Cyanobacteria:
Causes, Consequences, Controls

PA AWWA 2015

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Note: All information presented will be explained in greater detail in a publication in press at NE AWWA Journal, which will be available online.

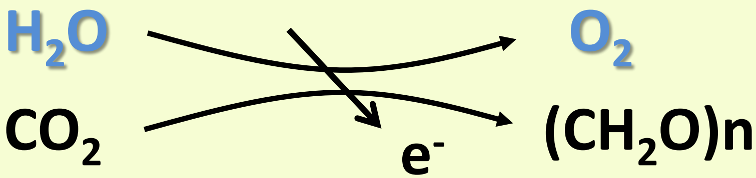
- **Cyanobacteria** is a **Phylum of Bacteria** that obtain energy via Photosynthesis
- **Cyanobacteria** are Prokaryotic (*Algae are Eukaryotic*)
- **Cyanobacteria** Have a High Protein Content (Amine Groups)
    - (Indeed, some Cyanobacteria are sold as Health Food Supplements)

"A Bluegreen Algae Bloom is Meat…not Salad"

Peter H. Rich, Ph.D.

Cyanobacteria account for more than half of the photosynthesis of the open ocean.

- **Cyanobacteria** have inhabited Earth for over 2.5 Billion Years
  - *Evolved the ability to use Water as an Electron Donor in Photosynthesis. (Why we have an Aerobic Atmosphere in which to live)*

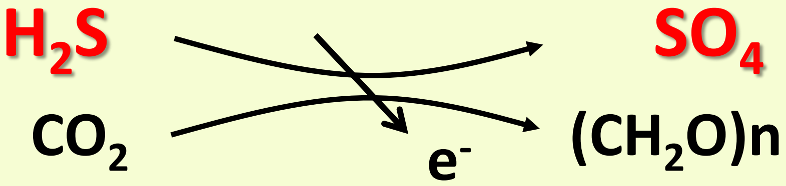


H_2O O_2

CO_2 e^- $(CH_2O)n$

Cyanobacteria have evolved many Competitive Strategies

- **Cyanobacteria *can just use Cyclic Photophosphorylation (PSI) with Alternate Electron Donors in Anaerobic Environments (Low Light Requirement)***

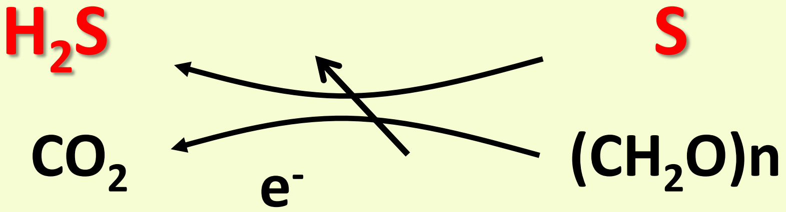


H_2S SO_4

CO_2 e^- $(CH_2O)n$

(Chemolithotrophy)
(Photolithotrophy)
(Golterman, 1975)

- Some **Cyanobacteria can reduce elemental sulfur**



H_2S S

CO_2 e^- $(CH_2O)n$

(*Anaerobic Respiration*)

Competitive Advantages: Physical Conditions

Light Intensity

Accessory Pigments – Harvest Green, Yellow, Orange Wavelengths

Can Live in Environments with only Green Light

Can Grow in Low Light (Deeper)

Gas Vesicles

Increase in Low Light when the growth rate slows

Increased Photosynthesis Decreases Gas Vesicles, reducing buoyancy

Carbohydrate Production and Consumption- Buoyancy Changes

Growth Rate

Slower than most Algae Under Optimal Light at 20 ^{o}C:

Cyanobacteria	0.3 – 1.4 Doublings / Day
Diatoms	0.8 – 1.9 Doublings / Day

Long Retention Time favors Cyanobacteria

Biomass Accumulation more problematic than Growth Rate (Grazing)

Temperature

High Optimum Temperature

(>25 ^{o}C; higher than for Diatoms and Green Algae)

Akinetes- Dormant Resting Cells (Light and Temp Triggers)

Competitive Advantages: Chemical Conditions

High Affinity for Phosphorus and Nitrogen

- Can out-compete Other Phytoplankton when N or P becomes Limiting
- High Phosphorus Storage Capacity (2-4 Cell Divisions; upto 32x Biomass)
- Low N:P Ratio Favors Cyanobacteria
  - Esp. N-Fixing Cyanobacteria

Carbon Source

- Free Carbon Dioxide is needed by Phytoplankton
- No Free CO_2 available above pH 8.3
- Cyanobacteria are more capable of using Carbonate (and low CO_2)
  - (and can live as heterotrophs or chemotrophs)

Silica and Inorganic Nitrogen (Nitrate)

- Diatoms and Green Algae become limited by Silica and Nitrate
  - Cyanobacteria are released from competition
- Some Cyanobacteria Fix Atmospheric Nitrogen

Competitive Advantages: Biological and Ecological Conditions

Slow Grazing Rate favors Cyanobacteria

- Land-Locked Alewife Populations
- Not Grazed to the same extent as other Phytoplankton

Taste and Odor Episodes

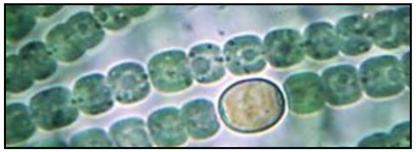
Geosmin (G) and 2-Methyl Isoborneol (MIB) Producers

Hyella sp.		Epiphytic		MIB
cf. Microcoleus sp.		Epiphytic	G	
Anabaena circinalis		Planktonic	G	
Anabaena crassa		Planktonic	G	
Anabaena lemmermanii		Planktonic	G	
Anabaena macrospora		Planktonic	G	
Anabaena solitaria		Planktonic	G	
Anabaena viguieri		Planktonic	G	
Aphanizomenon flos-aquae		Planktonic	G	
Aphanizomenon gracile		Planktonic	G	
Oscillatoria limosa		Planktonic		MIB
Planktothrix agardhii	*Oscillatoria agardhii*	Planktonic	G	MIB
Planktothrix cryptovaginata	*Lyngbya cryptovaginata*	Planktonic		MIB
Planktothrix pernornata	*Oscillatoria pernornata*	Planktonic		MIB
Planktothrix pernornata var. attenuata	*Oscillatoria pernornata var. attenuata*	Planktonic		MIB
Pseudanabaena catenata		Planktonic	G	MIB
Pseudanabaena limnetica	*Oscillatoria limnetica*	Planktonic		MIB
Symploca muscorum		Soil	G	

Cyanotoxins

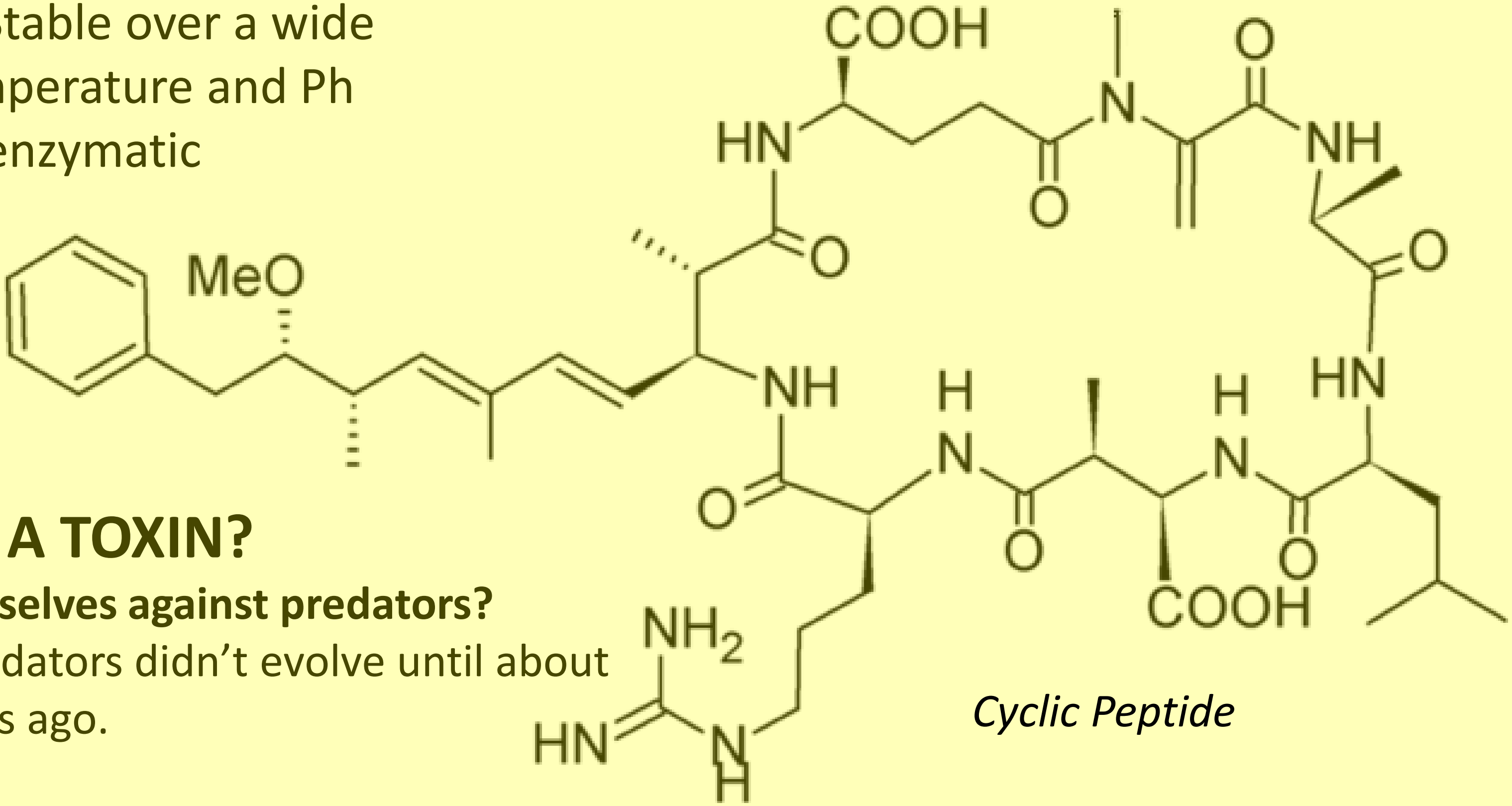
TOXIN GROUP	Cyanobacteria genera	Affects	Ecostrategist Categories	Natural Forcing Factors
Alkaloids				
Anatoxin-a	***Anabaena, Aphanizomenon,*** *Planktothrix (Oscillatoria)*	Nerve Synapse	Buoyant N-Fixers	N:P Ratio, pH, Temp, De, Light Penetration, Grazing Rate
Aplysiatoxins	*Planktothrix (Oscillatoria), Lyngbya, Schizothrix*	Skin Rash	Benthic, Stratifying,	Stratification Boundaries, Light Penetration
Cylindrospermopsins	*Cylindrospermopsis,* ***Aphanizomenon***	Liver Function	Buoyant N-Fixers	N:P Ratio, pH, Temp, De, Light Penetration, Grazing Rate
Lyngbyatoxin	*Lyngbya*	Gastro-Intestinal, Skin	Benthic, Stratifying, Buoyant	Stratification Boundaries, Light Penetration
Saxitoxins	***Aphanizomenon*** *, Cylindrospermopsis*	Nerves	Buoyant N-Fixers	N:P Ratio, pH, Temp, De, Light Penetration, Grazing Rate
Cyclic Peptides				
Microcystins	*Microcystis,* ***Anabaena*** *, Planktothrix (Oscillatoria), Nostoc*	Liver Function	Buoyant N-Fixers	N:P Ratio, pH, Temp, De, Light Penetration, Grazing Rate
Nodularin	*Nodularia*	Liver Function	Brackish	Nitrogen Availability and Form

Cyanotoxins are not produced by all species of a genera, and a specific population may or may not be producing a toxin.



