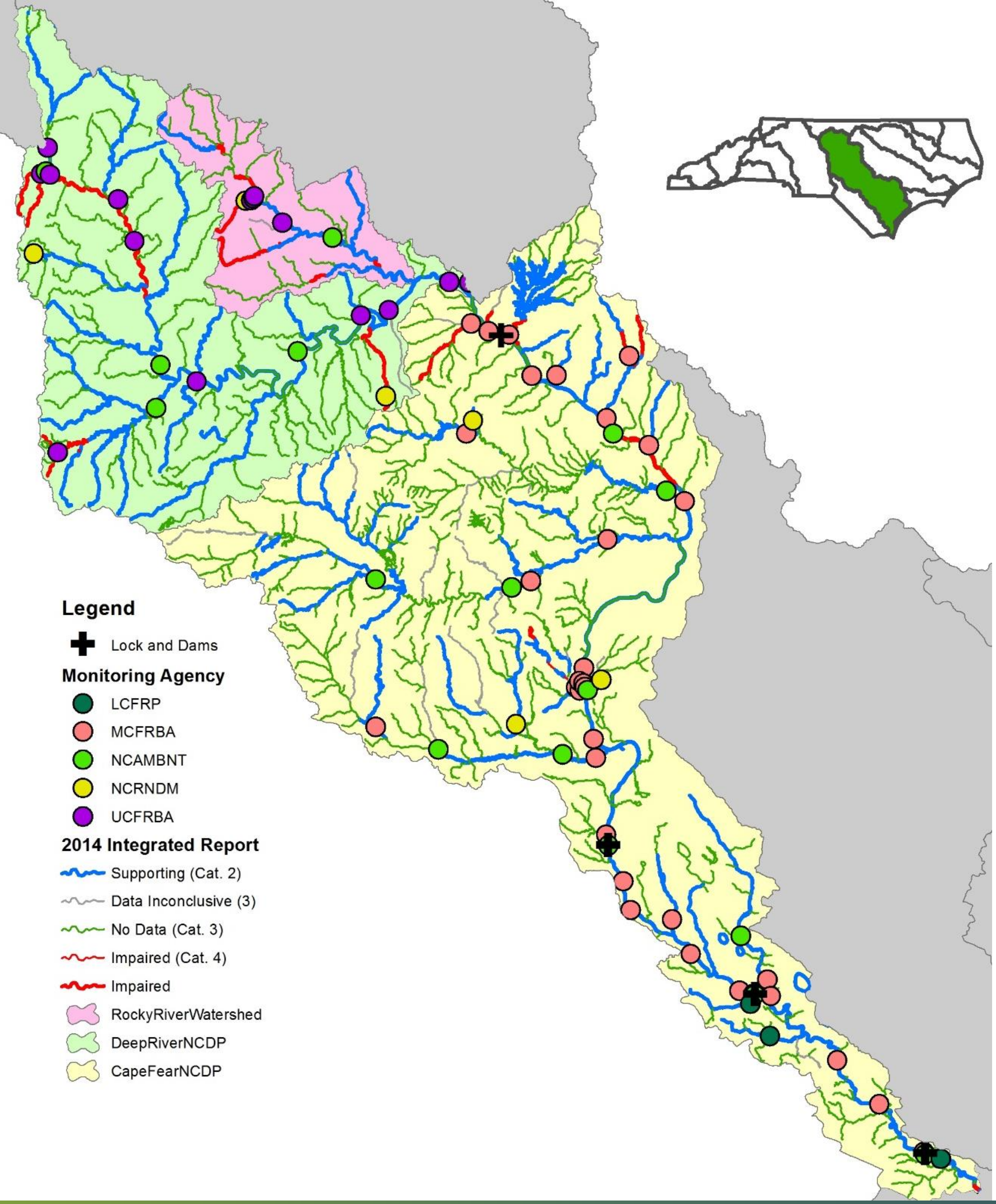
127 Permitted CAFO’s

Cape Fear River Basin Permitted CAFO's



Link to permits map-
http://ncdenr.maps.arcgis.com/apps/webappviewer/index.html?id=8753d6967d044098a4f50414c5f4594b

1357 Permitted CAFO's

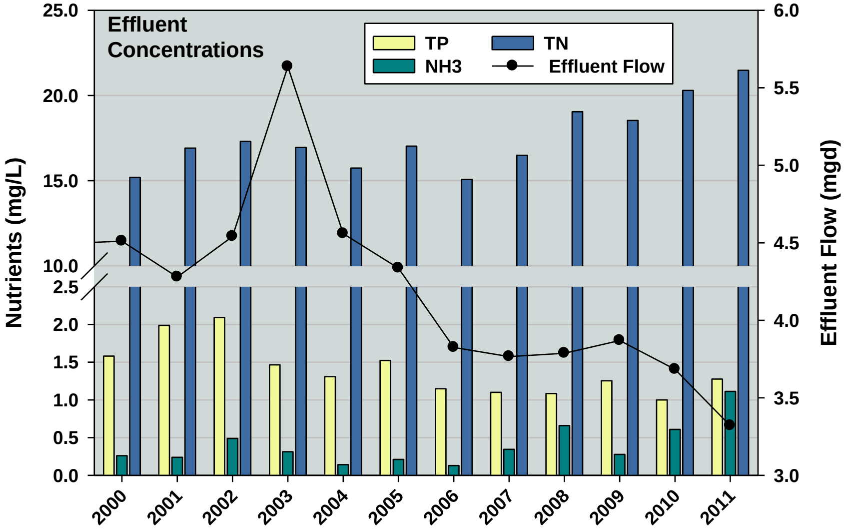


Central
Cape Fear River Basin
2014 IR
(2008-2012 data window)

Criteria Exceeded:

- Biology Integrity – Bugs
- Biology Integrity – Fish
- Low Dissolve Oxygen
- Low pH
- Fecal Coliform
- Turbidity
- Chlorophyll *a*
- Copper
- Zinc

Issues



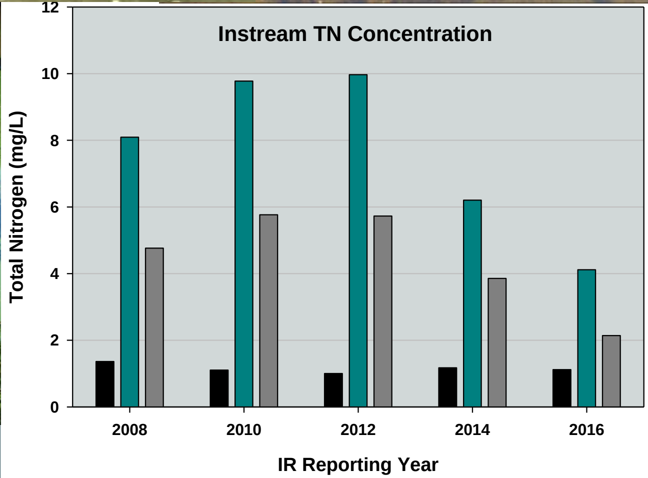

Cape Fear River at Buckhorn Dam


Deep River above Haw River

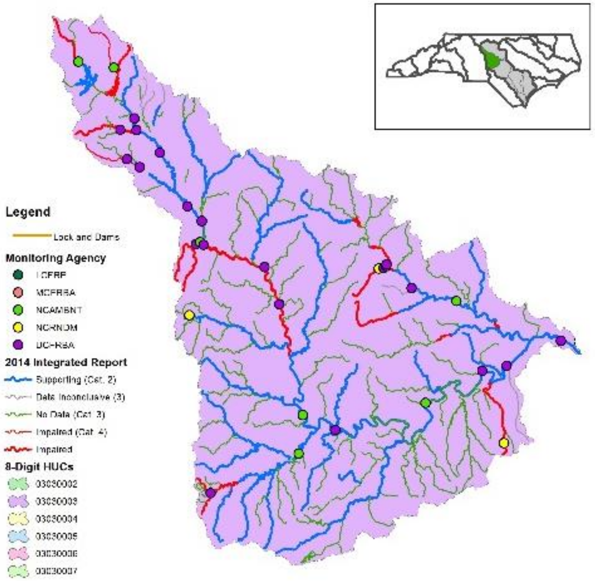

Rocky River


Rocky River


Cape Fear River behind L&D #1



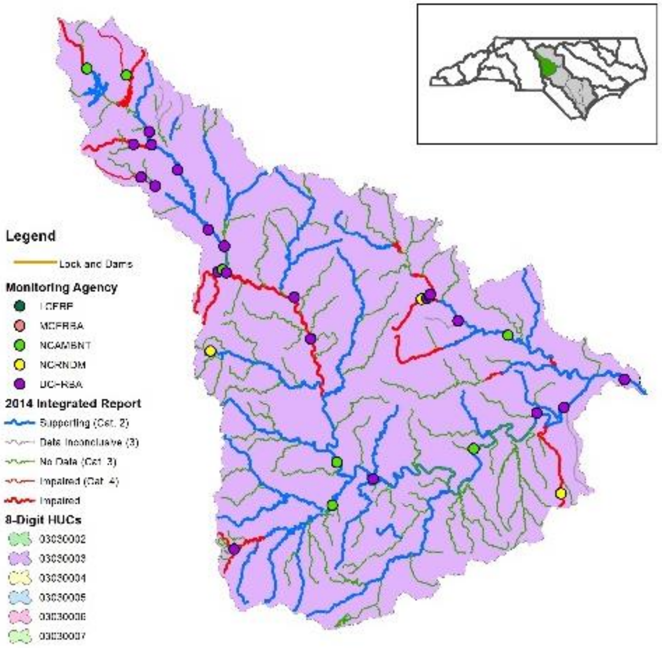
Deep River Watershed - 03030003



Deep River Subbasin - 03030003

- High nutrient concentration in the Deep and Rocky Rivers
- History of algal bloom developing in the lower Deep River during low flow periods. 2010 Algal study found Chl *a* conc. ranging between 11 and 47 µg/L (mainly bluegreen *Pseudanabaena)*
- 26 total NPDES permits – 5 Major and 21 Minor

Deep River Watershed - 03030003



Deep River Subbasin - 03030003

- High Chl *a* concertation's in the Deep River;

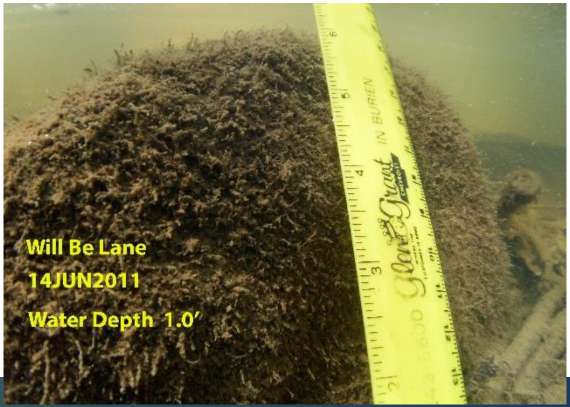
  below confluence with Haskett Ck.

- High Chl *a* conc. in the Rocky River watersheds drinking water reservoirs

- High Chl *a* conc. behind Woody's dam on the lower portion of the Rocky River

- Thick periphytic growth throughout the Rocky River, mainly below Loves Ck.


15-501
14JUN2011
Water Depth 1.0'


Will Be Lane
14JUN2011
Water Depth 1.0'

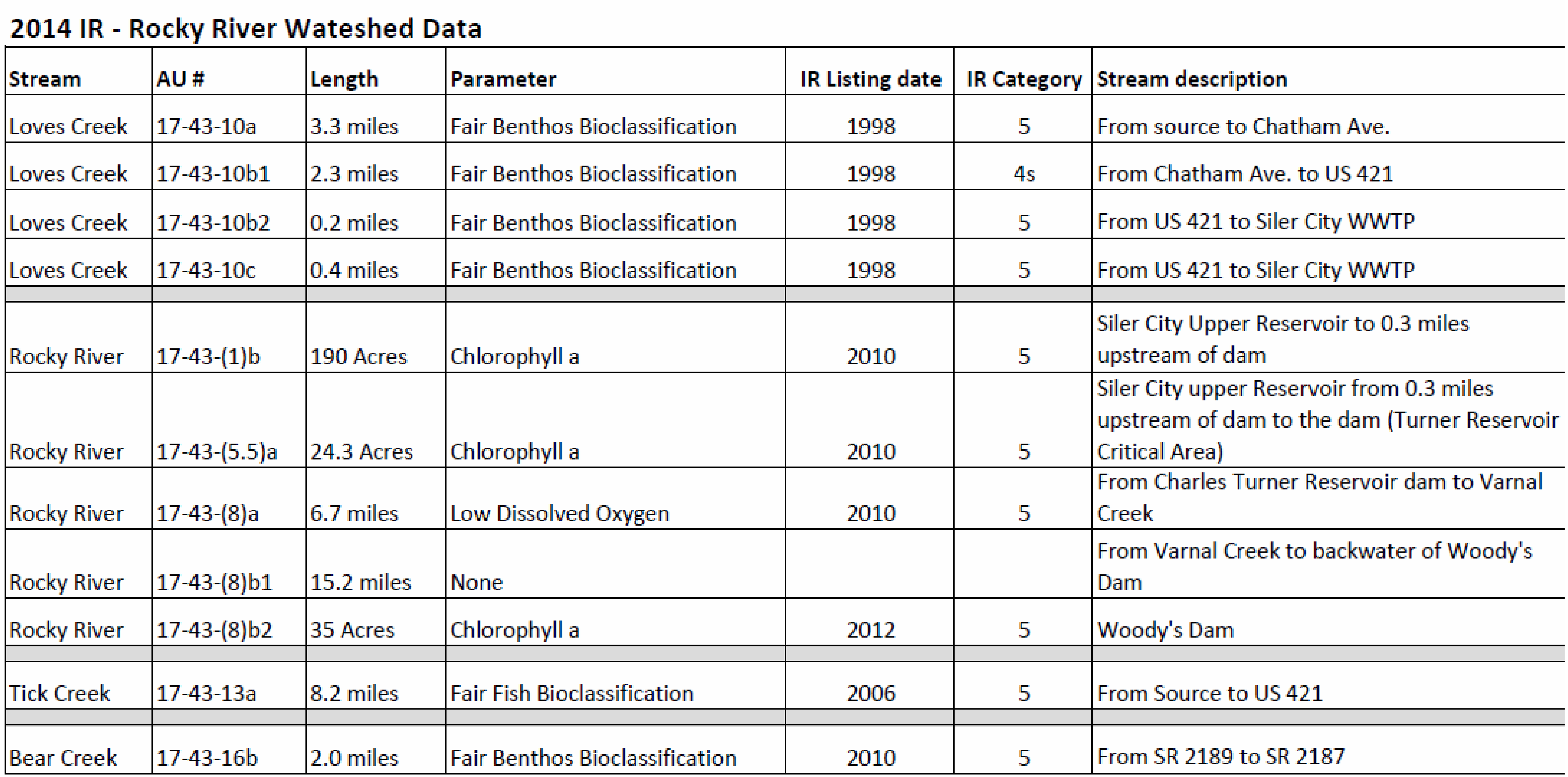
Deep River bloom 2010

- Green film across entire river
- Two miles long

Deep River ≈ Haywood

Deep River above Haw River

Rocky River Subbasin



2014 IR - Rocky River Wateshed Data

Stream	AU #	Length	Parameter	IR Listing date	IR Category	Stream description
Loves Creek	17-43-10a	3.3 miles	Fair Benthos Bioclassification	1998	5	From source to Chatham Ave.
Loves Creek	17-43-10b1	2.3 miles	Fair Benthos Bioclassification	1998	4s	From Chatham Ave. to US 421
Loves Creek	17-43-10b2	0.2 miles	Fair Benthos Bioclassification	1998	5	From US 421 to Siler City WWTP
Loves Creek	17-43-10c	0.4 miles	Fair Benthos Bioclassification	1998	5	From US 421 to Siler City WWTP
Rocky River	17-43-(1)b	190 Acres	Chlorophyll a	2010	5	Siler City Upper Reservoir to 0.3 miles upstream of dam
Rocky River	17-43-(5.5)a	24.3 Acres	Chlorophyll a	2010	5	Siler City upper Reservoir from 0.3 miles upstream of dam to the dam (Turner Reservoir Critical Area)
Rocky River	17-43-(8)a	6.7 miles	Low Dissolved Oxygen	2010	5	From Charles Turner Reservoir dam to Varnal Creek
Rocky River	17-43-(8)b1	15.2 miles	None			From Varnal Creek to backwater of Woody's Dam
Rocky River	17-43-(8)b2	35 Acres	Chlorophyll a	2012	5	Woody's Dam
Tick Creek	17-43-13a	8.2 miles	Fair Fish Bioclassification	2006	5	From Source to US 421
Bear Creek	17-43-16b	2.0 miles	Fair Benthos Bioclassification	2010	5	From SR 2189 to SR 2187