Microcystins :

- chemically Stable over a wide range of Temperature and Ph
- resistant to enzymatic hydrolysis



Cyclic Peptide

WHY MAKE A TOXIN?

To defend themselves against predators?

But: Animal predators didn't evolve until about 600 million years ago.

Protects proper function of several proteins under intense sunlight?

M**olecular pantry?**

Stores Nitrogen and Carbon when plentiful, supplies it when not abundant.

A number of studies have linked increased toxin production with increased nitrogen concentrations. Perhaps the N Storage Function is a critical factor (re: "Toledo, OH").

Cyanobacteria Ecostrategists

Scum-Forming Ecostrategists

e.g. *Anabaena, Aphanizomenon, Microcystis*

High Photosynthesis- Carbohydrates Accumulate- Ballast-Sink

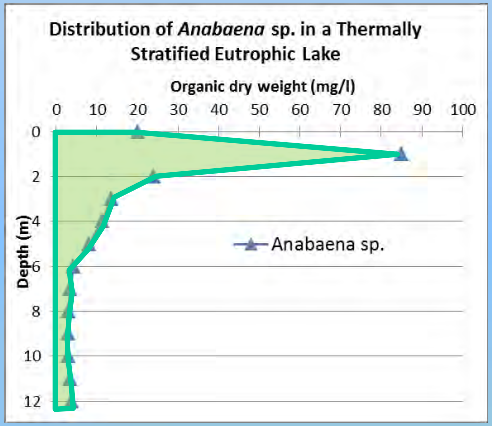
Respiration Consumes Carbohydrate- New Gas Vesicles- Buoy

Nitrogen Fixing Ecostrategists

e.g. *Anabaena, Aphanizomenon, Cylindrospermopsis, Nodularia, Nostoc*

N-Fixation Requires High Light Energy (“Expensive to perform”)

Management: Important to Reduce P while Maintaining Higher N:P

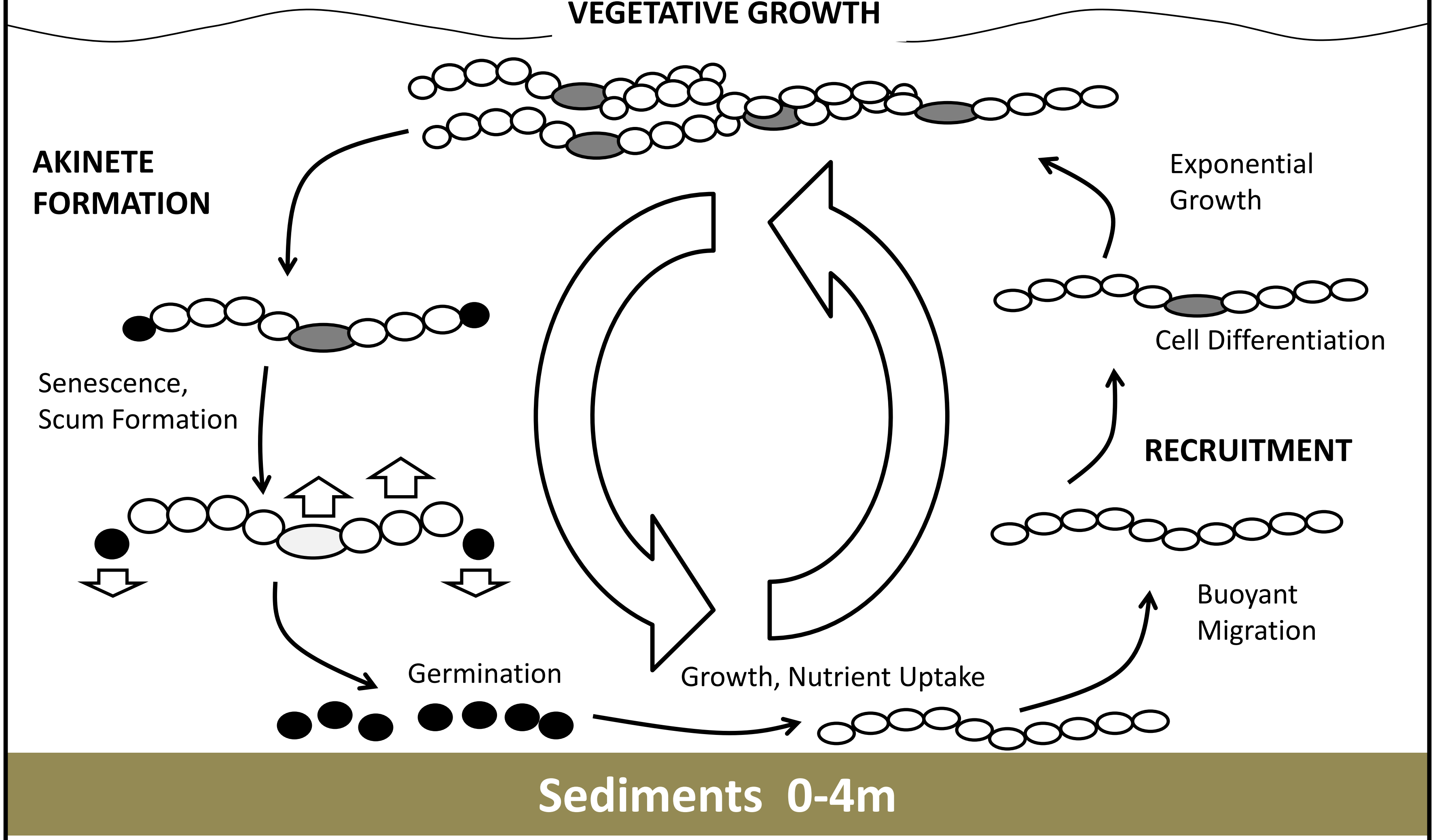


Benthic Ecostrategists

e.g. *Oscillatoria*

Life Cycle of N-Fixing Akinete-Forming Cyanobacteria

(*Gleotrichia, Anabaena, Aphanizomenon*)



VEGETATIVE GROWTH

AKINETE FORMATION

Senescence, Scum Formation

Germination

Growth, Nutrient Uptake

Exponential Growth

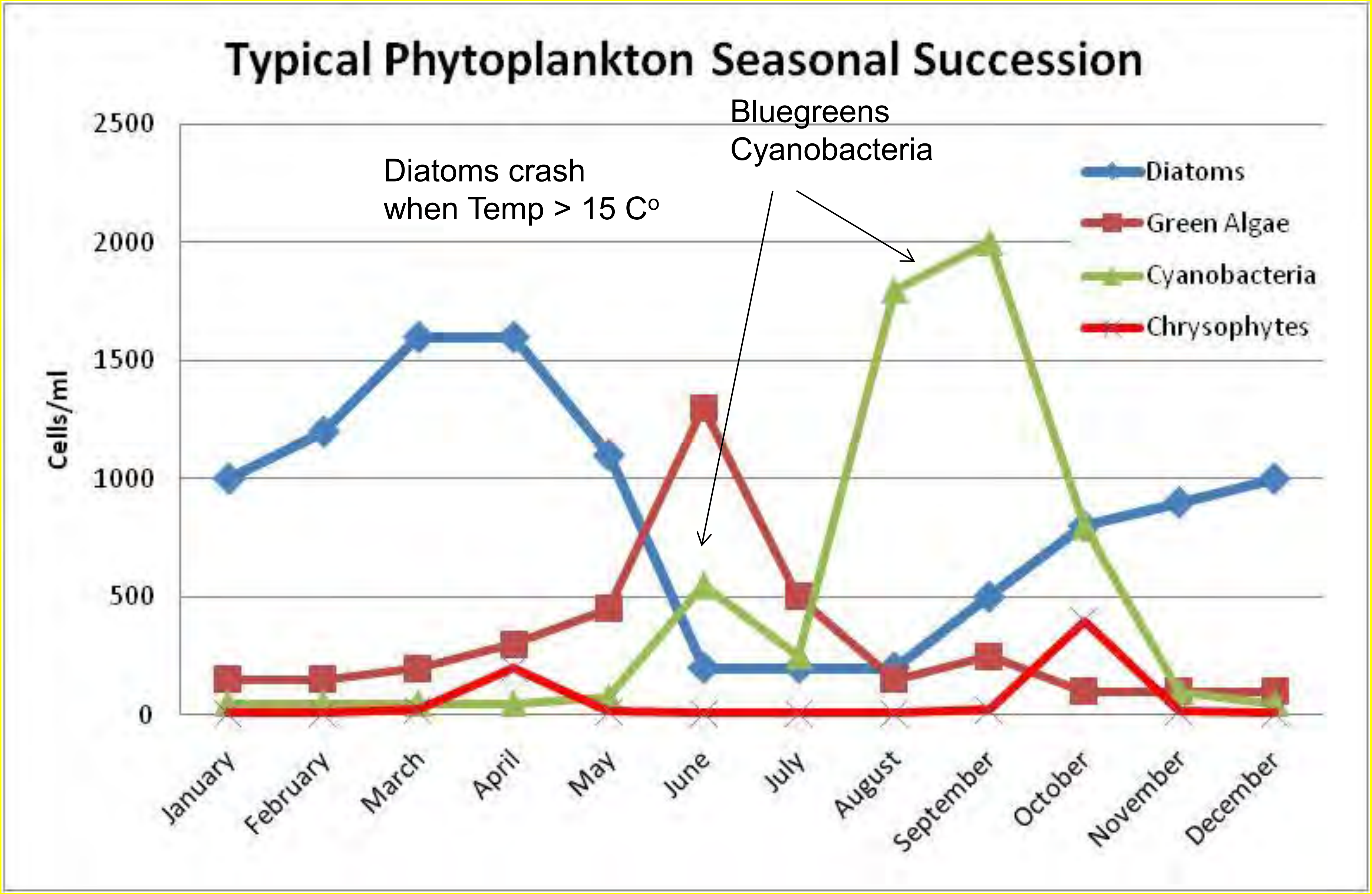
Cell Differentiation

RECRUITMENT

Buoyant Migration

Sediments 0-4m

○ Vegetative Cells ◍ Heterocysts, N-Fixation ● Akinetes

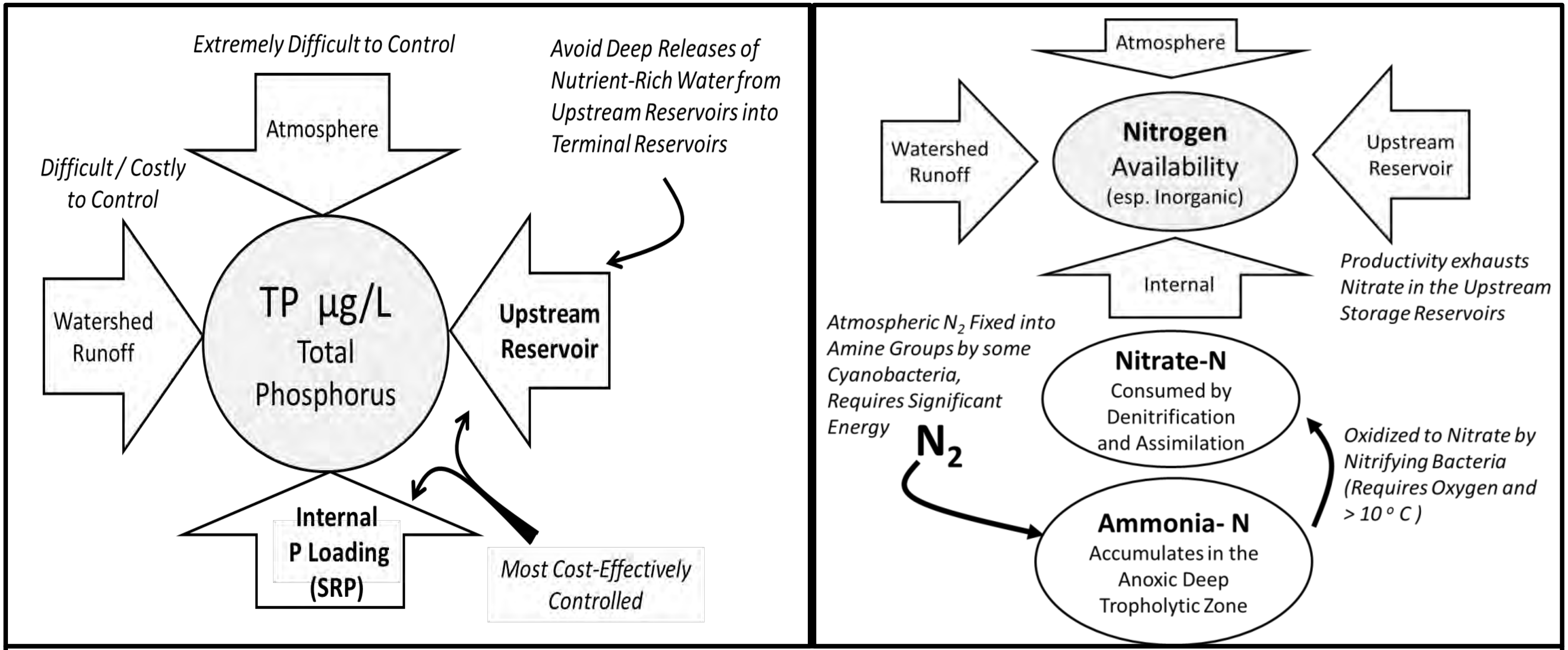


Typical Phytoplankton Seasonal Succession

Diatoms crash when Temp > 15 C°

Bluegreens Cyanobacteria

DIATOMS → GREENS → BLUEGREENS → DIATOMS



Extremely Difficult to Control

Atmosphere

Avoid Deep Releases of Nutrient-Rich Water from Upstream Reservoirs into Terminal Reservoirs

Difficult / Costly to Control

Watershed Runoff

TP µg/L Total Phosphorus

Upstream Reservoir

Internal P Loading (SRP)

Most Cost-Effectively Controlled

Atmosphere

Watershed Runoff

Nitrogen Availability (esp. Inorganic)

Upstream Reservoir

Internal

Productivity exhausts Nitrate in the Upstream Storage Reservoirs

Atmospheric N_2 Fixed into Amine Groups by some Cyanobacteria, Requires Significant Energy

N_2

Nitrate-N Consumed by Denitrification and Assimilation

Oxidized to Nitrate by Nitrifying Bacteria (Requires Oxygen and > 10 ° C)

Ammonia- N Accumulates in the Anoxic Deep Tropholytic Zone

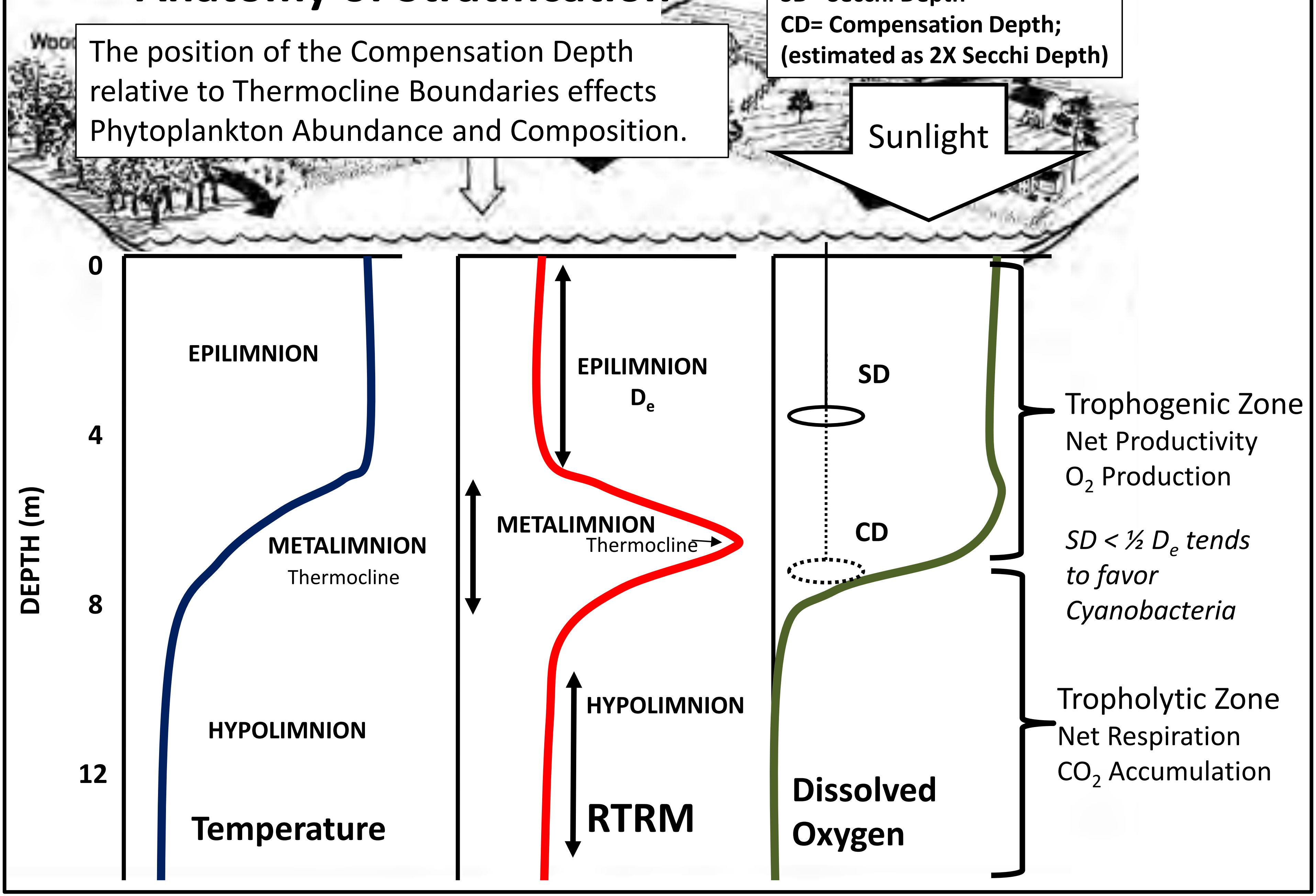
Sources of Nitrogen and Phosphorus in Water Supply Reservoirs and Management Implications.

Figure 2. Sources of Nitrogen and Phosphorus in Water Supply Reservoirs Management needs to control external watershed sources to "Protect the Future of the Resource"; while targeting the sources that are most cost-effectively controlled to "Improve the Expression of Trophic State".

Anatomy of Stratification

The position of the Compensation Depth relative to Thermocline Boundaries effects Phytoplankton Abundance and Composition.

SD= Secchi Depth
CD= Compensation Depth;
(estimated as 2X Secchi Depth)

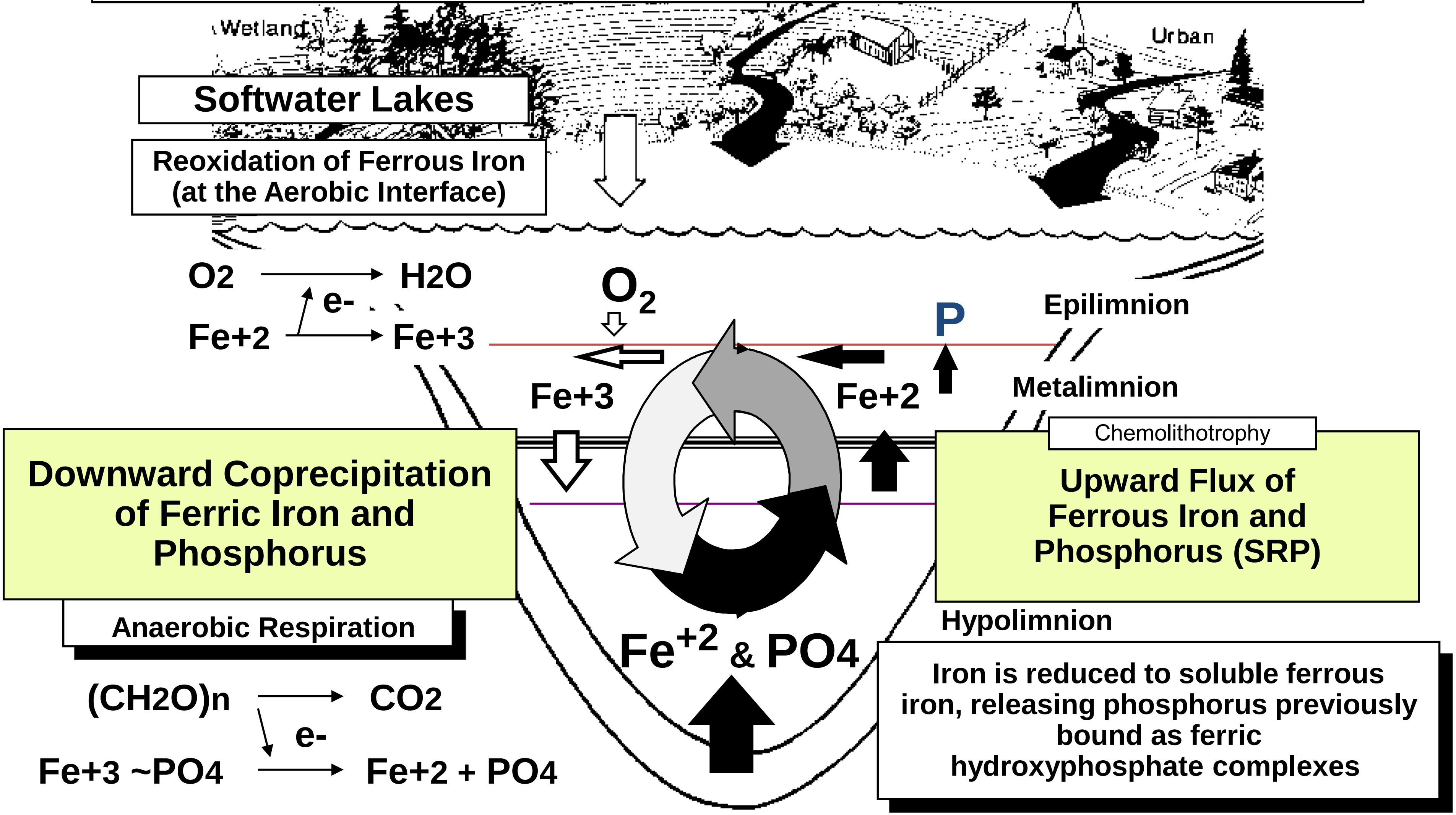


Trophogenic Zone
Net Productivity
O_2 Production

SD < ½ D_e tends to favor Cyanobacteria

Trophlytic Zone
Net Respiration
CO_2 Accumulation

Iron Cycle in New England Reservoirs



Softwater Lakes

Reoxidation of Ferrous Iron (at the Aerobic Interface)