2014 Impaired Waters List (data window 2008-2012)

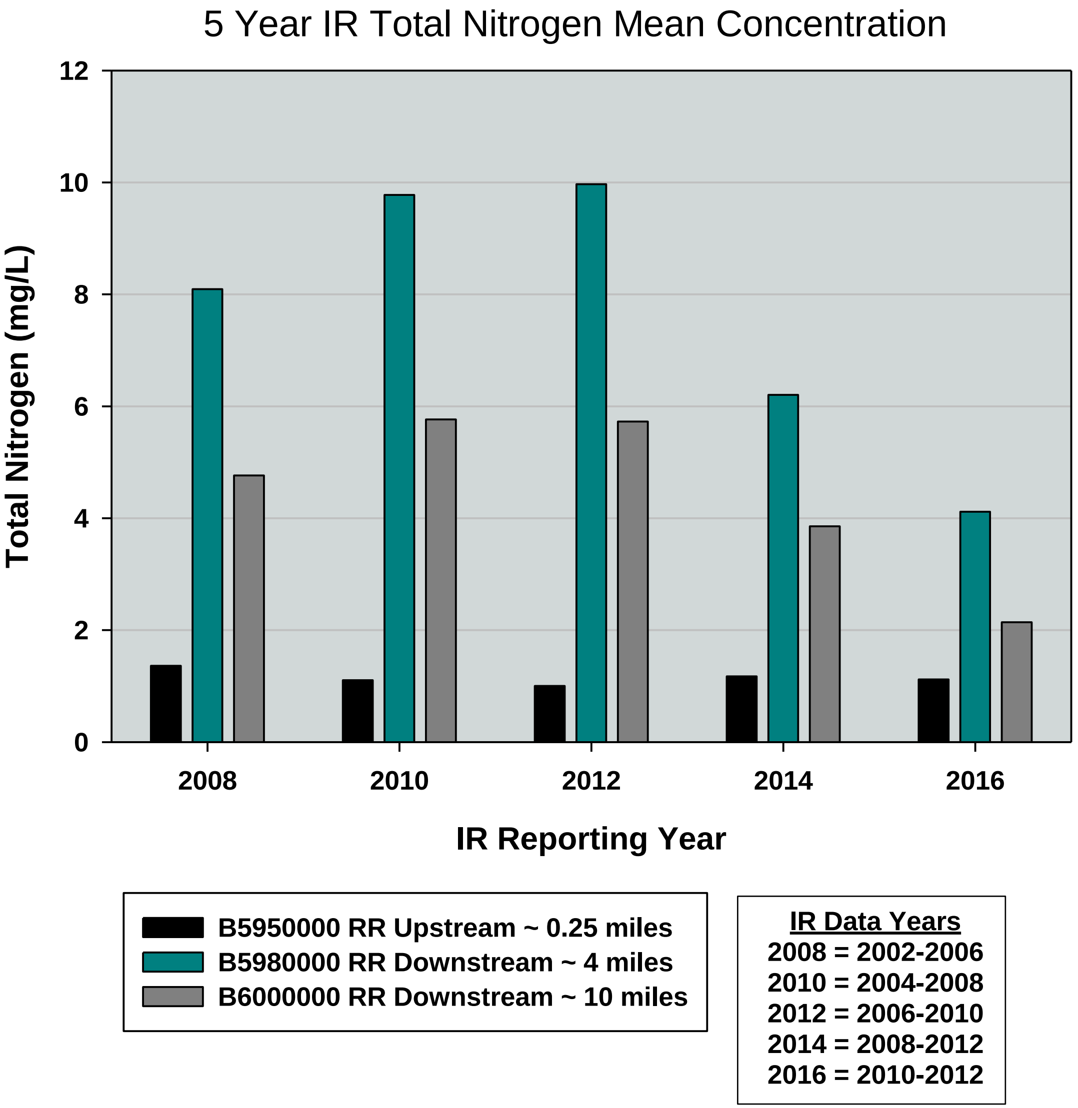
IR Category Definitions

Categories 4 and 5 – Exceeds Criteria and are identified as IMPAIRED

5 = Exceeding criteria, no approved TMDL in place for assessed parameter

4s = Biological data exceeding criteria, another aquatic life parameter is assessed in category 4 or 5

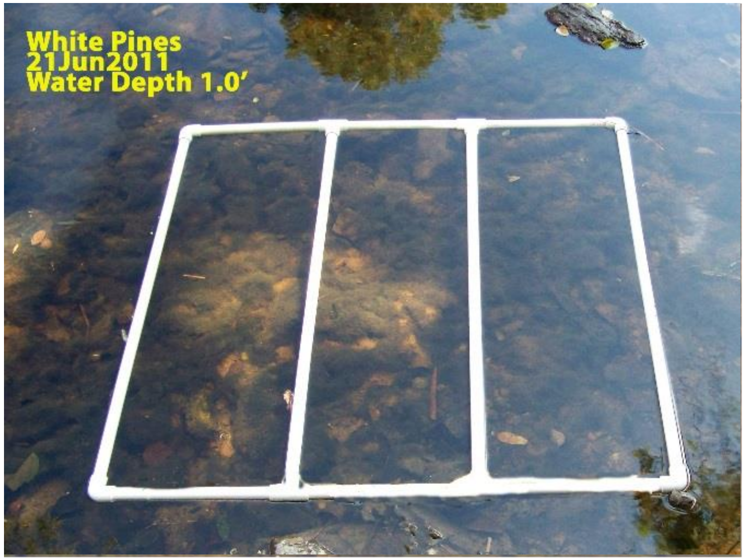
Rocky River Subbasin



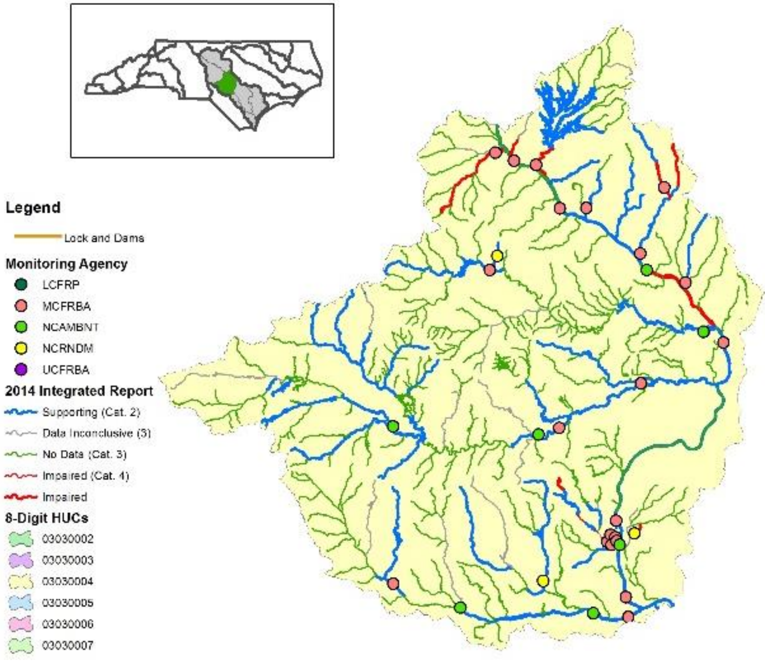
<u>IR Data Years</u>

2008 = 2002-2006
2010 = 2004-2008
2012 = 2006-2010
2014 = 2008-2012
2016 = 2010-2012

Periphyton is a complex mixture of algae, cyanobacteria, heterotrophic microbes, and detritus attached to submerged aquatic surfaces.



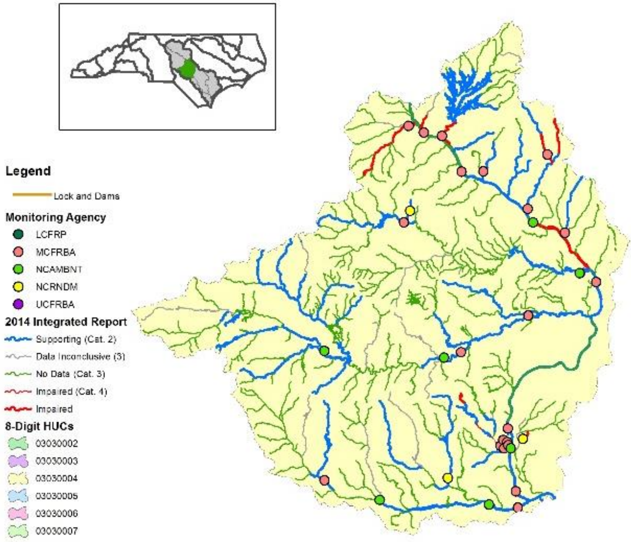
Middle Cape Fear River



Middle Cape Fear River Subbasin - 03030004

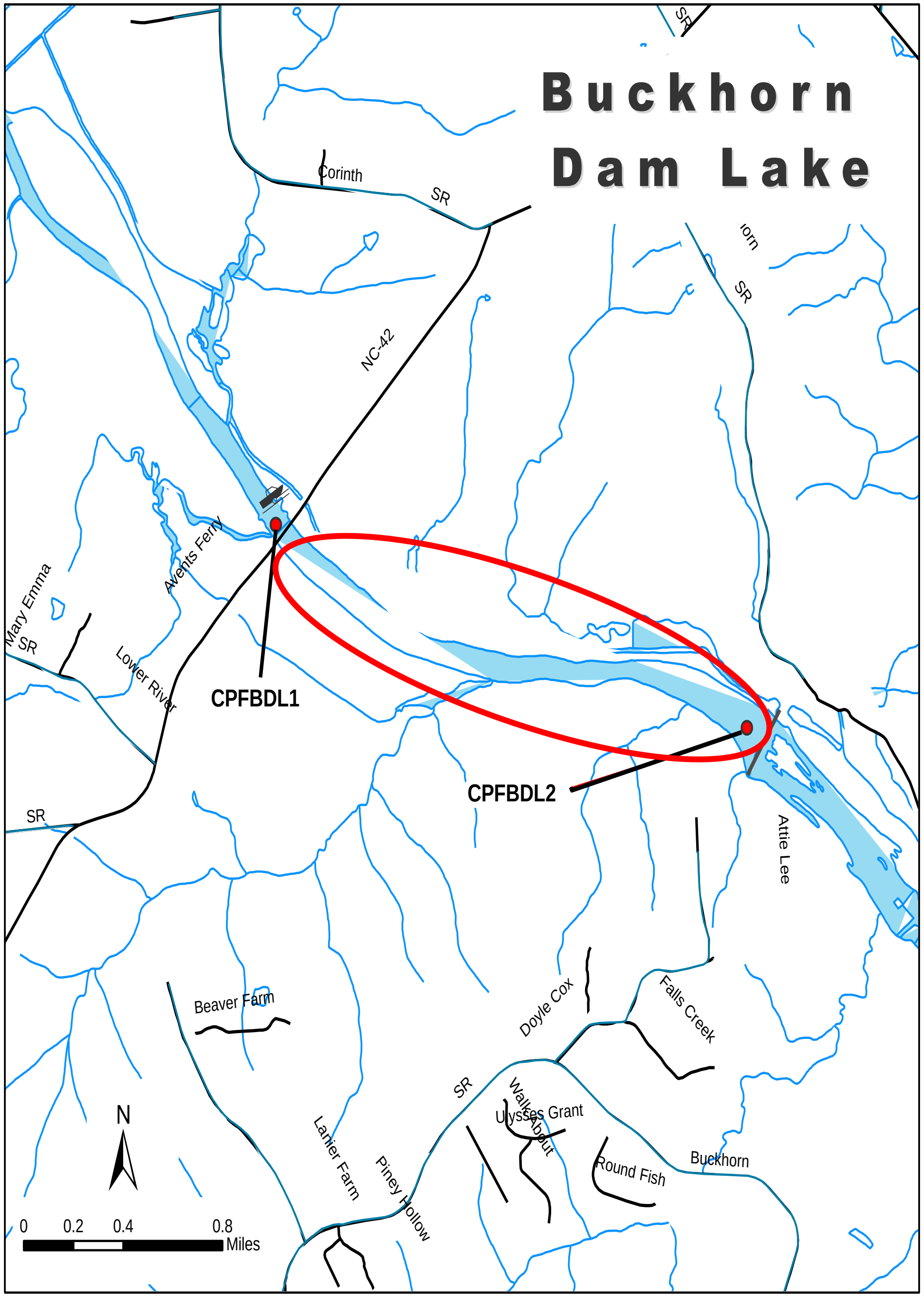
- High nutrient concentration
- High Chl *a* concentrations on the Cape Fear River behind Buckhorn Dam.
- History of algal bloom developing in the Haw River below Jordan Lake Dam down the Cape Fear River to Buckhorn Dam.
- 2010 Algal study found Chl *a* concentrations ranging between 12 and 62 µg/L (mainly bluegreen *Pseudanabaena)*

Middle Cape Fear River Basin



Middle Cape Fear River Subbasin - 03030004

- Higher flows below Buckhorn dam prevent the development of algal blooms until the Cape Fear River slows down behind lock and dam # 3
- 26 total NPDES permits – 11 Major and 15 Minor



Cape Fear River at Buckhorn Dam

Behind Buckhorn Dam [AU # 18-(5.5); from NC Hwy 42 to Buckhorn Dam].

DWR Study	Sample Date	Chl a (µg/L)	Secchi (m)	DO (mg/L)	pH	Cond. (µmhos/cm)	Temp (°C)	Turbidity (NTU)	1Day Flow (cfs)	7Day Flow (cfs)
2010 Algal Study	7/19/2010	32	0.75	7.1	6.3	182	29.6	NA	691	673
2010 Algal Study	8/12/2010	48	0.70	9.1	8.5	168	31.4	NA	596	594
2010 Algal Study	8/30/2010	45	0.70	9.8	8.7	188	30.1	NA	628	908
2010 Algal Study	9/23/2010	46	0.90	9.9	8.5	197	28.0	NA	502	548
2010 Algal Study	10/21/2010	38	0.65	8.1	7.4	175	23.7	NA	621	597
2013 Lakes	5/22/13	4	0.30	7.0	7.2	84	20.9	33.0	6,000	2,324
2013 Lakes	6/24/13	22	0.80	6.8	7.5	125	27.6	1.4	1,480	3,014
2013 Lakes	7/22/13	11	0.80	4.1	7.4	133	28.6	9.7	1,920	5,183
2013 Lakes	8/27/13	14	0.60	6.7	7.4	126	25.7	14.0	996	4,042
2013 Lakes	9/30/13	48	0.60	6.4	7.6	157	21.7	9.9	564	608
	Mean	31	0.68	7.5	7.7	154	26.7	13.6	1,400	1,849
	Median	35	0.70	7.1	7.5	163	27.8	9.9	660	791
	n	10	10	10	10	10	10	5	10	10
	Min	4	0.30	4.1	6.3	84	20.9	1.4	502	548
	Max	48	0.90	9.9	8.7	197	31.4	33.0	6,000	5,183
	n>40 µg/L Chl a	4								
	%>40 µg/L Chl a	40 %								
	% Confidence	98.72 %								

2010 Algal Study site 7/Station Code CPFBD; 2013 Lakes Assessment Station CPFBDL2.

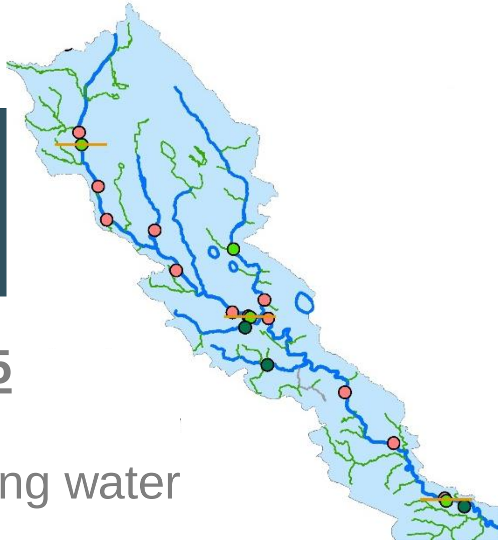
Central Cape Fear River Basin

Lower Cape Fear River Subbasin (down to L&D #1) - 03030005

- Historically high Chl *a* concentrations behind lock and dam structures.
- History of potentially toxic algal blooms developing during low flow periods (*Microcystis* blooms started in 2009)
- 2010 Algal study found Chl *a* conc. ranging between 2.1 and 39 µg/L (mainly bluegreen *Microcystis aeruginosa).*

- Major bloom events are not resulting in exceedance of the Chl *a* standard.