$$\mathrm{O2} \longrightarrow \mathrm{H2O}$$
e-
$$\mathrm{Fe{+}2} \longrightarrow \mathrm{Fe{+}3}$$

Downward Coprecipitation of Ferric Iron and Phosphorus

Anaerobic Respiration

$$\mathrm{(CH2O)n} \longrightarrow \mathrm{CO2}$$
e-
$$\mathrm{Fe{+}3 \sim PO4} \longrightarrow \mathrm{Fe{+}2 + PO4}$$

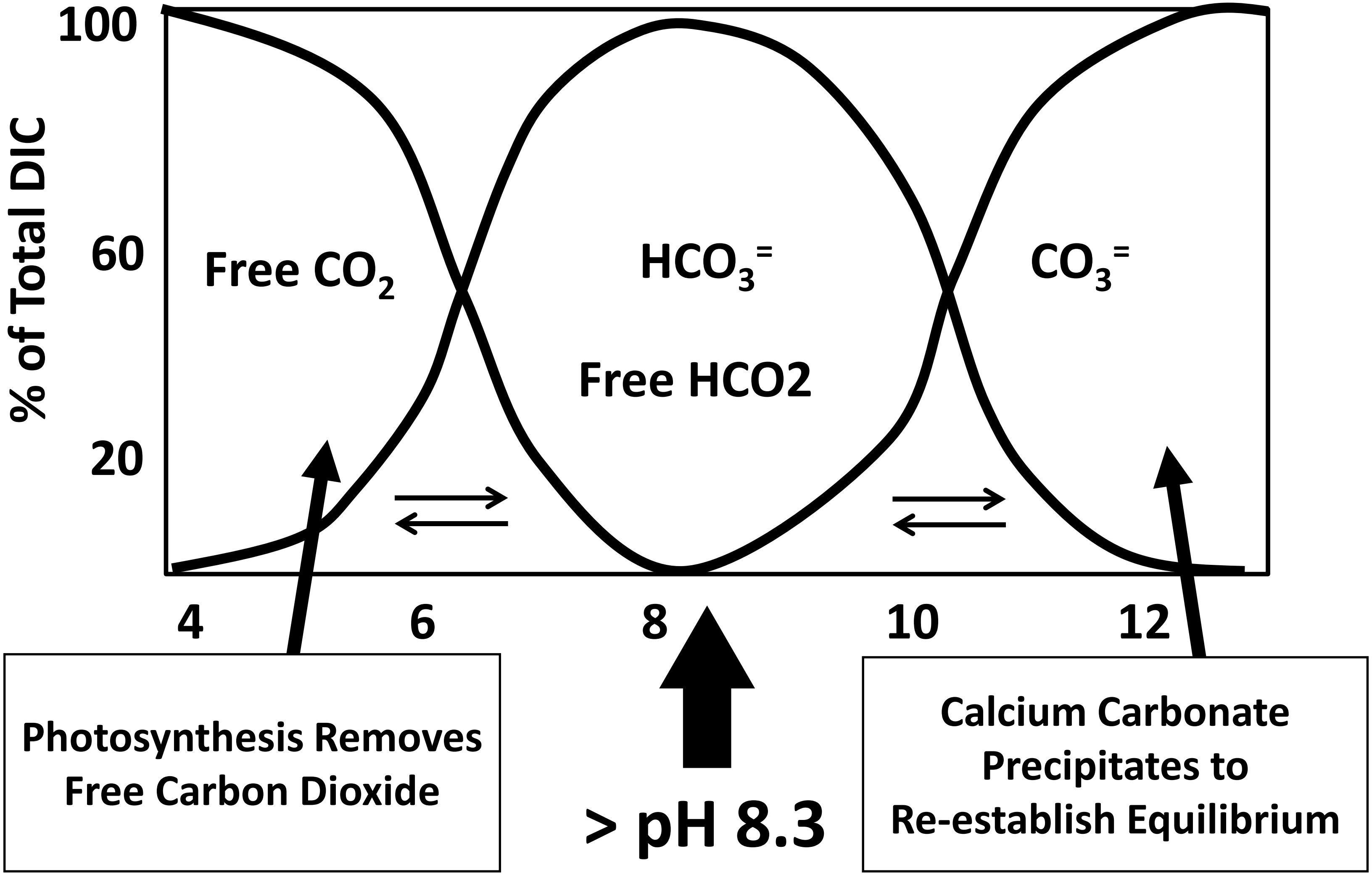
Upward Flux of Ferrous Iron and Phosphorus (SRP)

Iron is reduced to soluble ferrous iron, releasing phosphorus previously bound as ferric hydroxyphosphate complexes

Benthic Detrital Electron Flux (BDEF) is largely carried by the Ferric-Ferrous Redox Couple

Carbonate Buffering System in Fresh Water

DECALCIFICATION PHOSPHORUS REMOVAL



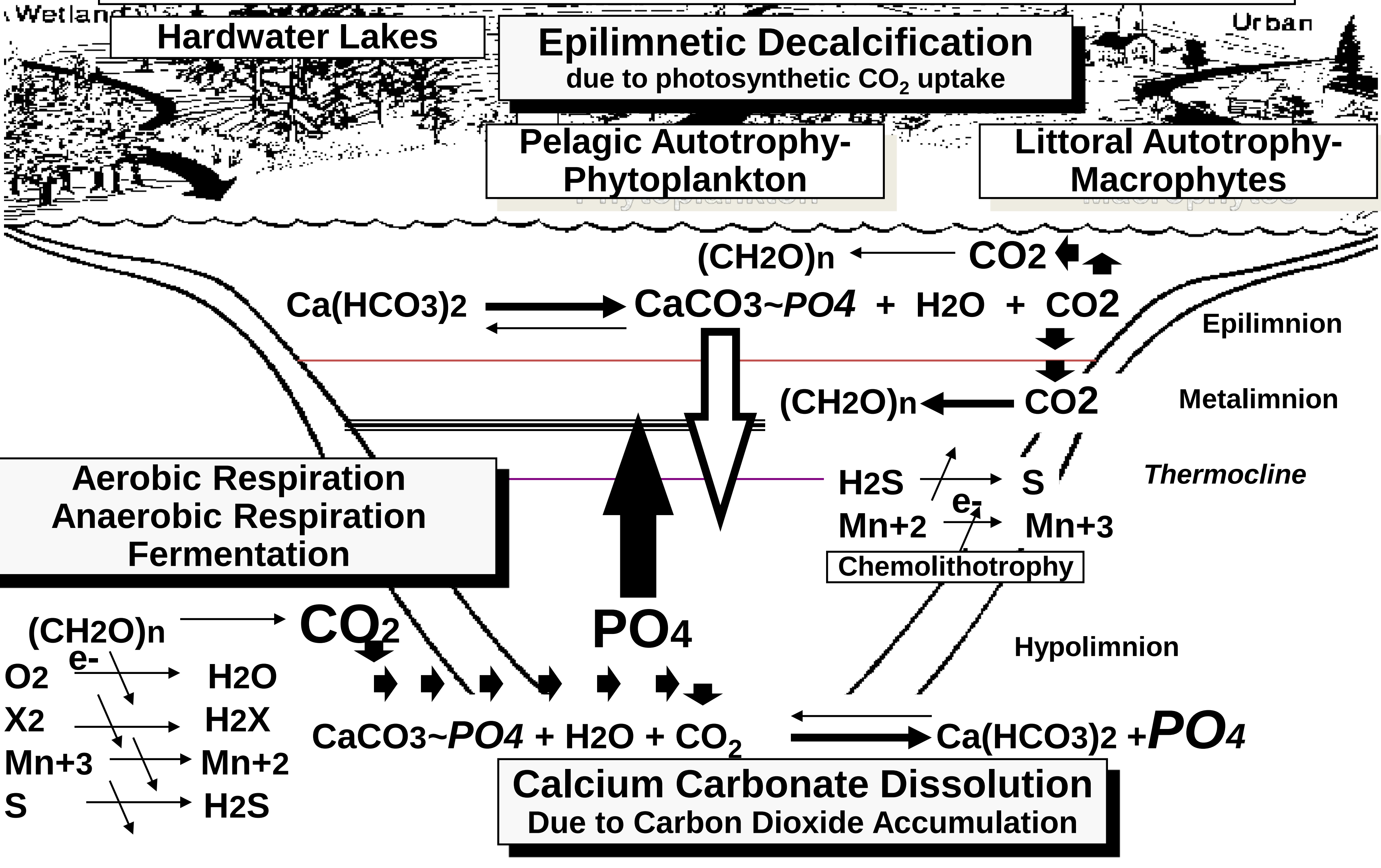
Photosynthesis Removes Free Carbon Dioxide

> pH 8.3

Calcium Carbonate Precipitates to Re-establish Equilibrium

Many algae are more dependent on Free Carbon Dioxide as a carbon source than Cyanobacteria