Central Cape Fear River Basin



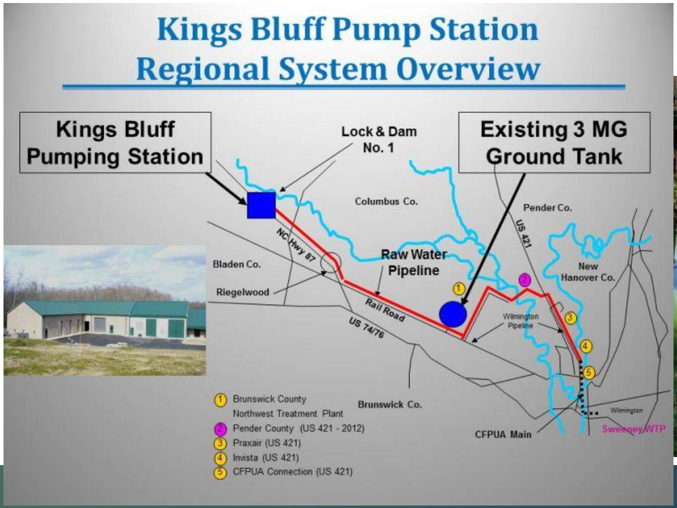
Lower Cape Fear River Subbasin (down to L&D #1) - 03030005

- Taste and odor problems reported in Brunswick County drinking water system due to algal blooms
- High instream nutrient concentration
- 5 total NPDES permits – 3 Major and 2 Minor
- CAFO’s located in the watershed

Cape Fear Public Utility Authority

LOWER CAPE FEAR WATER AND SEWER AUTHORITY · INCORPORATED 1970 · WATER · GOVERNMENT · INDUSTRY

Water is Our Business



Kings Bluff Pump Station
Regional System Overview

① Brunswick County Northwest Treatment Plant
② Pender County (US 421 - 2012)
③ Praxair (US 421)
④ Invista (US 421)
⑤ CFPUA Connection (US 421)

Cape Fear River behind L&D #1

2009 Cape Fear River Bluegreen Algal Bloom

Cape Fear River headed down to Riegelwood

OCT 23 2009

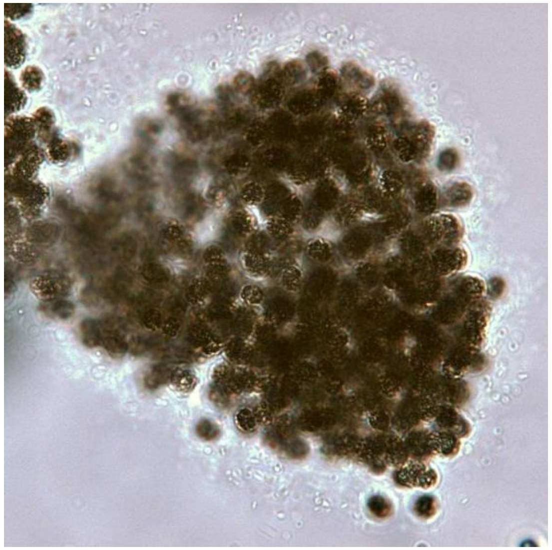
Cape Fear River behind L&D #1 9/24/09

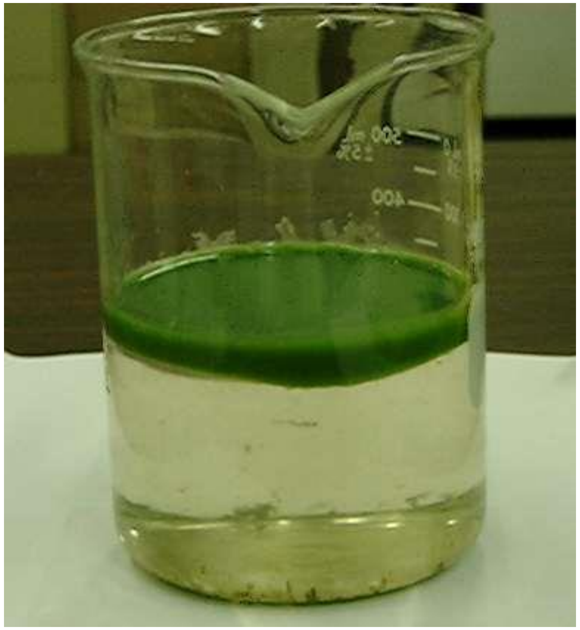
Microcystis aeruginosa

2009 Cape Fear River Bluegreen Algal Bloom

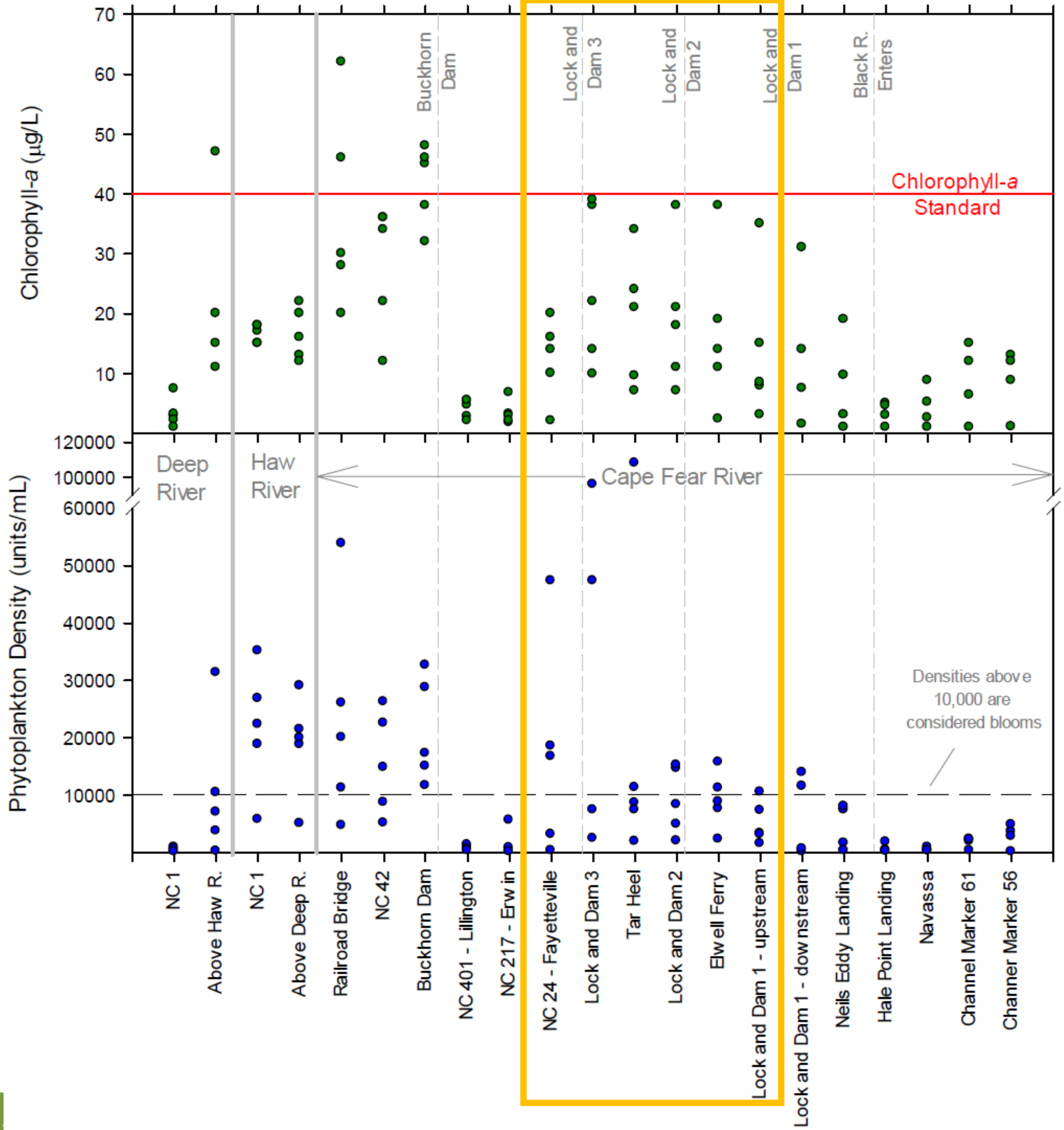
Microcystis aeruginosa

- Blue green algae
- Colonies can be visible (flecks in water)
- Forms surface blooms
- Causes taste and odors
- Potentially toxic

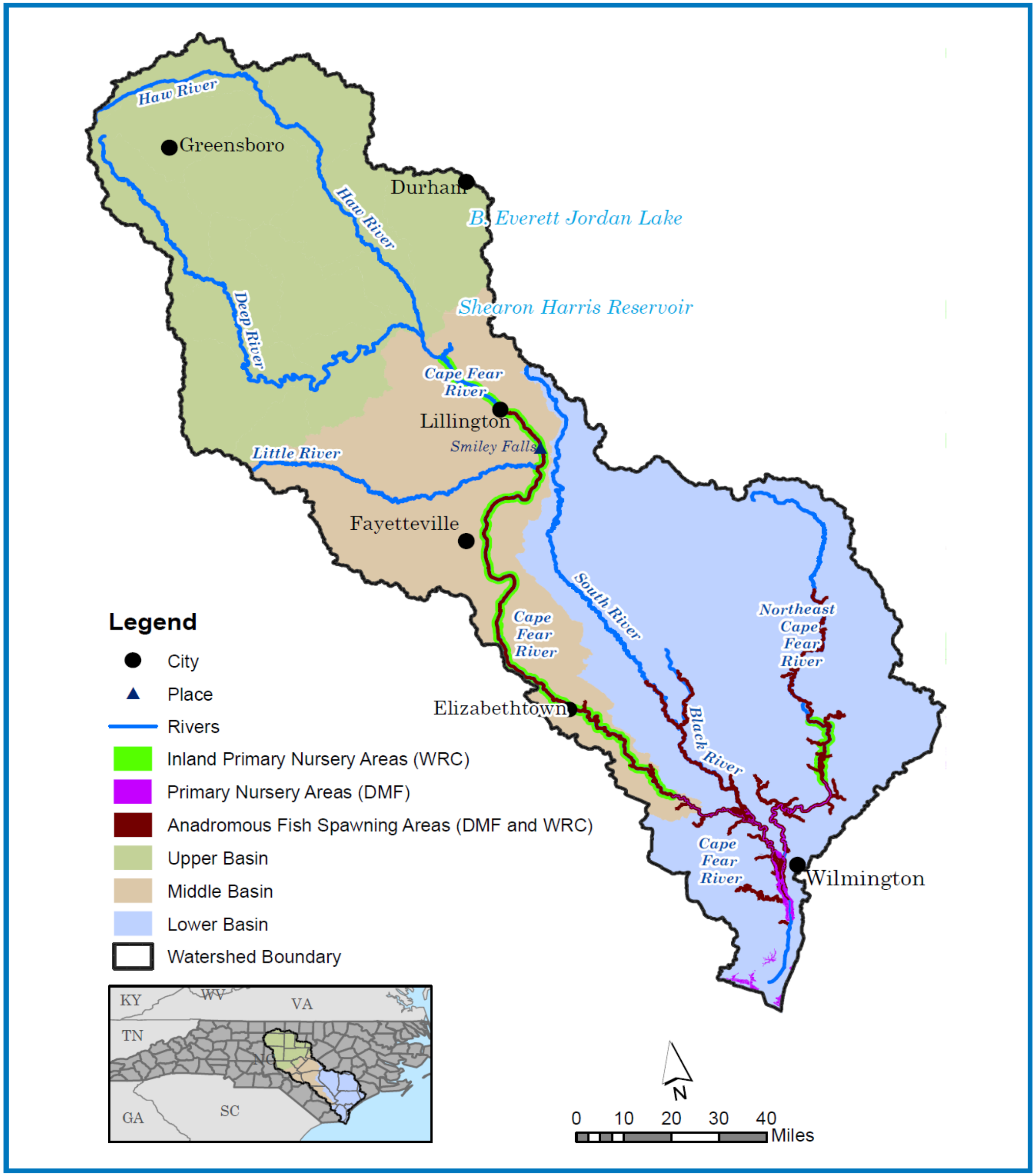




2010 CFR Algal Study Results



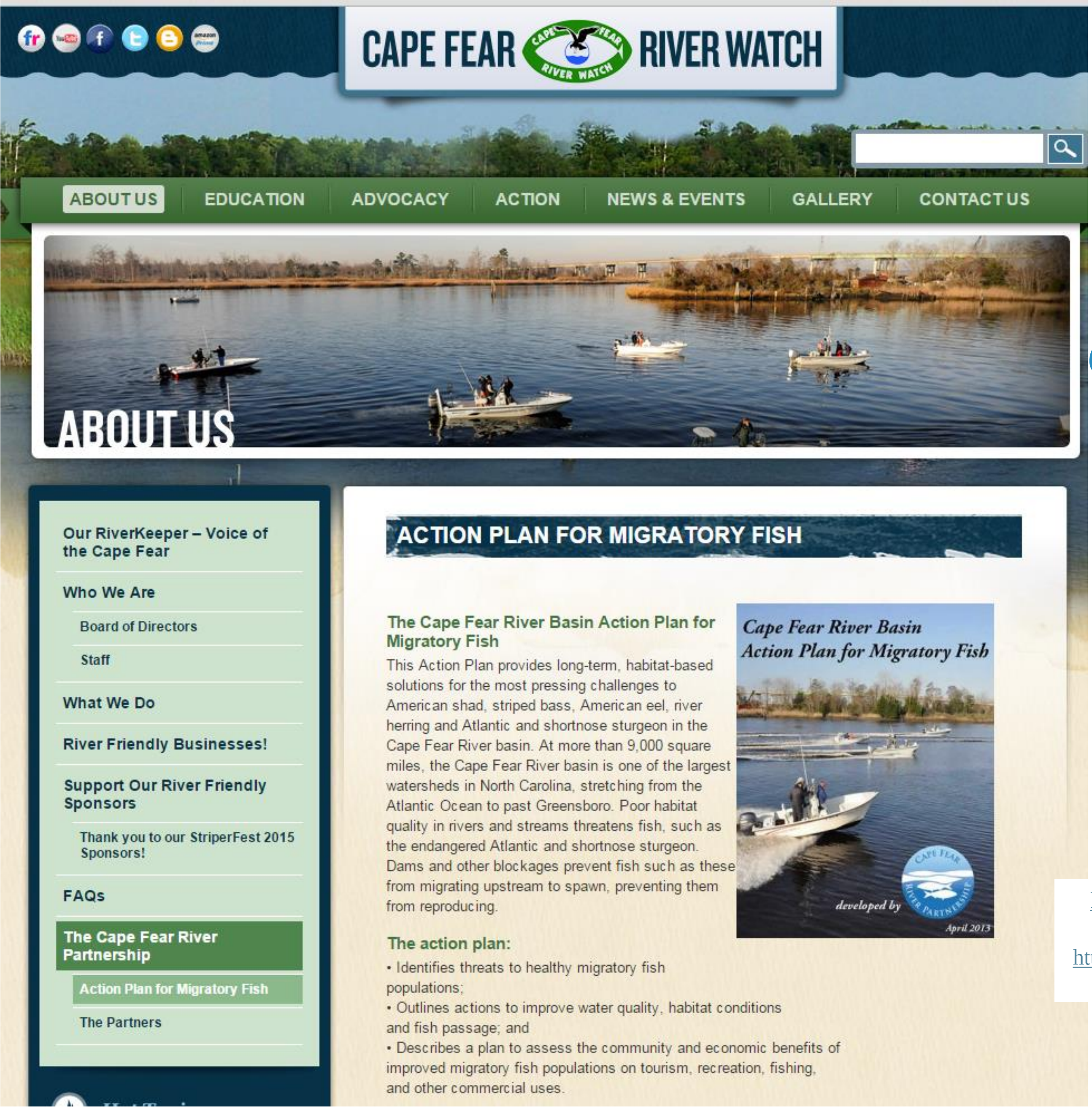
Bloom Magnitude	Density Units/mL
Mild	10,000- 20,000
Moderate	20,000- 30,000
Sever	30,000- 100,000
Extreme	>100,000



Cape Fear River Basin Anadromous Fish Spawning Areas and Primary Nursery Area

Map from Cape Fear River Partnership
Cape Fear River Basin Action Plan for Migratory Fish.
http://www.habitat.noaa.gov/protection/capefear/pdf/CapeFearActionPlan.pdf

Cape Fear River Partnership
~
Cape Fear River Basin Action Plan for Migratory Fish



ACTION PLAN FOR MIGRATORY FISH

The Cape Fear River Basin Action Plan for Migratory Fish

This Action Plan provides long-term, habitat-based solutions for the most pressing challenges to American shad, striped bass, American eel, river herring and Atlantic and shortnose sturgeon in the Cape Fear River basin. At more than 9,000 square miles, the Cape Fear River basin is one of the largest watersheds in North Carolina, stretching from the Atlantic Ocean to past Greensboro. Poor habitat quality in rivers and streams threatens fish, such as the endangered Atlantic and shortnose sturgeon. Dams and other blockages prevent fish such as these from migrating upstream to spawn, preventing them from reproducing.

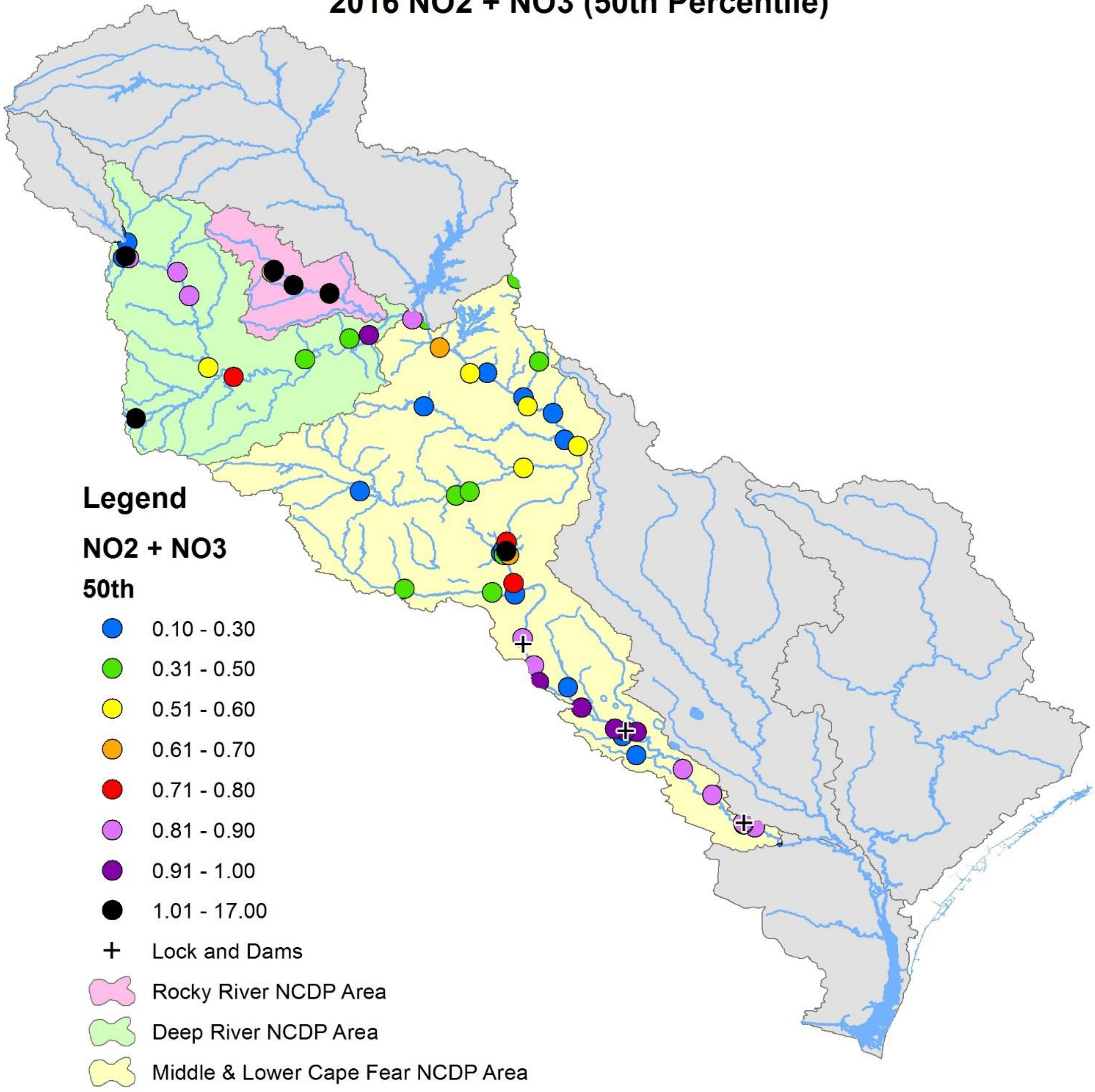
The action plan:

- Identifies threats to healthy migratory fish populations;
- Outlines actions to improve water quality, habitat conditions and fish passage; and
- Describes a plan to assess the community and economic benefits of improved migratory fish populations on tourism, recreation, fishing, and other commercial uses.

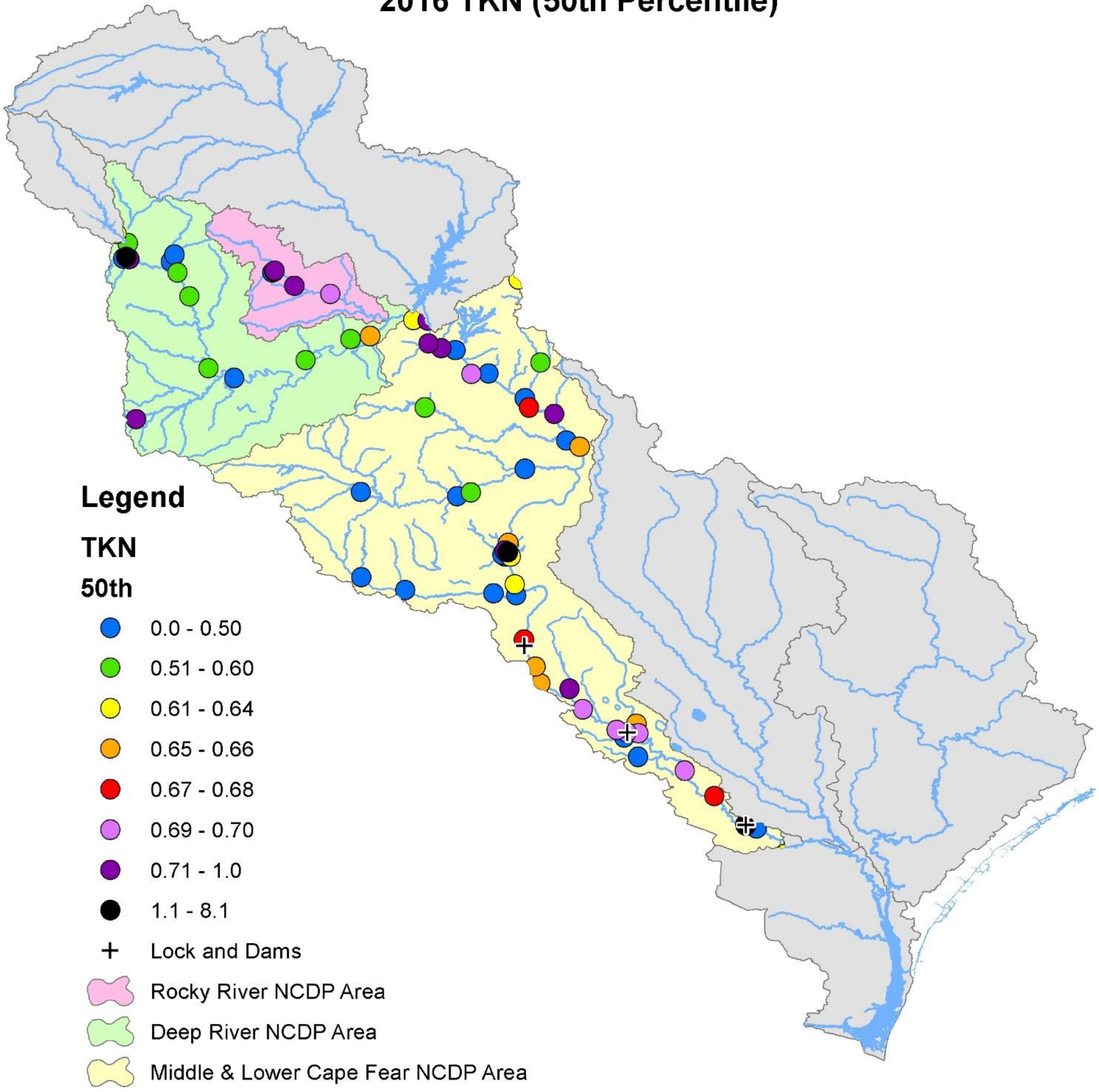
http://www.capefearriverwatch.org/about-us/the-cape-fear-river-partnership/action-plan-for-migratory-fish

http://www.habitat.noaa.gov/protection/capefear/pdf/CapeFearActionPlan.pdf

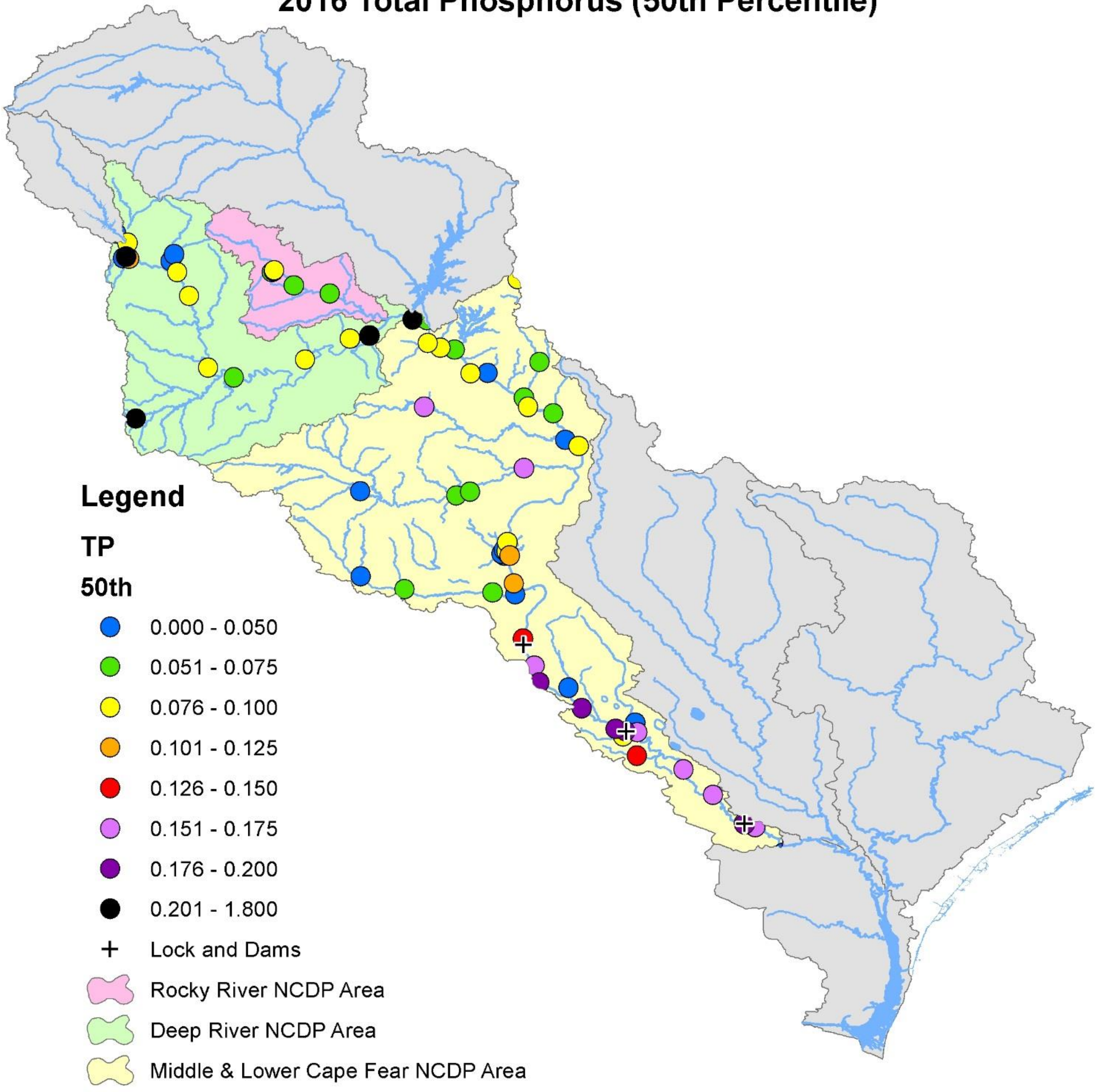
2016 NO2 + NO3 (50th Percentile)



2016 TKN (50th Percentile)



2016 Total Phosphorus (50th Percentile)



Questions

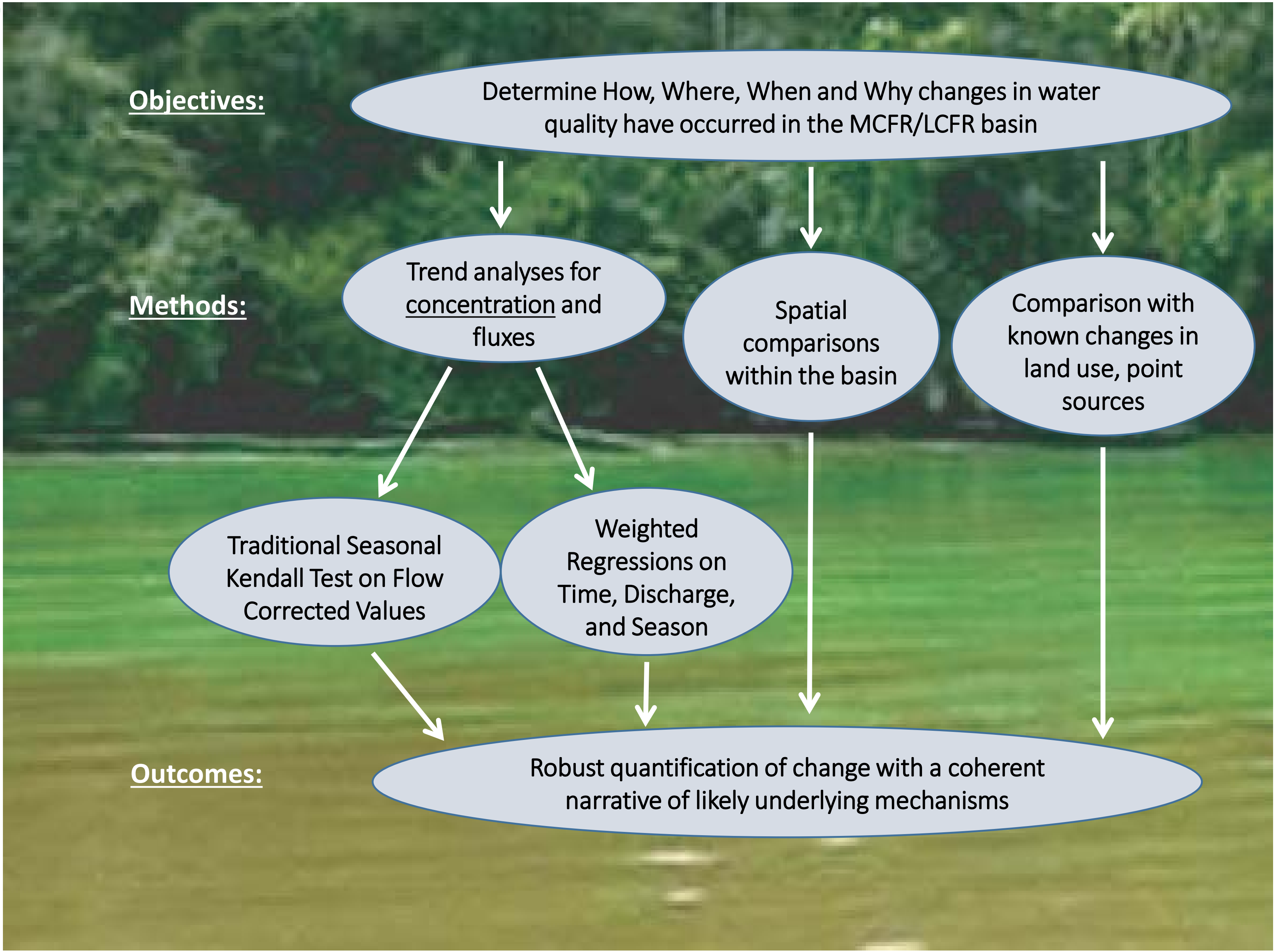
Department of Environmental Quality

Determining Water Quality Change and Drivers on the Middle Cape Fear River:

An Introduction to Two New Projects

Nathan Hall
NC Nutrient Criteria Development Plan
Scientific Advisory Council Meeting
20 April 2016
Raleigh, NC

Cape Fear R. Trend Analysis Project



Objectives:

Determine How, Where, When and Why changes in water quality have occurred in the MCFR/LCFR basin

Methods:

Trend analyses for concentration and fluxes

Spatial comparisons within the basin

Comparison with known changes in land use, point sources

Traditional Seasonal Kendall Test on Flow Corrected Values

Weighted Regressions on Time, Discharge, and Season

Outcomes:

Robust quantification of change with a coherent narrative of likely underlying mechanisms