Carbonate System P Dynamics



Hardwater Lakes

Epilimnetic Decalcification
due to photosynthetic CO_2 uptake

Pelagic Autotrophy-Phytoplankton

Littoral Autotrophy-Macrophytes

$(CH_2O)_n \leftarrow CO_2$

$Ca(HCO_3)_2 \rightleftharpoons CaCO_3{\sim}PO_4 + H_2O + CO_2$

Epilimnion

$(CH_2O)_n \leftarrow CO_2$

Metalimnion

Thermocline

$H_2S \rightarrow S$

e-

$Mn^{+2} \rightarrow Mn^{+3}$

Chemolithotrophy

Aerobic Respiration
Anaerobic Respiration
Fermentation

$(CH_2O)_n \rightarrow CO_2$

PO_4

Hypolimnion

e-

$O_2 \rightarrow H_2O$

$X_2 \rightarrow H_2X$

$Mn^{+3} \rightarrow Mn^{+2}$

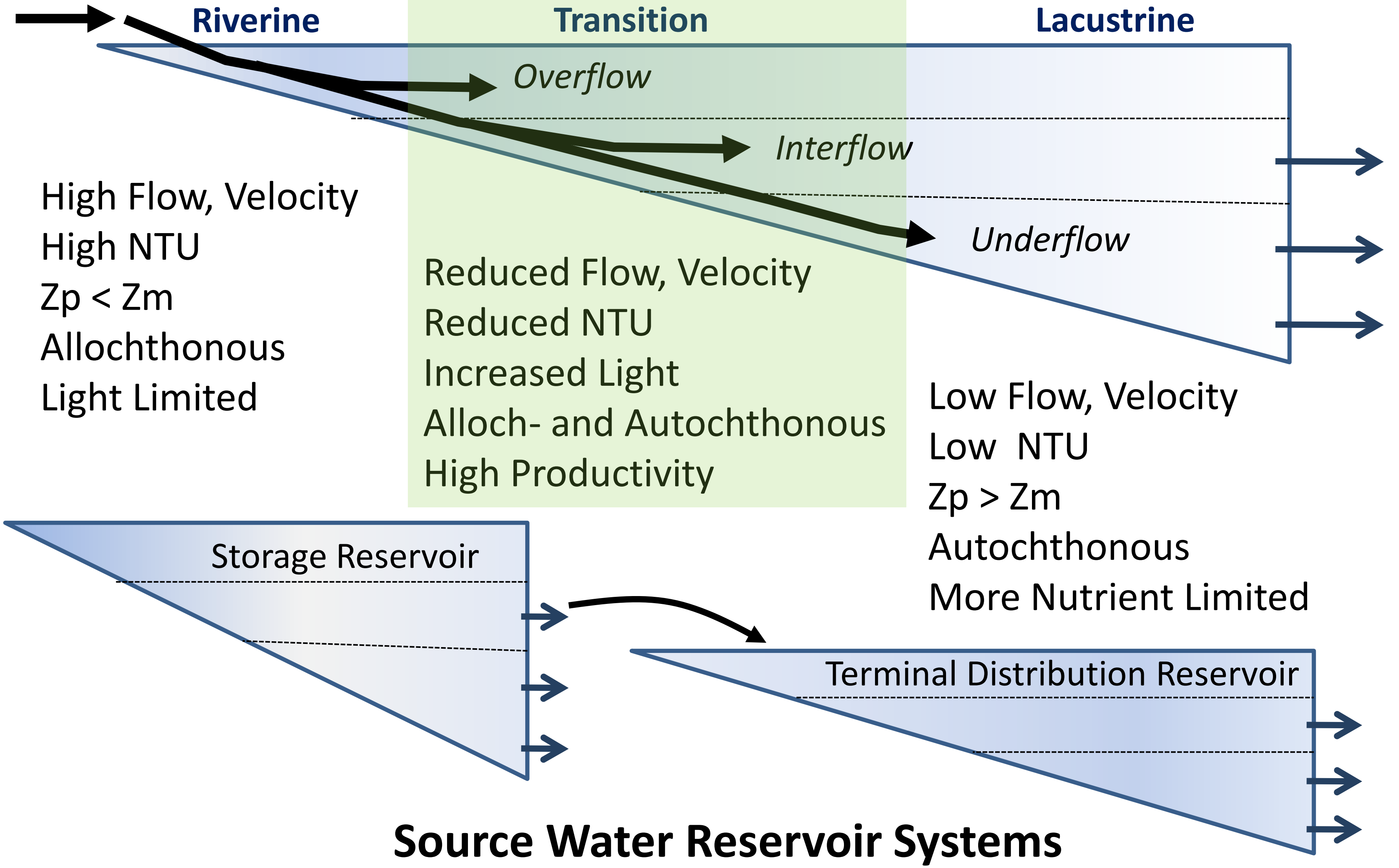
$S \rightarrow H_2S$

$CaCO_3{\sim}PO_4 + H_2O + CO_2 \rightleftharpoons Ca(HCO_3)_2 + PO_4$

Calcium Carbonate Dissolution
Due to Carbon Dioxide Accumulation

Benthic Detrital Electron Flux (BDEF) is largely carried by the Sulfur Cycle

(Modified after Thornton, K.W. et.al., 1990)



Riverine

Transition

Lacustrine

Overflow

Interflow

Underflow

High Flow, Velocity
High NTU
Zp < Zm
Allochthonous
Light Limited

Reduced Flow, Velocity
Reduced NTU
Increased Light
Alloch- and Autochthonous
High Productivity

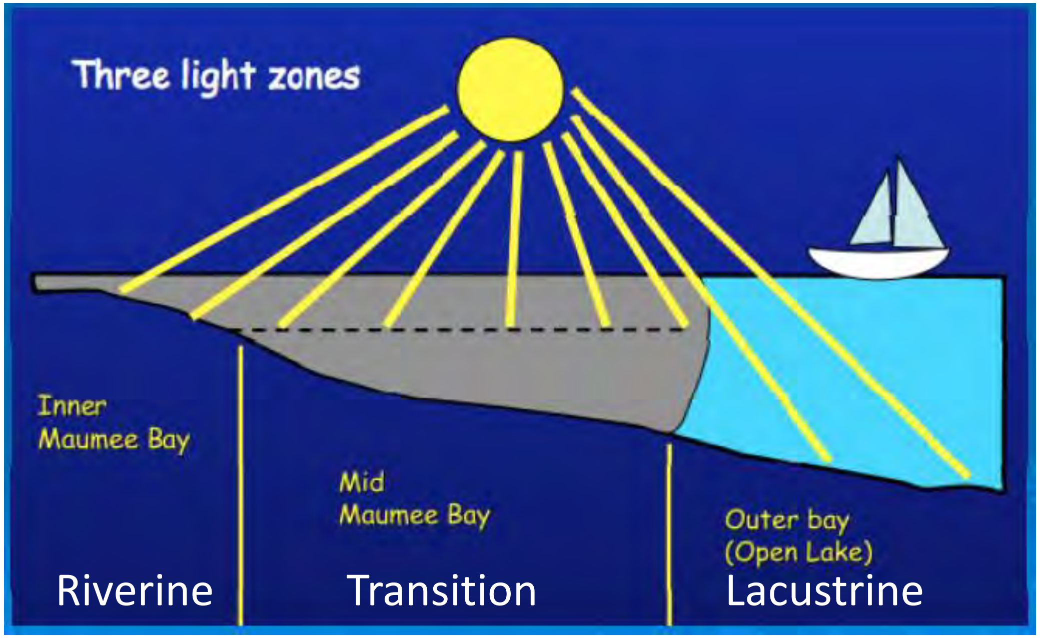
Low Flow, Velocity
Low NTU
Zp > Zm
Autochthonous
More Nutrient Limited

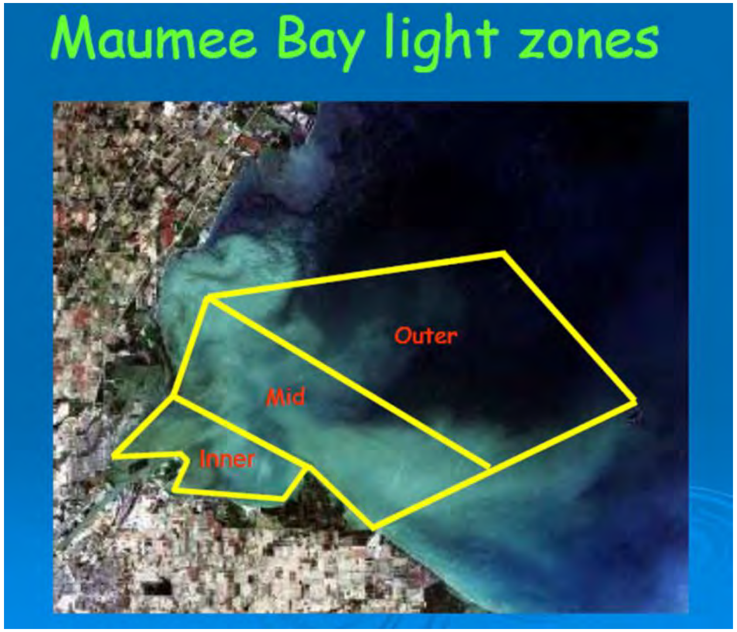
Storage Reservoir

Terminal Distribution Reservoir

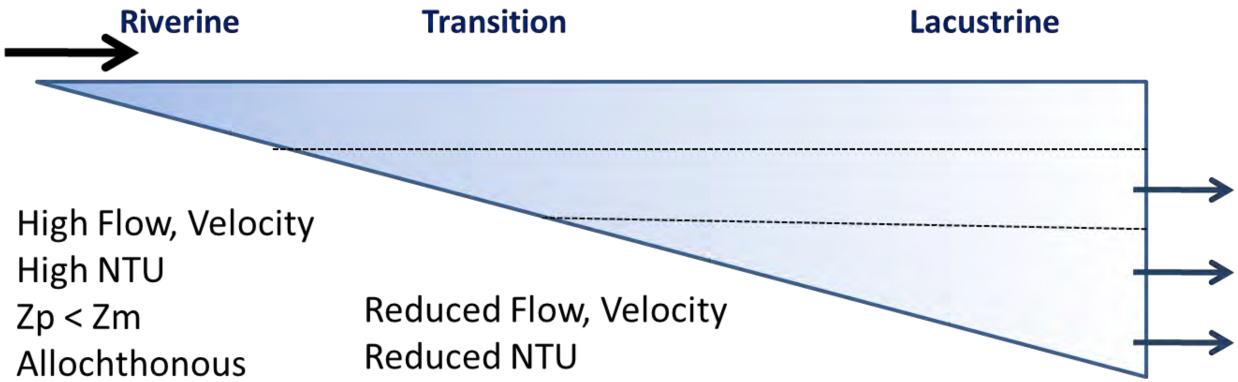
Source Water Reservoir Systems

Bottom releases from storage reservoirs can be rich in nutrients and anaerobic respiration products, and can stimulate Cyanobacteria in downstream reservoirs. Nitrate is often exhausted in Storage Reservoirs, favoring N-Fixing Cyanobacteria in downstream reservoirs.





Analogous to Run-of-River Impoundments in New England



Riverine

High Flow, Velocity
High NTU
$Z_p < Z_m$
Allochthonous
Light Limited

Transition

Reduced Flow, Velocity
Reduced NTU
Increased Light
Alloch- and Autochthonous
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Lacustrine

Low Flow, Velocity
Low NTU
$Z_p > Z_m$
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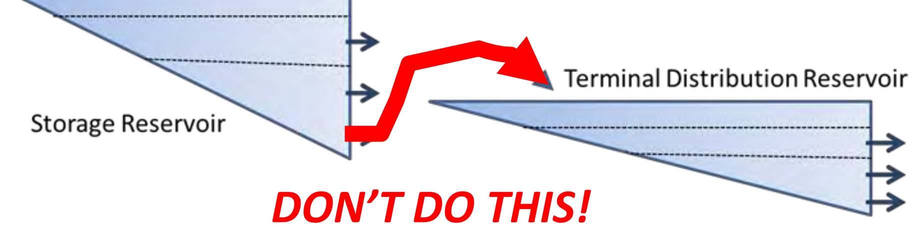
More Nutrient Limited



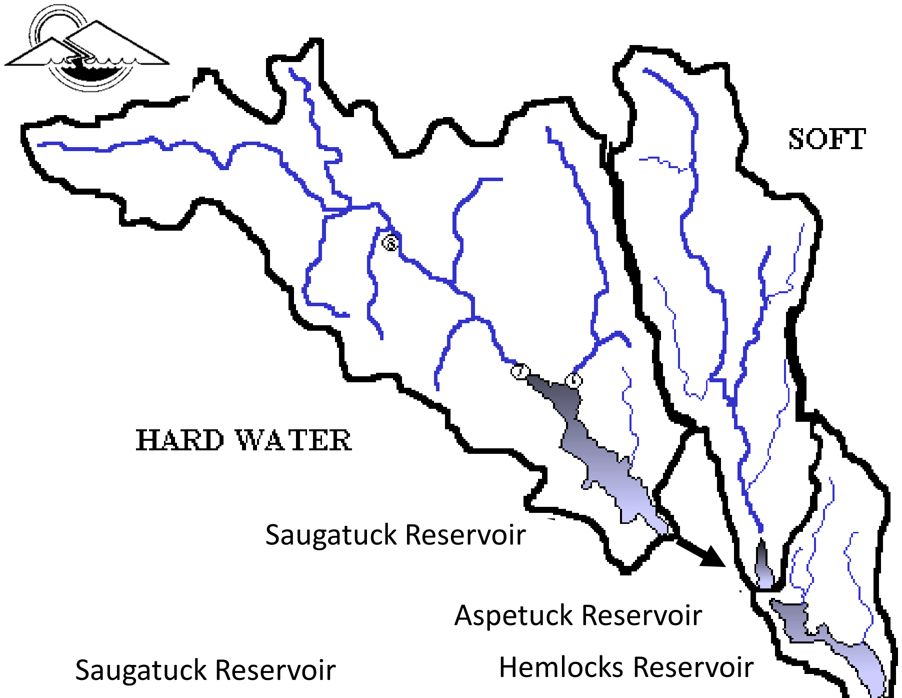
DON'T DO THIS!

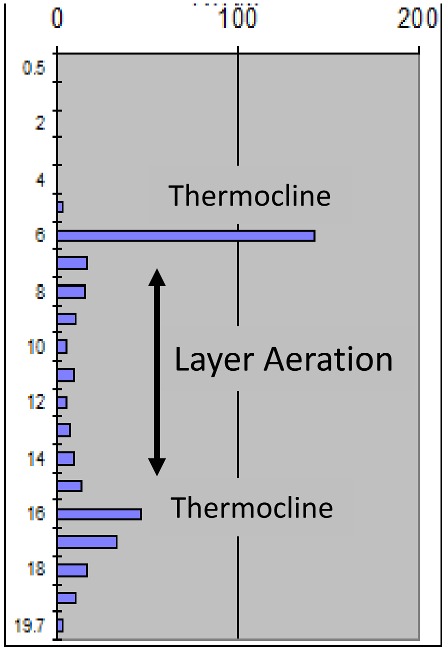
History of Cyanobacteria Blooms in Western Lake Erie

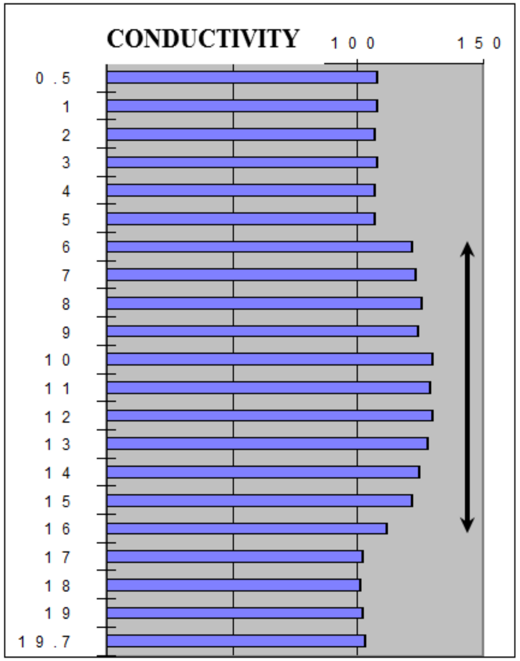
US EPA

1950s to 1970	P and N Load Increases Increased Phytoplanktonic Productivity Initially by Diatoms…then Greens…then N-Fixing Cyanobacteria
1970s	US Clean Water Act; US-Canada Agreements to Reduce Loading e.g. Phosphate Detergent Bans *Aphanizomenon flos-aquae* (Scum Forming N-Fixer) ? P Control…but too much N Control? N:P Ratio Decreasing Frequency and Intensity of Blooms
Late 1970s and 1980s	No "Massive Blooms" - Moderate *Aphanizomenon flos-aquae*
1985-1990	Zebra Mussel and Quagga Mussel Infestation *(Selective grazing- favors Cyanobacteria)*
1990s	Massive *Microcystis aeruginosa* blooms in 1995 and 1998 *(Nitrate abundant, hence not a N-Fixing Cyanobacteria)*
2000s	*Microcystis aeruginosa* blooms common And benthic *Lyngbya sp.*
2014 August	Weather Patterns resulted in a Massive Microcystis aeruginosa bloom

The Weather Pattern Trigger in the Northeast will likely be an “aberrant winter”, either very cold/snowy or non-existent (and we’ve experienced both recently!)