Background image photo credit: Stephanie Pettergarrett, NCDENR-DWR

CFR Trend Analysis Project

Funding: NC WRRI

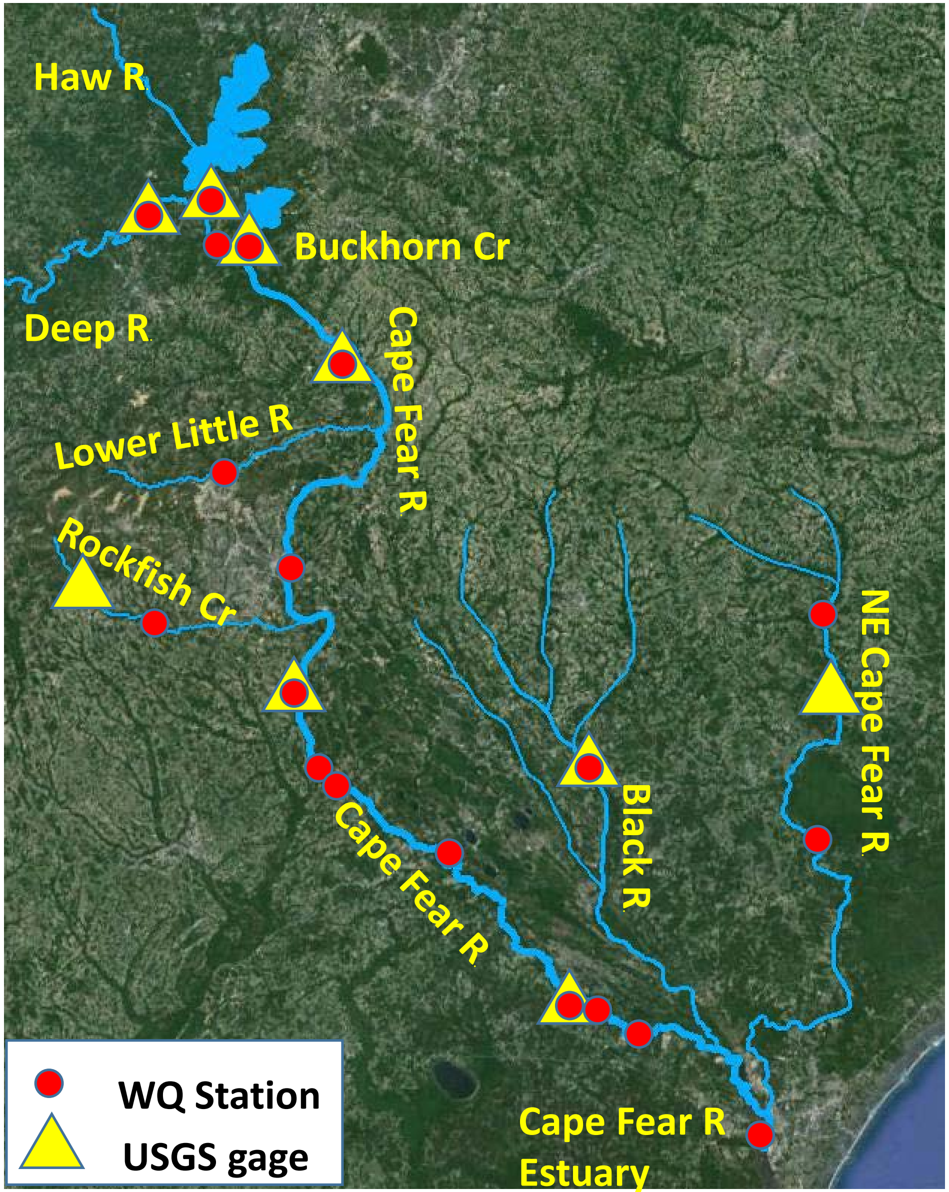
PIs: Hall, Paerl
Collaborators: MCFRBA, DWR, USGS

19 prioritized stations (DWR, MCFRBA, LCFRP):
a) Must have discharge record
b) Length and completeness of record
c) Stations with chlorophyll *a*
d) Spatial distribution

12 Parameters:
TN, TP, nitrate, ammonium, phosphate, TP, chl-a, TSS, DO, pH, conductivity, Secchi depth

Covers eutrophication related parameters in the main stem and major tributaries of middle and lower CFR, and one estuarine station.

Map of sites selected for trend analyses

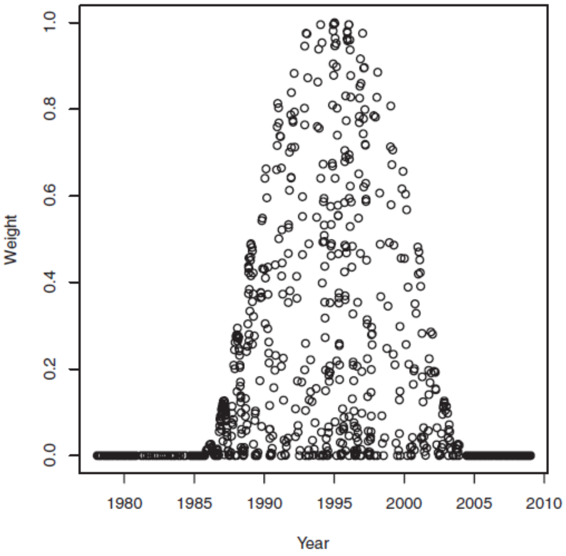


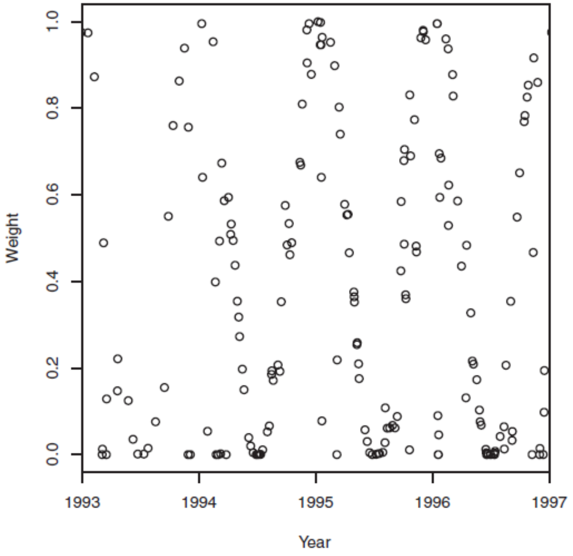
How the WRTDS model works

Concentration Estimate | Time Effect | Discharge Effect | Seasonality Effect | Error

$$\ln(c) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \cos(2\pi t) + \beta_4 \sin(2\pi t) + \varepsilon$$

During model fit, data are weighted by proximity of observed inputs to the time, discharge, and season of the estimation point.



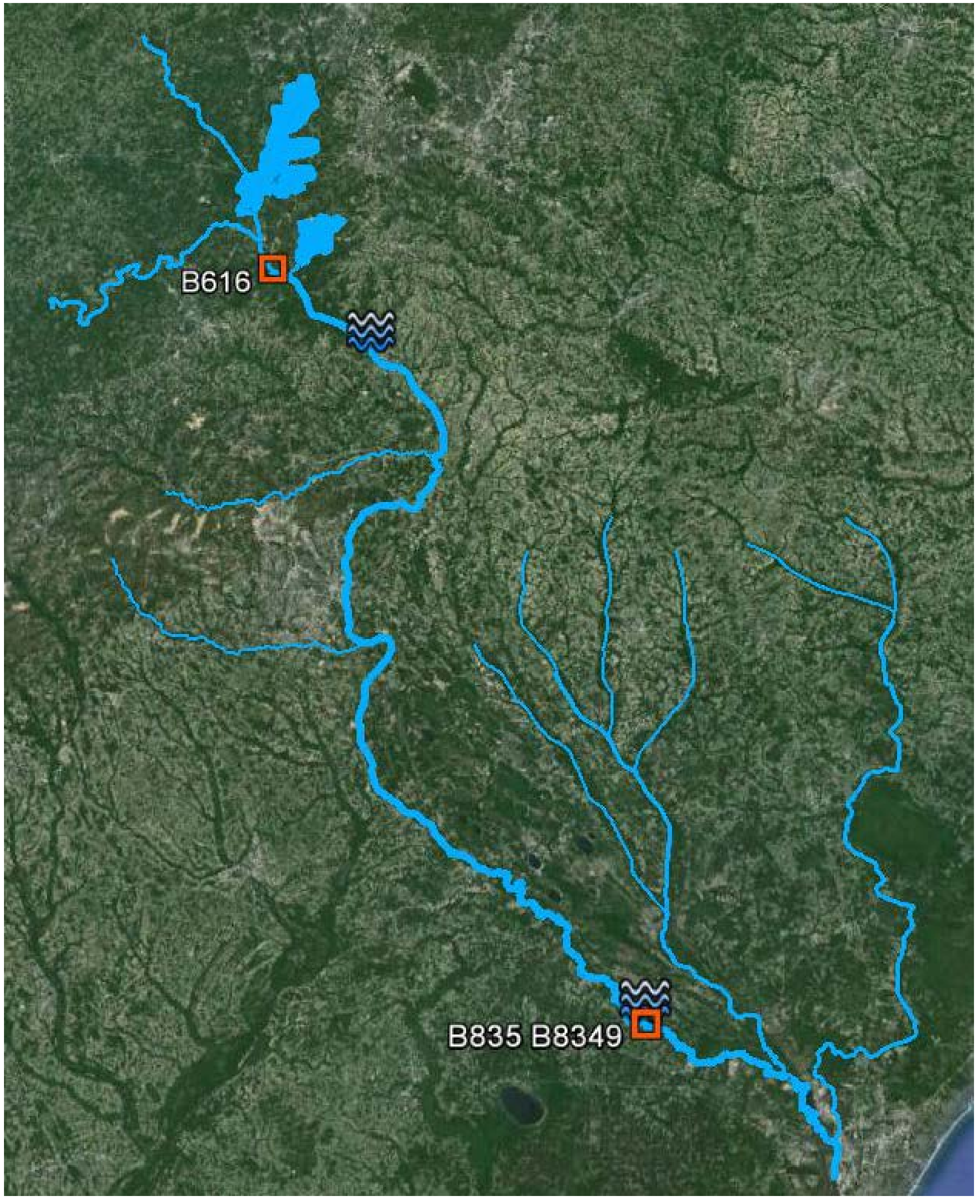


Improved accuracy of concentration and load estimates.

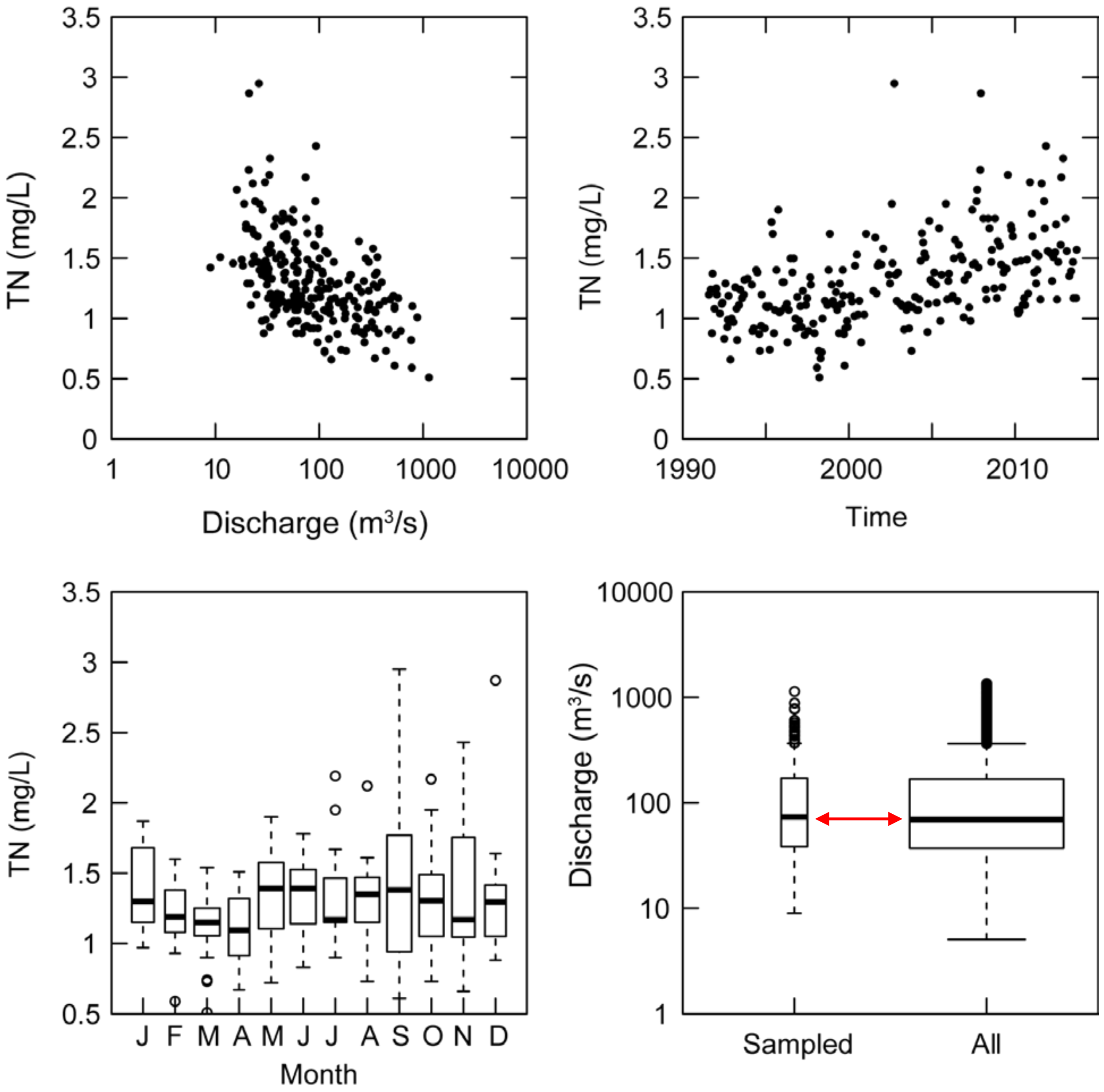
<u>Describes changes in trend, seasonality, or relation to flow. Potential clues to causes of change.</u>

Figures and WRTDS method from:
Hirsch, Moyer, and Archfield. 2010. Weighted Regressions on Time Discharge and Season:… JAWRA 46: 857-880

A preliminary look at some trends from the head and tail of the MCFR

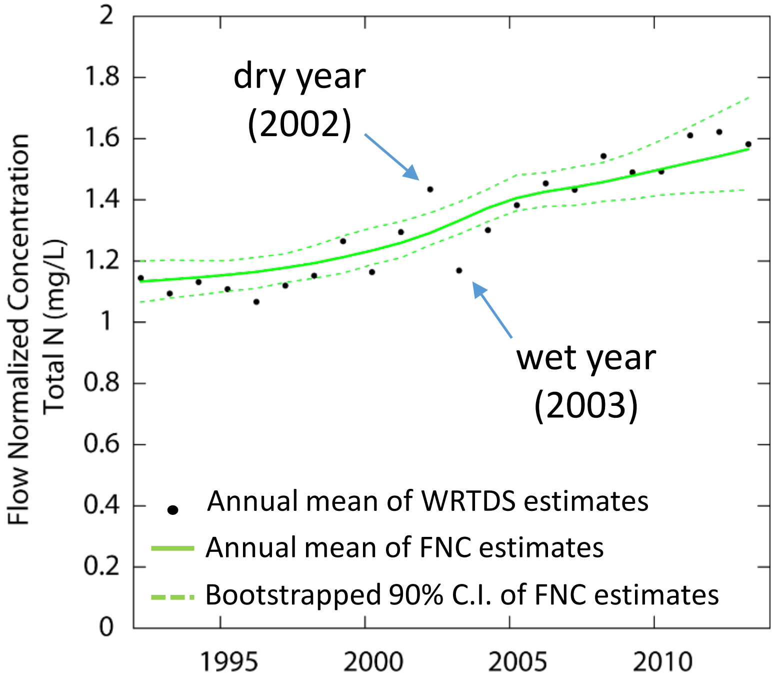


Overview of Raw TN Data at Station B8350000 at Lock and Dam 1



Long-term trend in TN at station B8350000 at Lock and Dam 1

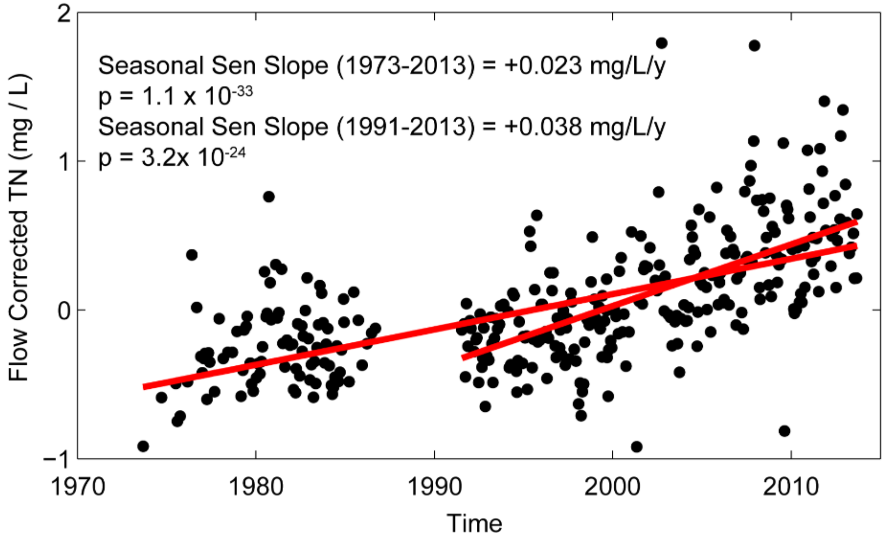
WRTDS Flow Normalized Concentration (FNC)



dry year (2002)