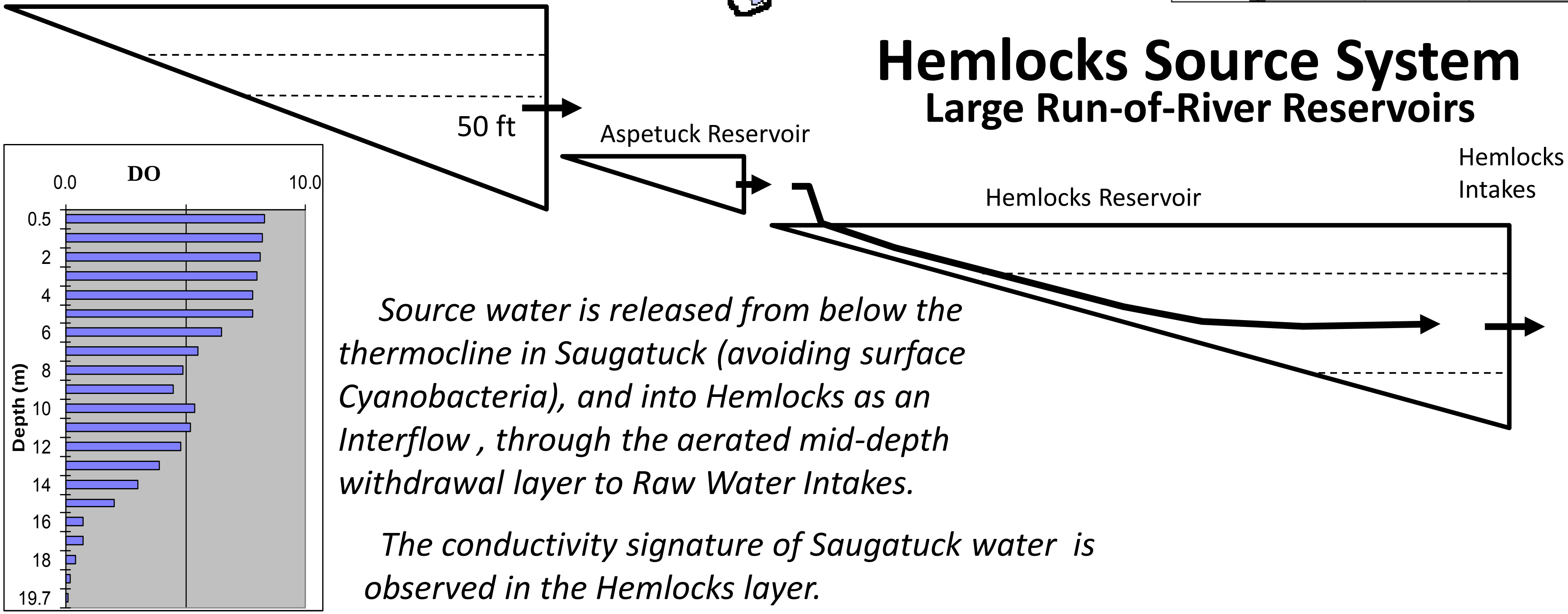






Hemlocks Source System

Large Run-of-River Reservoirs

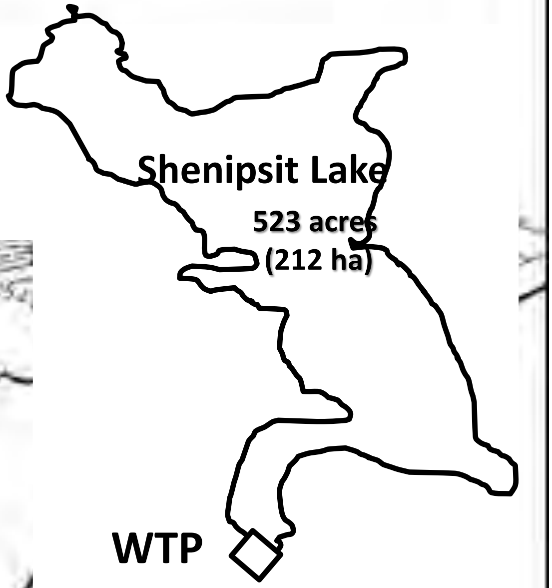


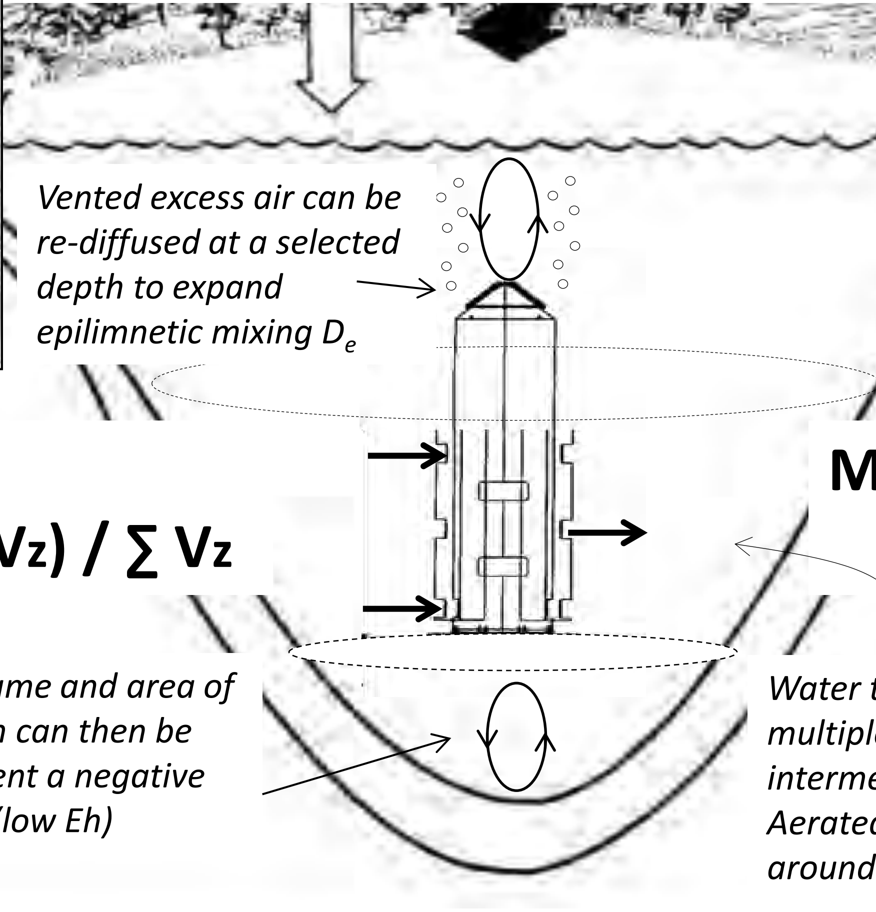
Source water is released from below the thermocline in Saugatuck (avoiding surface Cyanobacteria), and into Hemlocks as an Interflow , through the aerated mid-depth withdrawal layer to Raw Water Intakes.

The conductivity signature of Saugatuck water is observed in the Hemlocks layer.

LAYER AERATION

Depth-Selective Circulation





Vented excess air can be re-diffused at a selected depth to expand epilimnetic mixing D_e

MEAN DO=

$$\sum (DO_z \times V_z) / \sum V_z$$

MEAN TEMP=

$$\sum (T_z \times V_z) / \sum V_z$$

Layer Aeration reduces the volume and area of the deepest hypolimnion, which can then be aerated very efficiently to prevent a negative Oxidation-Reduction Potential (low Eh)

Water that is blended and aerated from multiple depths is returned at an intermediate depth and density. Aerated Layers are typically designed around raw water intake elevations.

The Layer DO, Temperature, and Thermocline Formation can be predicted using strata volumes and observed dissolved oxygen and temperature profiles

RQ Prior to Layer Aeration= 1.51 to 2.85

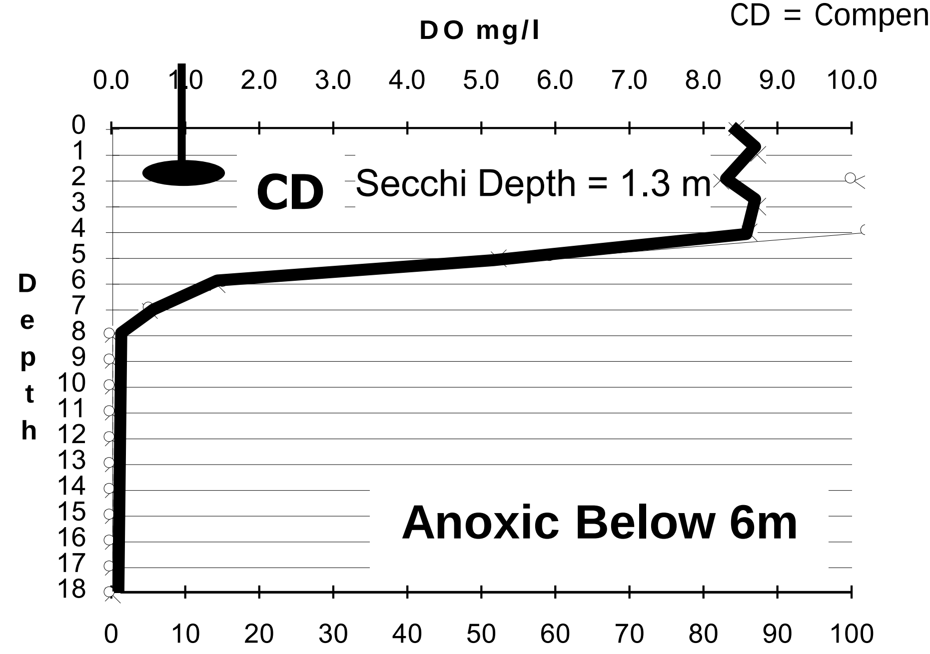
RQ During Early Years of Layer Aeration= 1.10 to 1.14