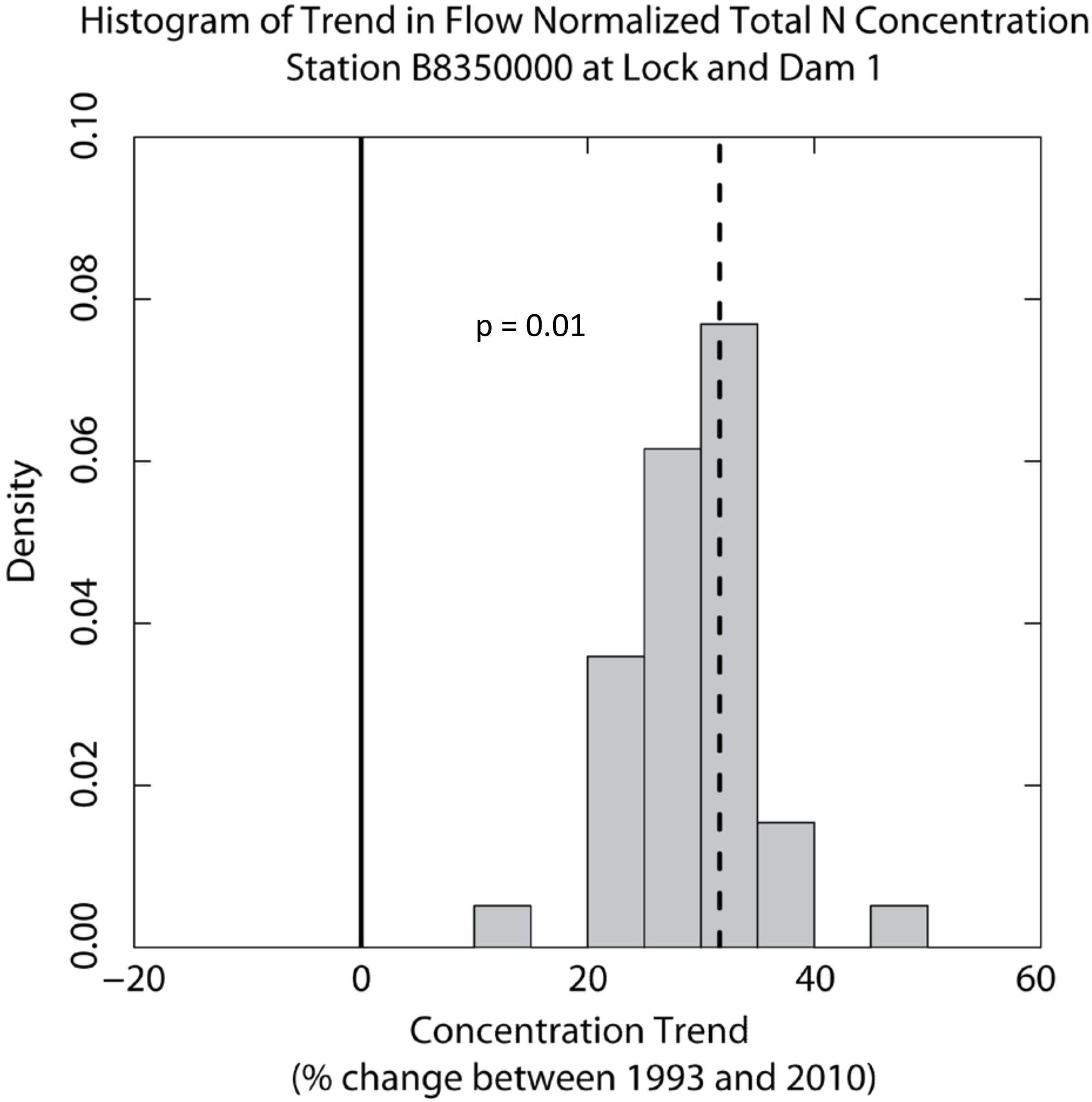
wet year (2003)

Seasonal Kendal Test on Flow Corrected Values

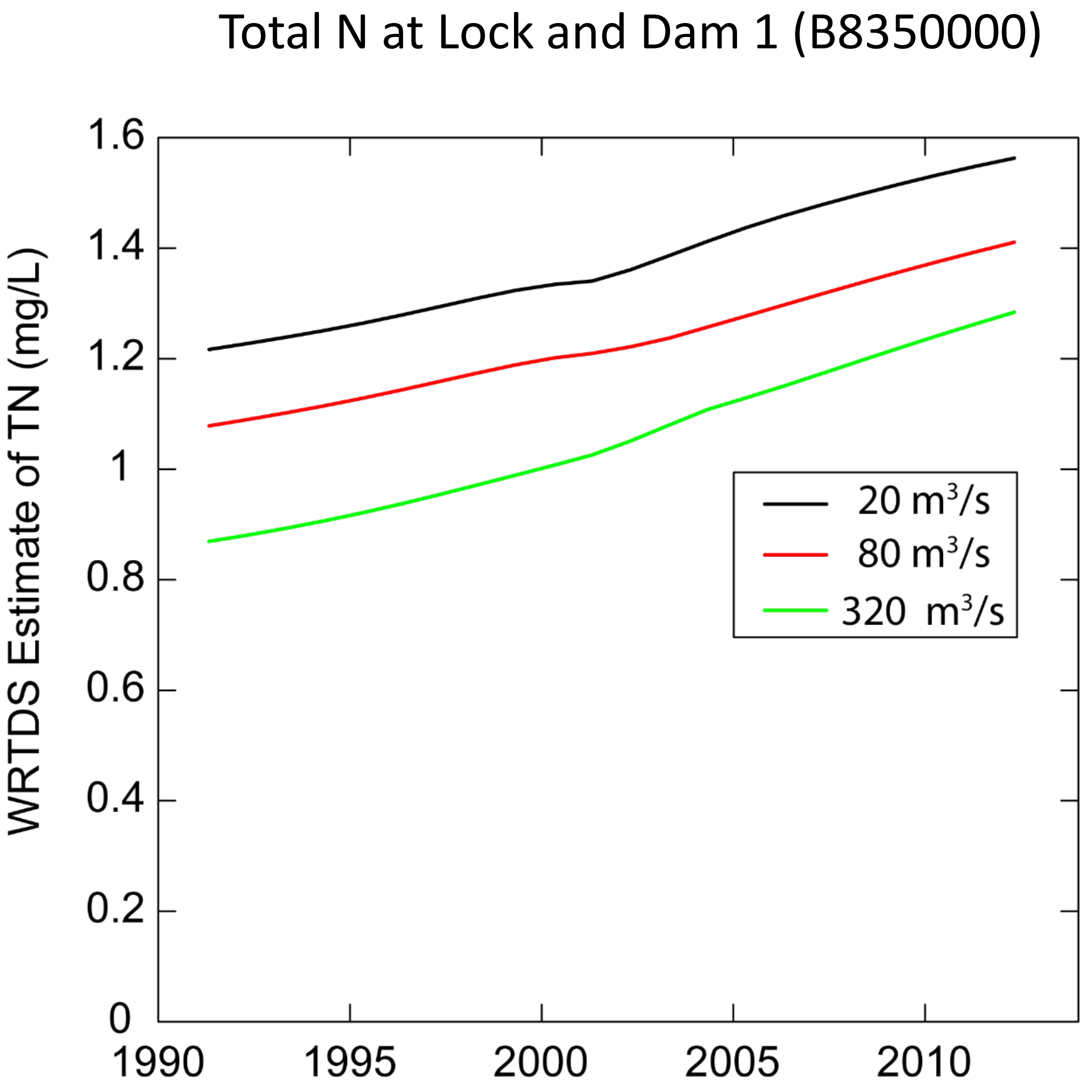


Seasonal Sen Slope (1973-2013) = +0.023 mg/L/y
$p = 1.1 \times 10^{-33}$
Seasonal Sen Slope (1991-2013) = +0.038 mg/L/y
$p = 3.2 \times 10^{-24}$

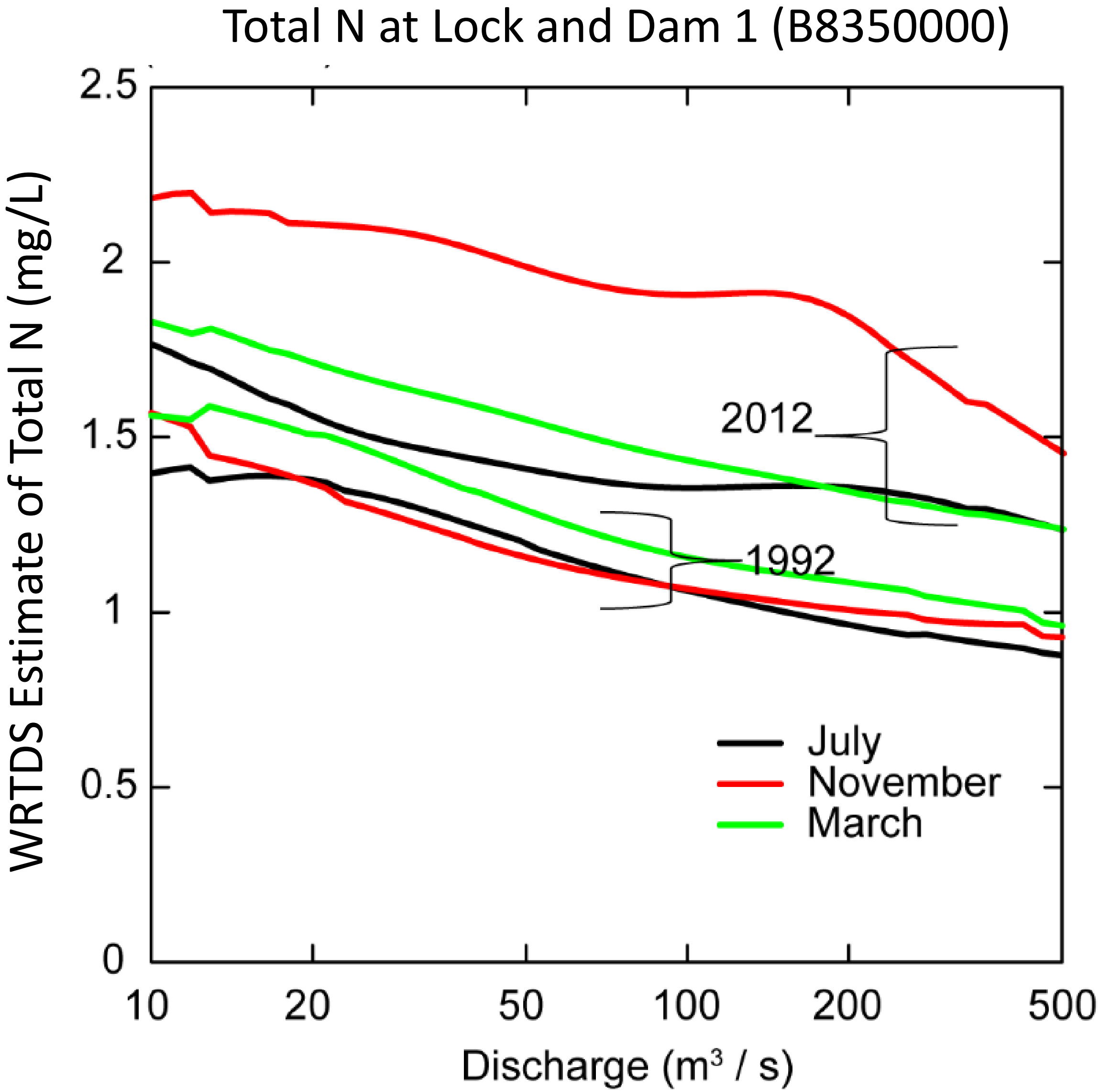
Assessing Uncertainty in Trends Using the WRTDS Approach



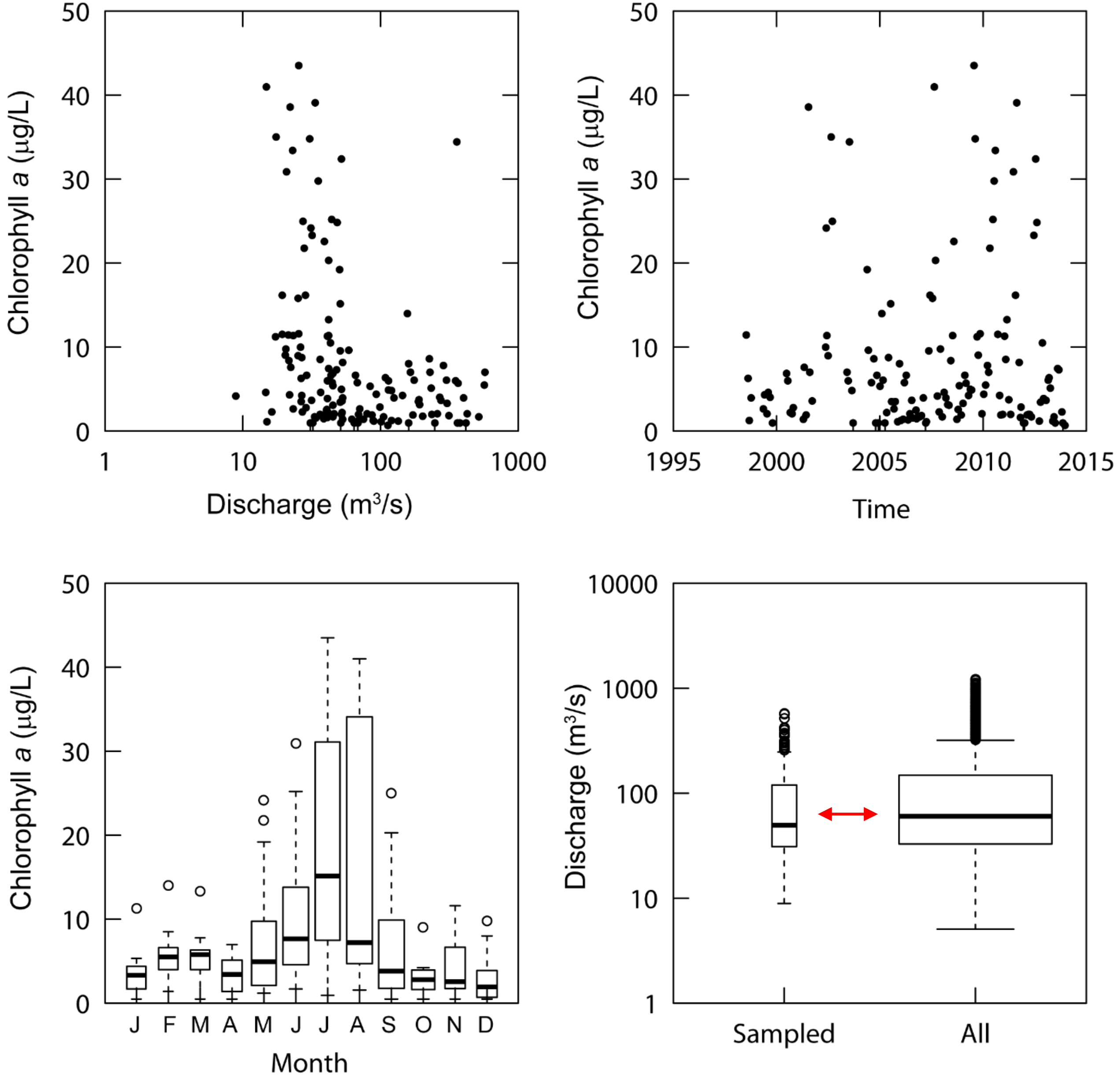
Exploratory Power: Changes in Concentration Under Different Flow Regimes



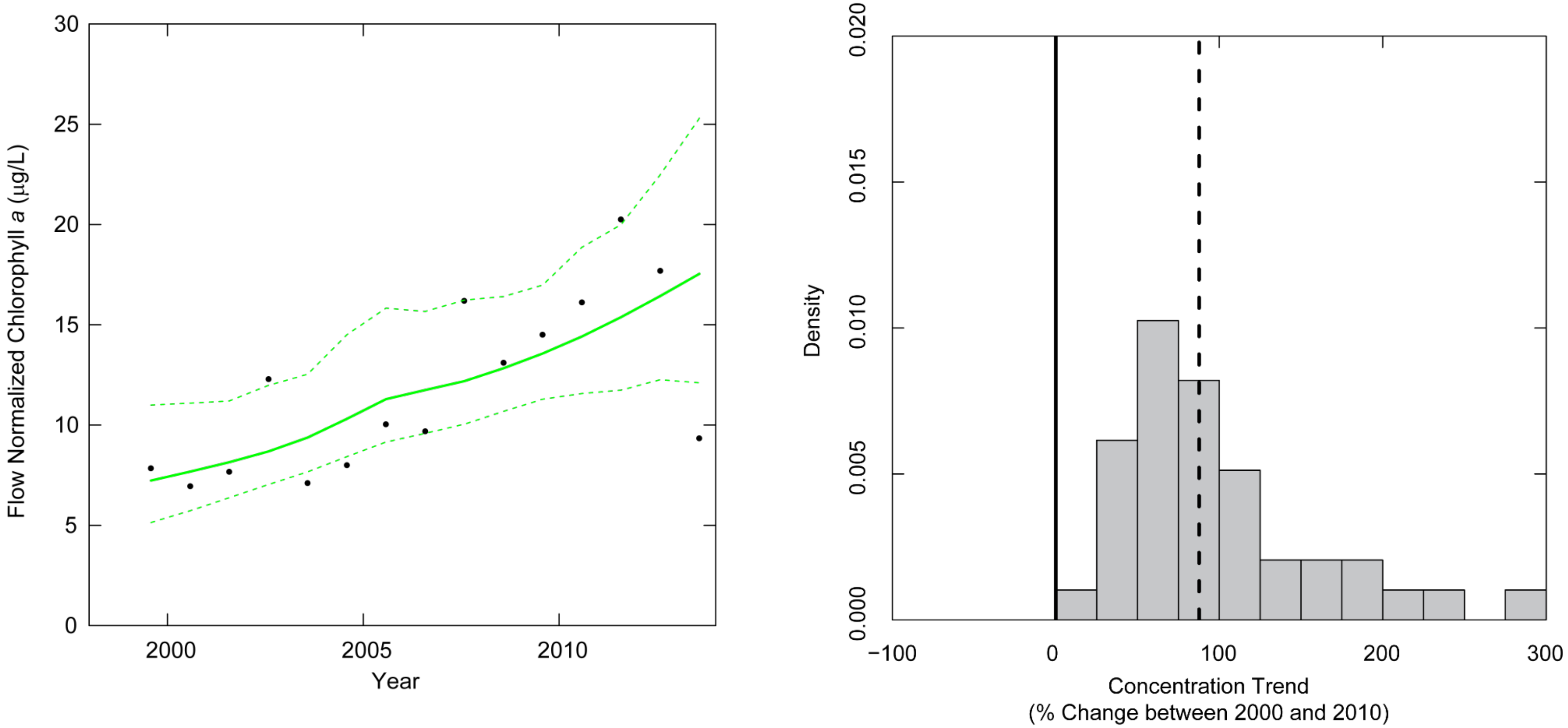
Exploratory Power: Changes in Concentration Vs Flow and Seasonality



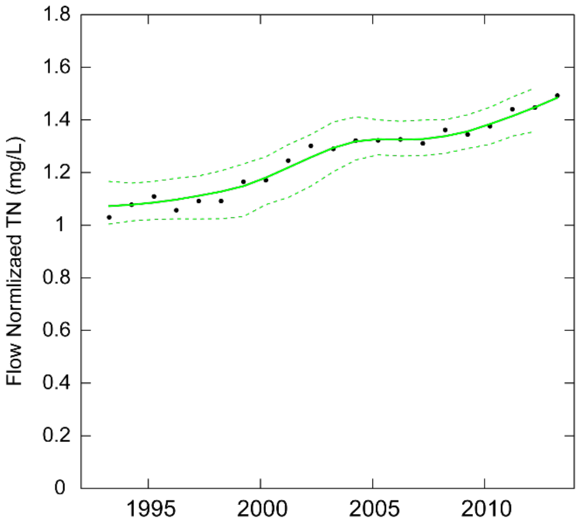
Overview of Chlorophyll *a* Data at Station B8349000 at Lock and Dam 1

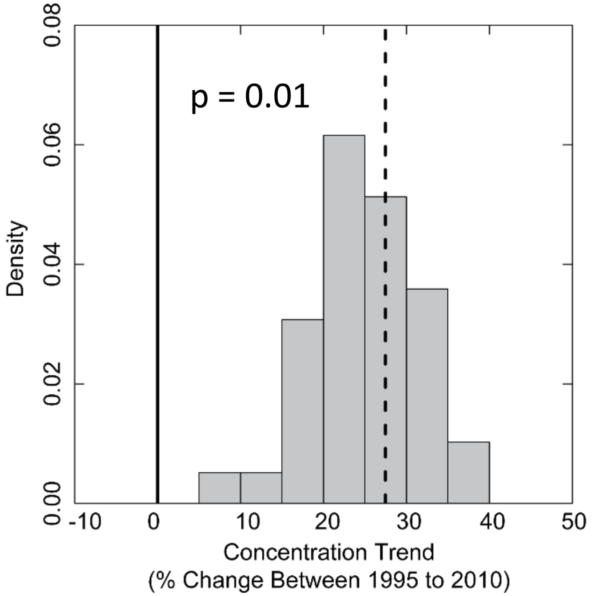


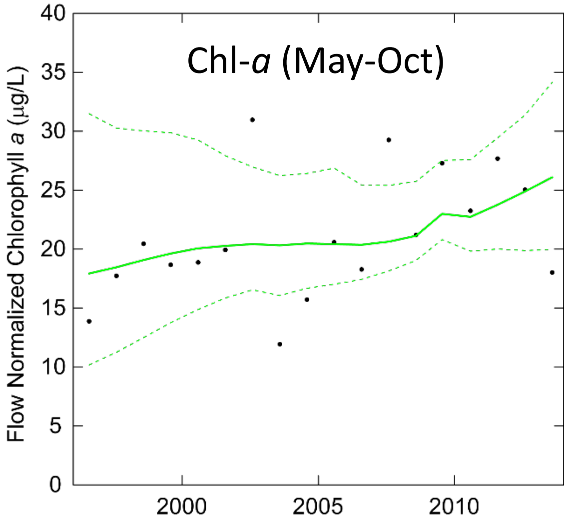
Long term trend in summer chlorophyll *a* (May-Oct) at station B8349000 at Lock and Dam 1

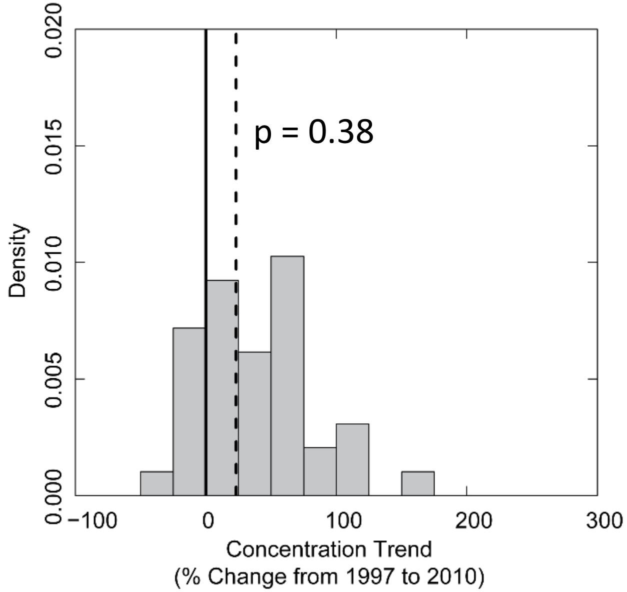


Trends in TN and Chlorophyll *a* at B6160000
Near Haw/Deep Confluence, Upstream of Buckhorn Dam









Sea Grant
North Carolina

Cape Fear R. *Microcystis* Bloom Project

UNC
INSTITUTE OF
MARINE SCIENCES

PLANKTOS
INSTRUMENTS

NC STATE
UNIVERSITY

Cape Fear
Public Utility Authority

Harnett
COUNTY
NORTH CAROLINA
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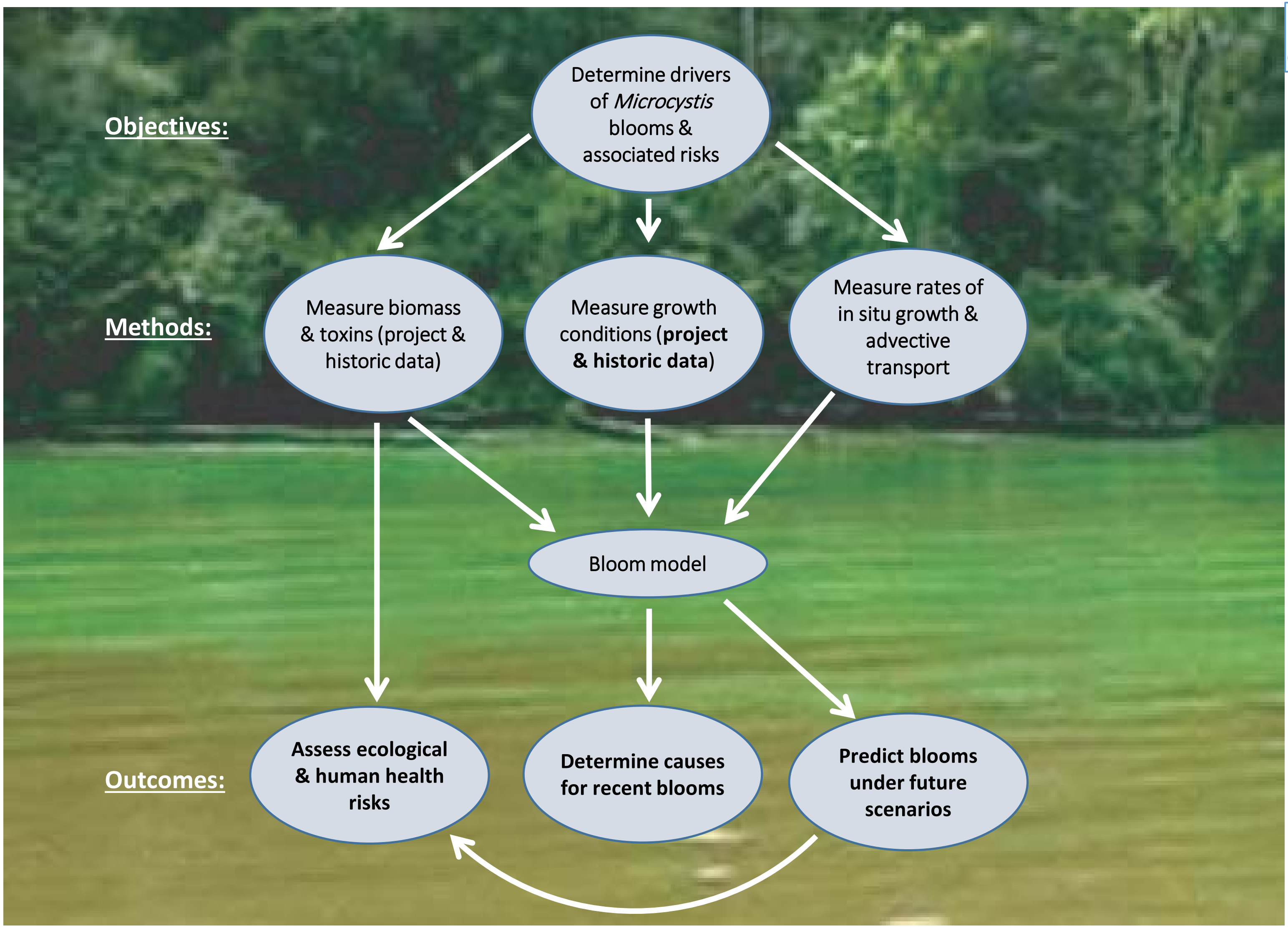
HOMETOWN UTILITY

BRUNSWICK COUNTY
NORTH CAROLINA



Objectives:

Determine drivers of *Microcystis* blooms & associated risks

Methods:

Measure biomass & toxins (project & historic data)

Measure growth conditions (**project & historic data**)

Measure rates of in situ growth & advective transport

Bloom model

Outcomes:

Assess ecological & human health risks

Determine causes for recent blooms

Predict blooms under future scenarios

Cape Fear River *Microcystis* bloom study

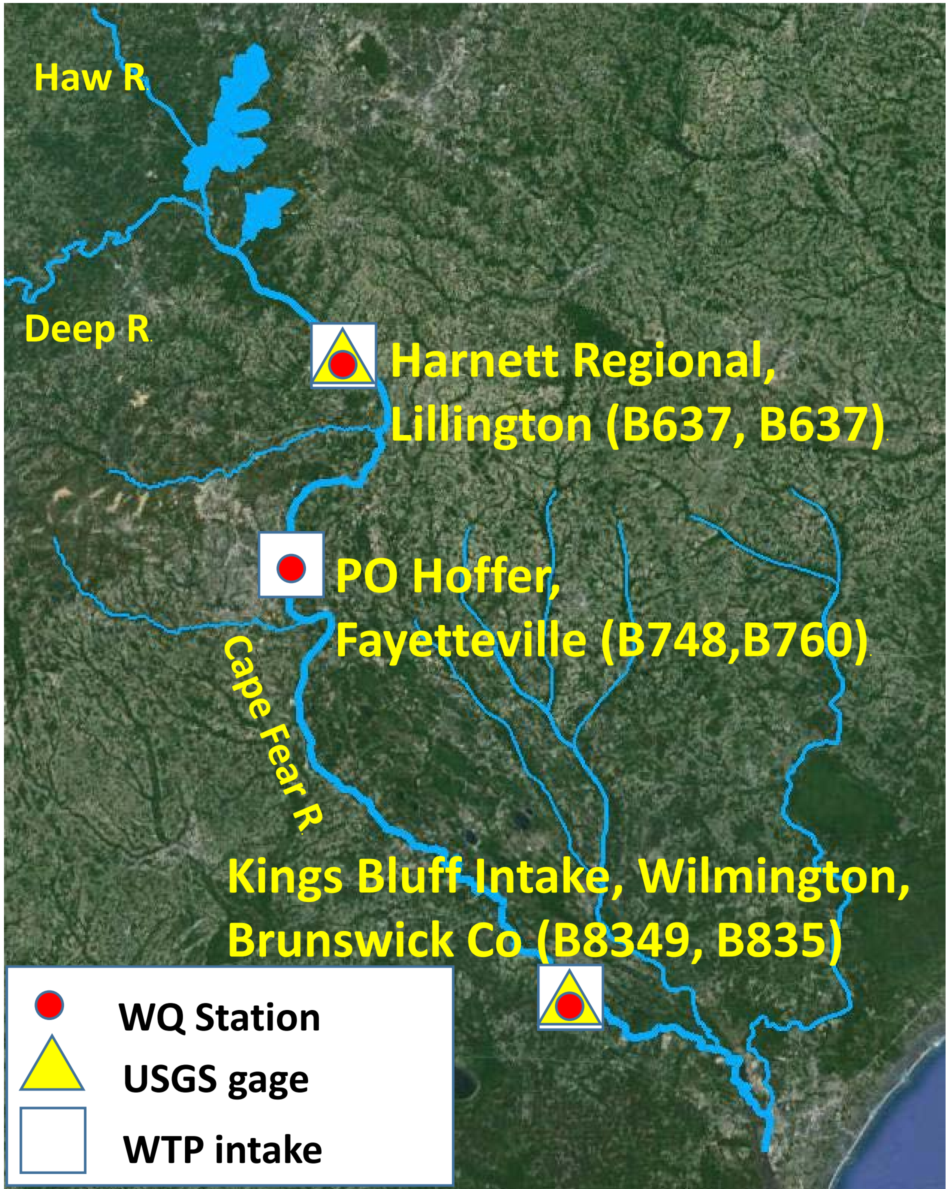
Funding:
NC Sea Grant

Who:
PIs-Paerl, Hall, Schnetzer, & Ensign
Collaborators- 4 WTPs, MCFRBA, DWR

When:
June-September of 2016 and 2017

Where:
3 WTP intakes collocated with
MCFRBA/ DWR stations

Map of focal sites



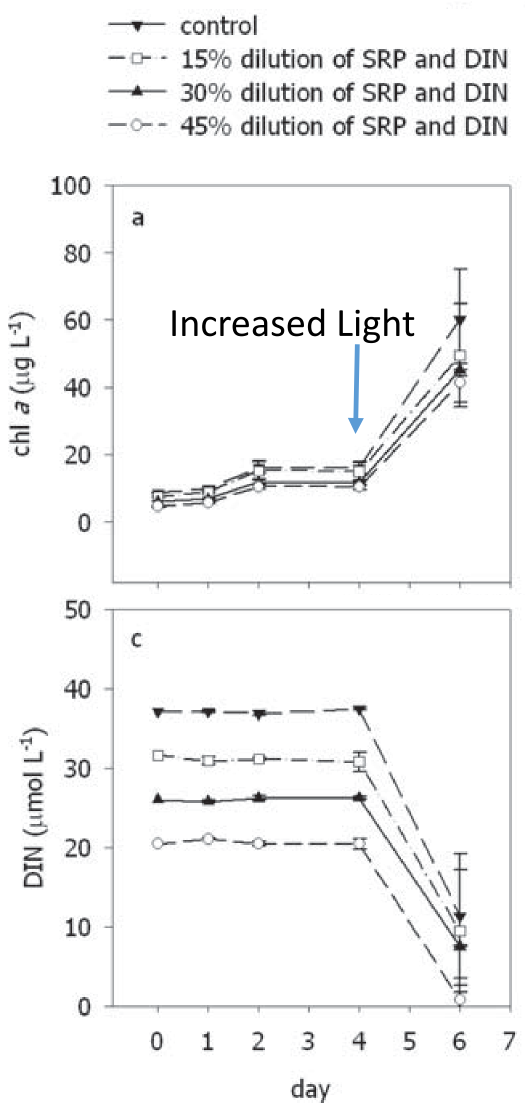
“the appropriate combination of environmental factors necessary to favor proliferation of Cyanobacteria seems unlikely to occur in the middle CFR”
(Dubbs and Whalen 2008)

Background image photo credit: Stephanie Pettergarrett, NCDENR-DWR

Photo credit: Me (I think?)

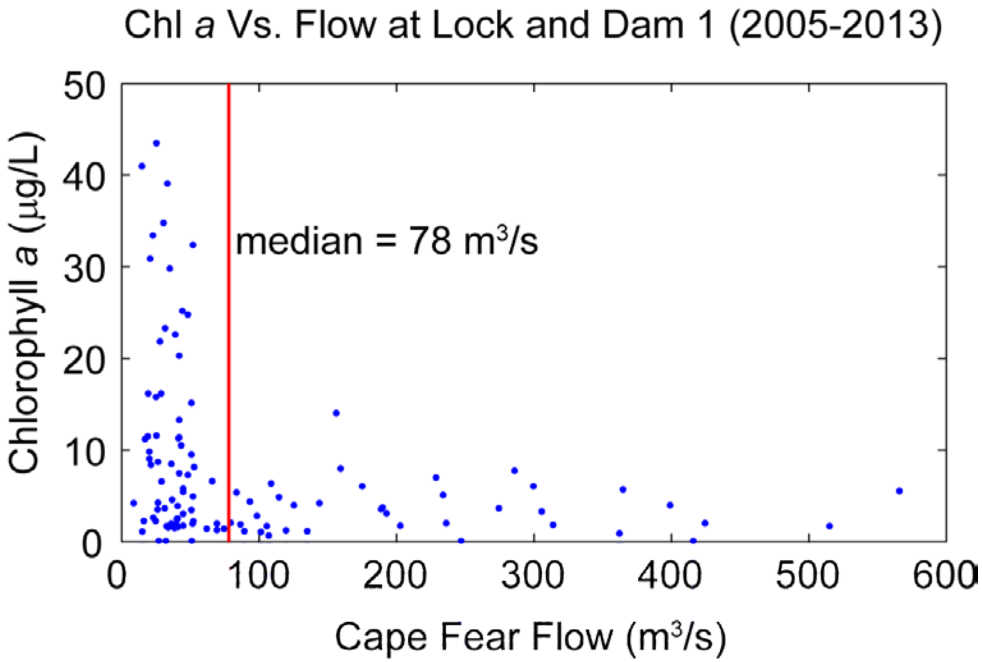
Blooms started the next summer in 2009,
then 2010, 2011, 2012

Hypothesis 1: Bloom development is regulated by river flow acting at the population level by controlling down-stream transit time and at the cellular level by controlling light availability (depth & turbidity).



Increased Light

Dubbs and Whalen 2008

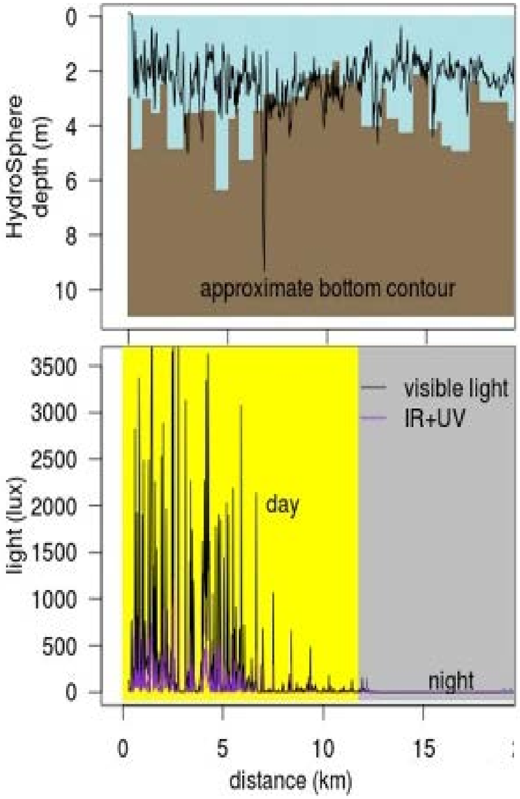

Chl *a* Vs. Flow at Lock and Dam 1 (2005-2013)

Hypothesis 2: Toxicity is related to *Microcystis* biomass.

Determining *in situ* growth rates during downstream transit

1) Direct measurement using novel Hydrosphere drifter assay

Hydrosphere Deployment on Neuse River



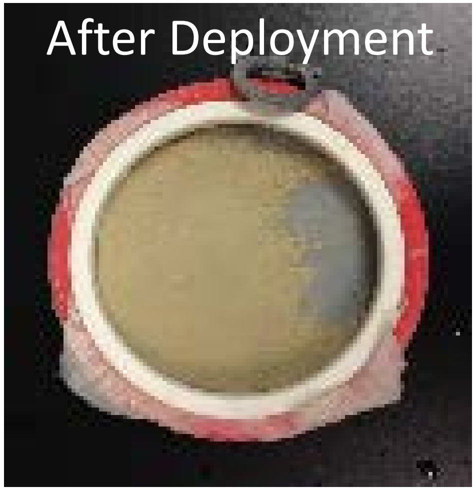
Ensign, Gardner, and Doyle, in prep

2) Modeled growth rate based on observed light and temperature conditions

3) Modeled biomass based on growth rate and time of travel (Christian et al. 1986)

Measurements of Biomass and Toxins

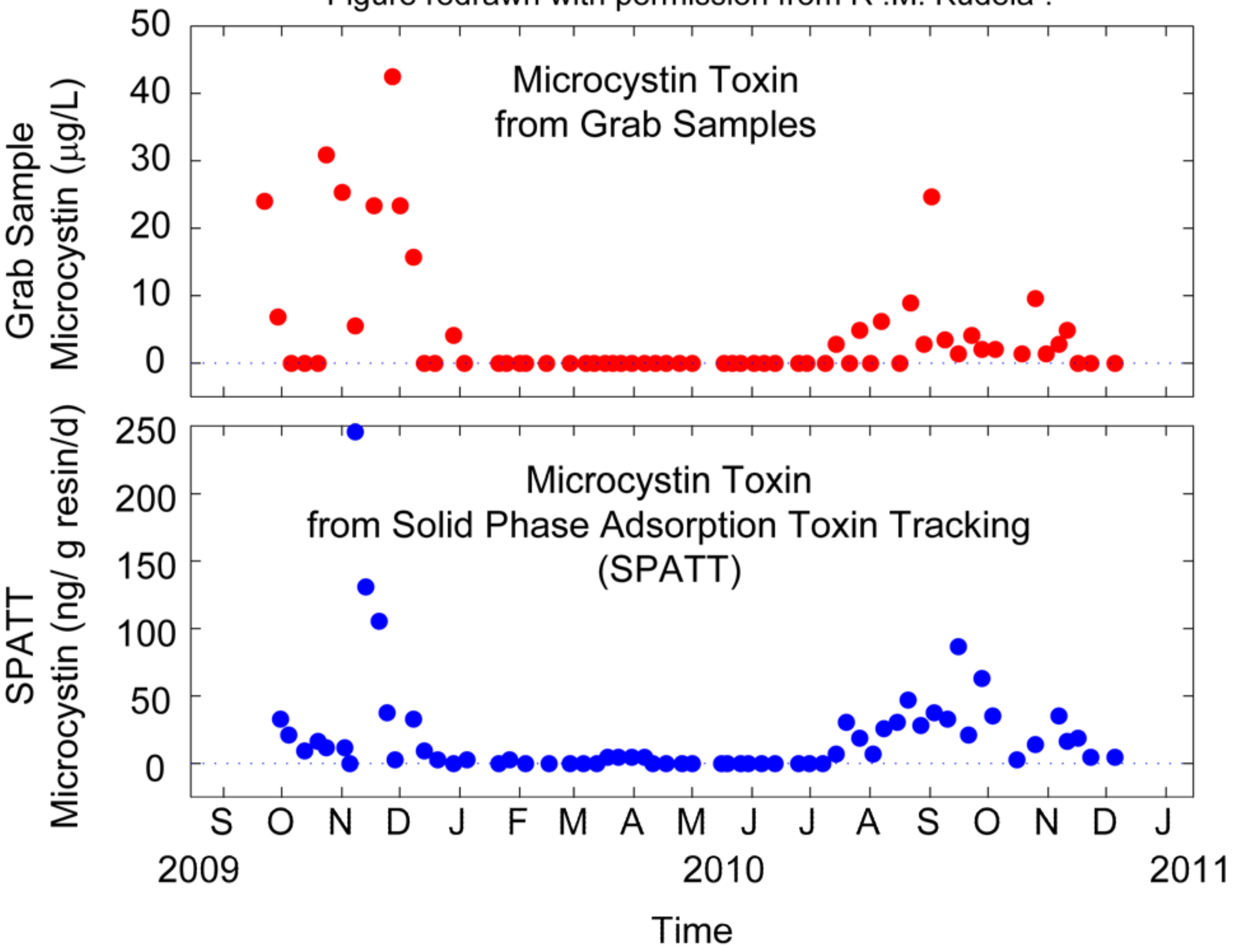
SPATT



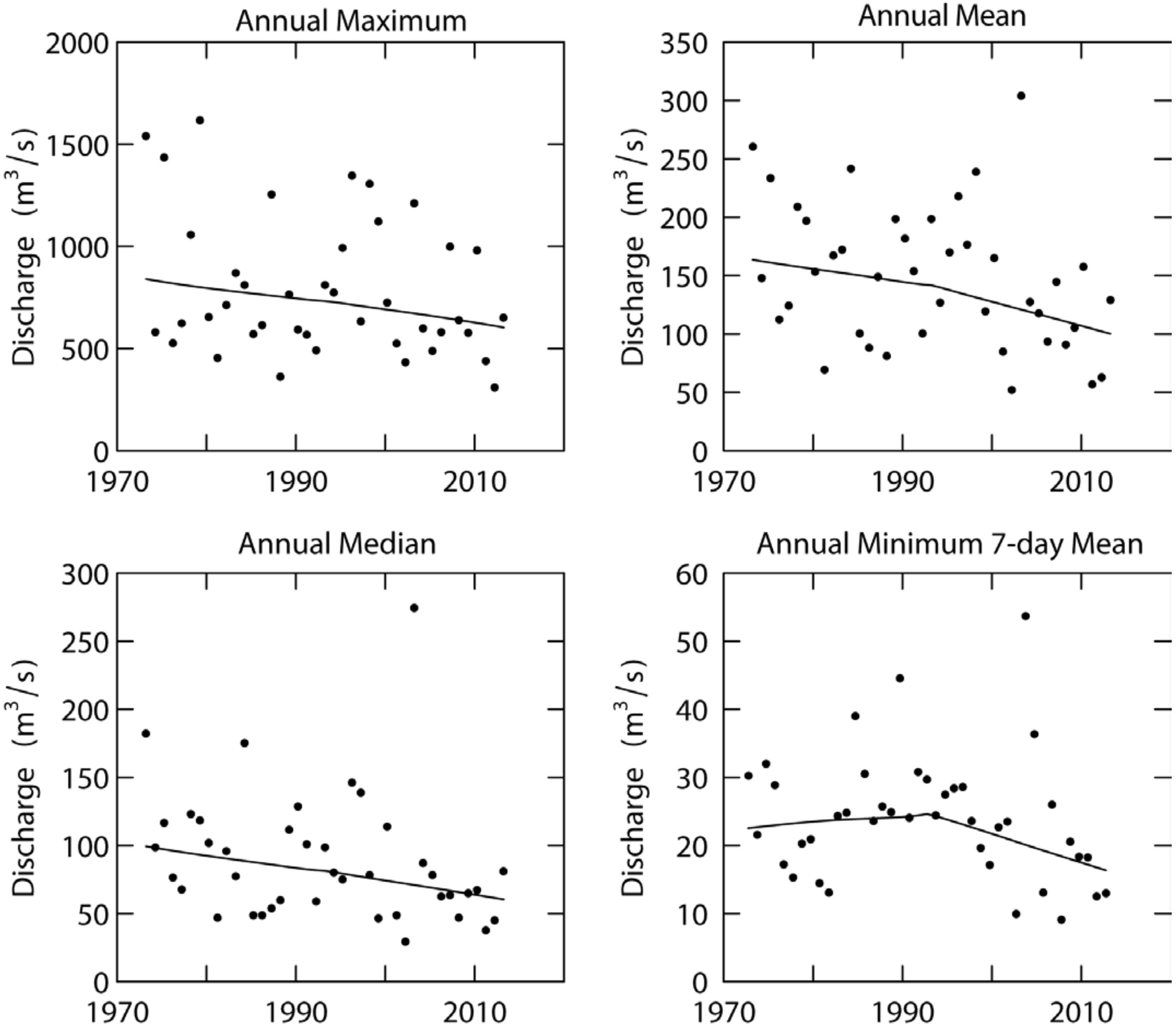
Biweekly measurements at 3 WTPs

1) Discrete microcystin dissolved & particulate
2) Discrete *Microcystis* and total biomass (chl-a)
3) SPATT deployments for time-integrated microcystin assessment

Figure redrawn with permission from R .M. Kudela[1].



Long-term Trends in Flow Statistics at Lock and Dam 1



F1000Research 2016, 5:151 Last updated: 22 FEB 2016

Associations between chlorophyll *a* and various microcystin-LR health advisory concentrations [version 1; referees: 1 approved with reservations]

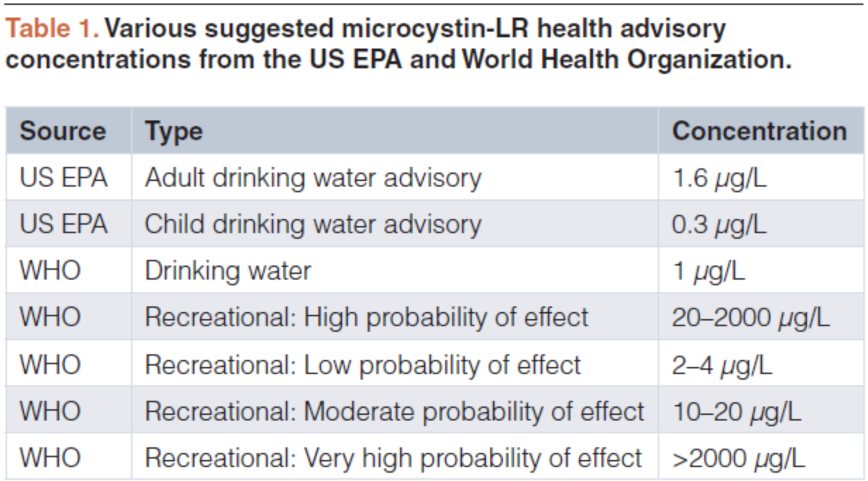


Table 1. **Various suggested microcystin-LR health advisory concentrations from the US EPA and World Health Organization.**

Source	Type	Concentration
US EPA	Adult drinking water advisory	1.6 μg/L
US EPA	Child drinking water advisory	0.3 μg/L
WHO	Drinking water	1 μg/L
WHO	Recreational: High probability of effect	20–2000 μg/L
WHO	Recreational: Low probability of effect	2–4 μg/L
WHO	Recreational: Moderate probability of effect	10–20 μg/L
WHO	Recreational: Very high probability of effect	>2000 μg/L

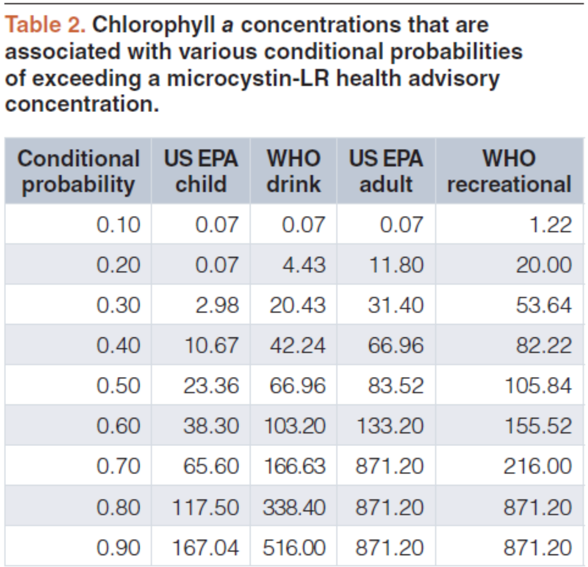


Table 2. **Chlorophyll *a* concentrations that are associated with various conditional probabilities of exceeding a microcystin-LR health advisory concentration.**

Conditional probability	US EPA child	WHO drink	US EPA adult	WHO recreational
0.10	0.07	0.07	0.07	1.22
0.20	0.07	4.43	11.80	20.00
0.30	2.98	20.43	31.40	53.64
0.40	10.67	42.24	66.96	82.22
0.50	23.36	66.96	83.52	105.84
0.60	38.30	103.20	133.20	155.52
0.70	65.60	166.63	871.20	216.00
0.80	117.50	338.40	871.20	871.20
0.90	167.04	516.00	871.20	871.20