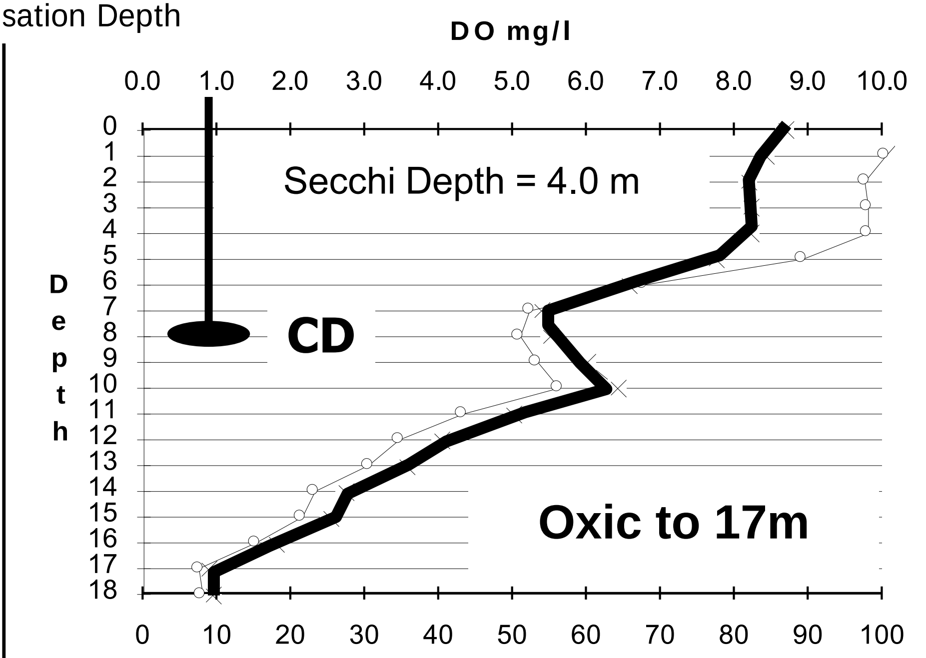
Shenipsit Source Water System

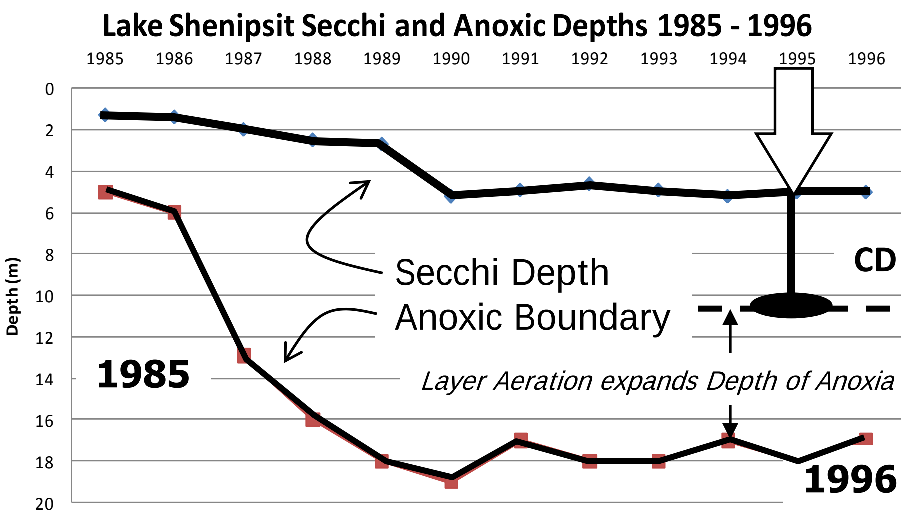
July 22, 1985

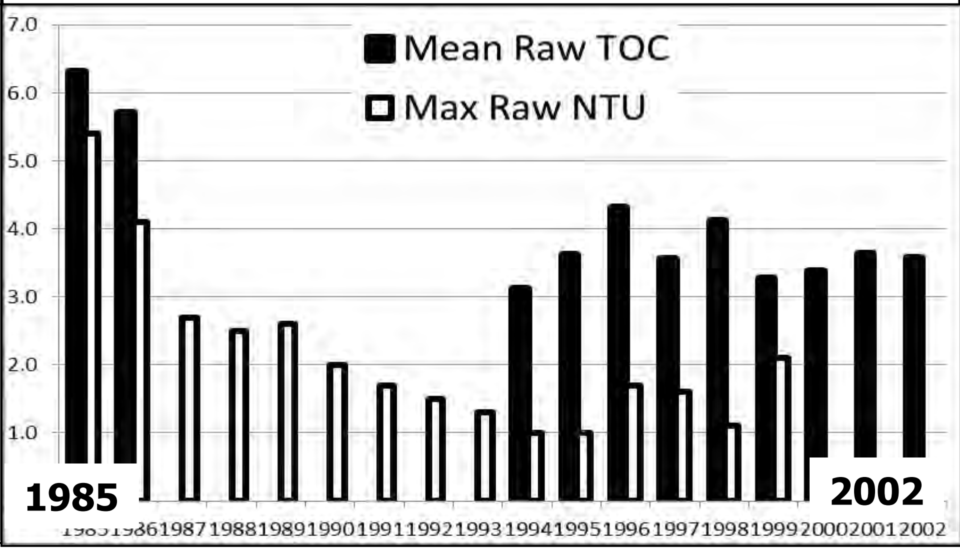
July 22, 1993

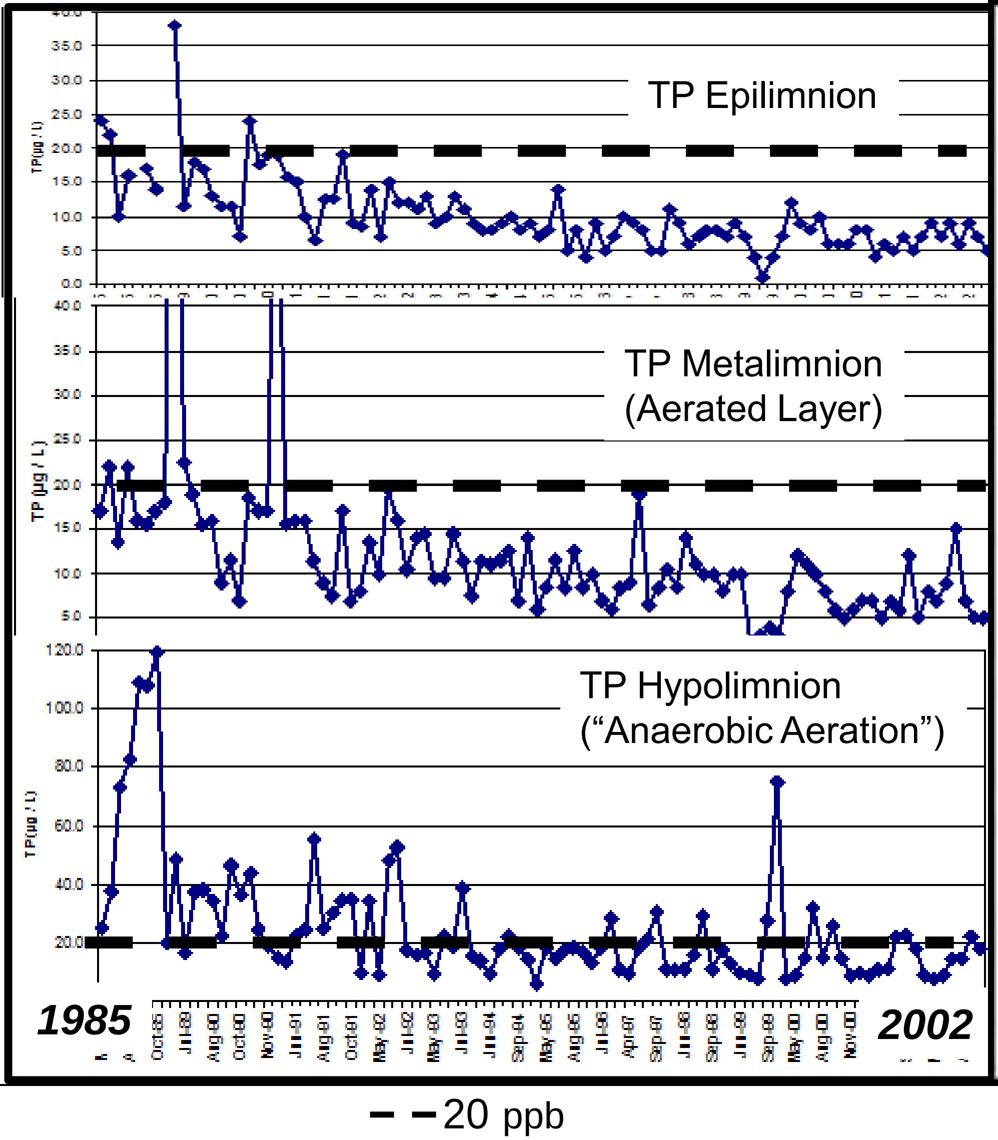
CD = Compensation Depth

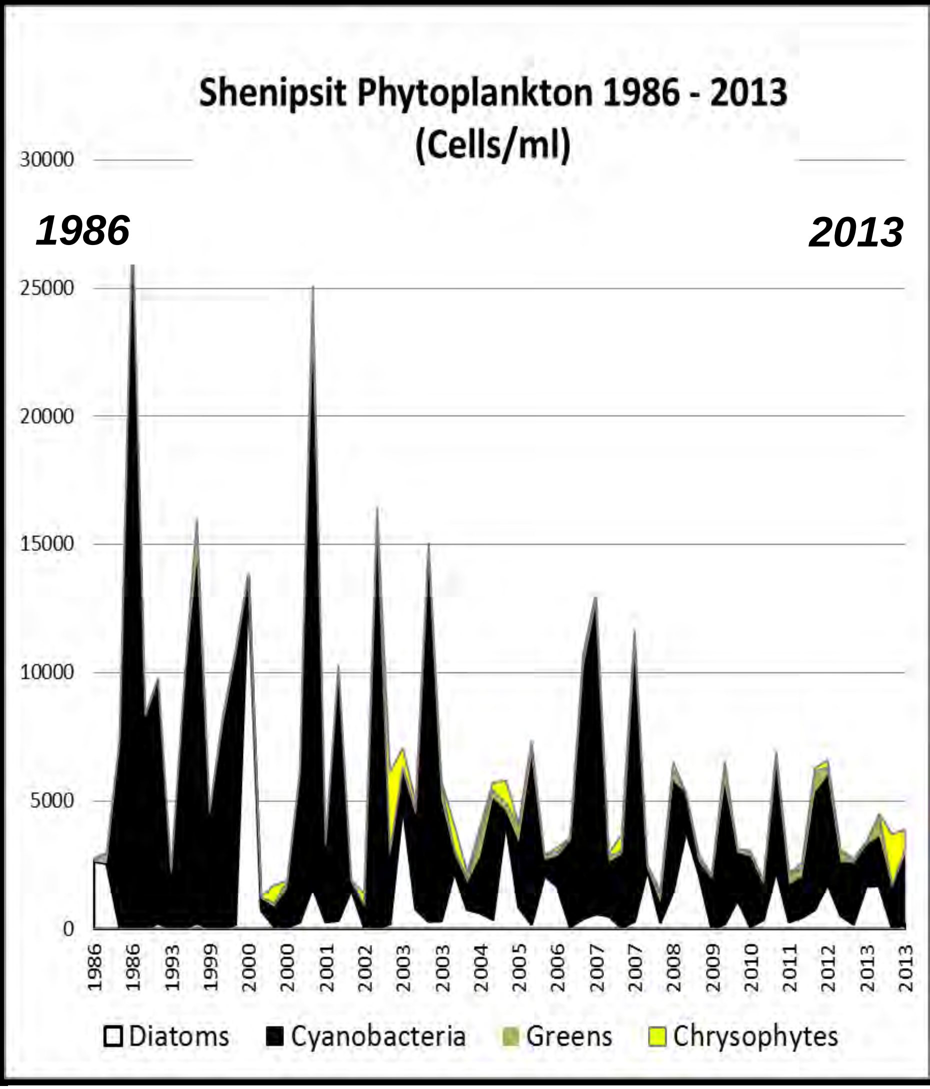




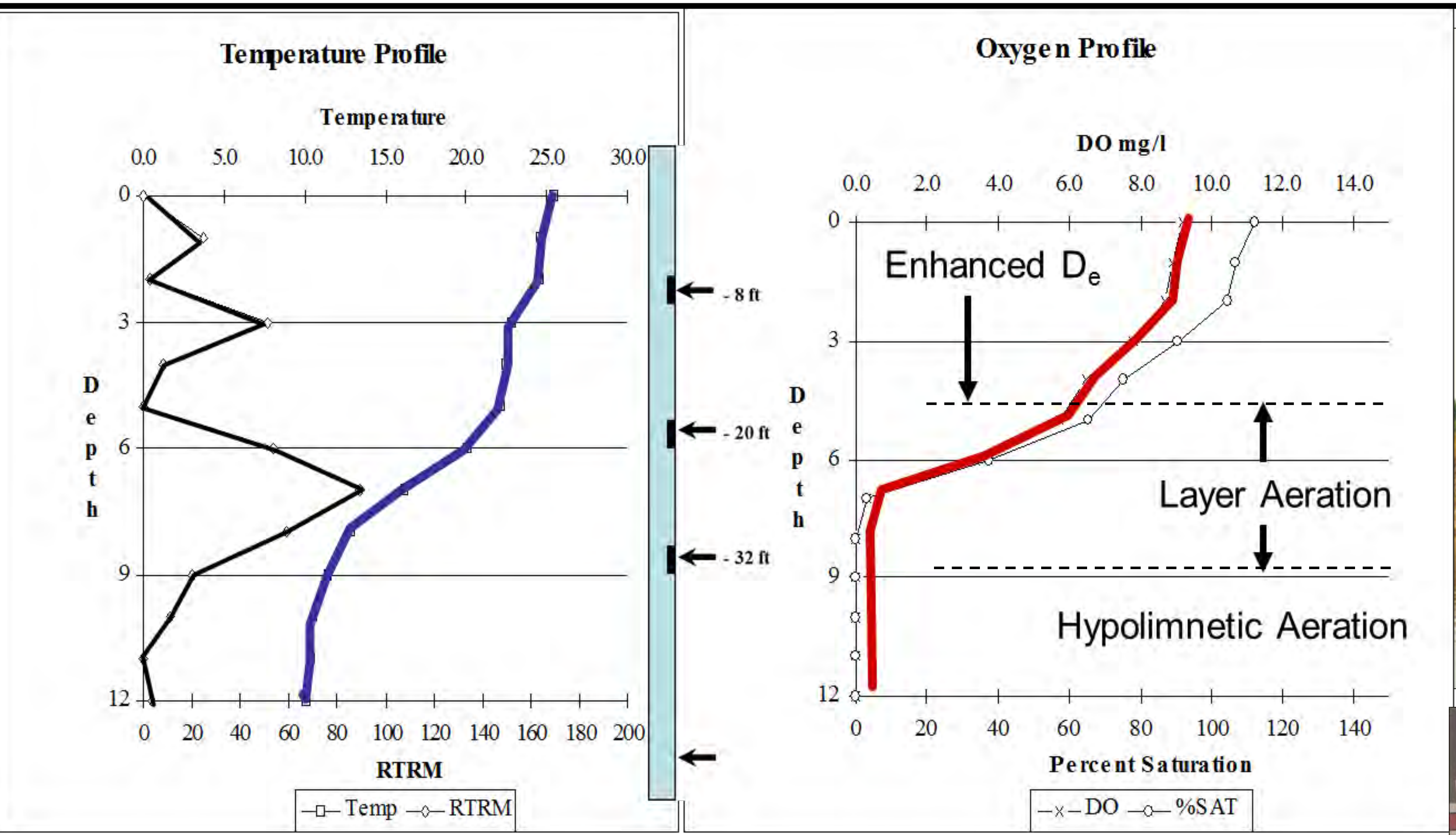








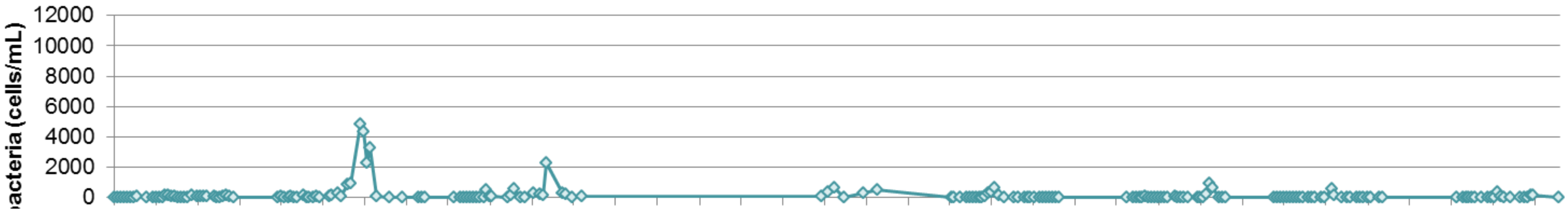
Layer Aeration decreased internal loading of phosphorus (SRP, TP) which decreased the abundance of phytoplankton (especially Cyanobacteria), increased light penetration (deepening the compensation depth), and improved habitat quality.



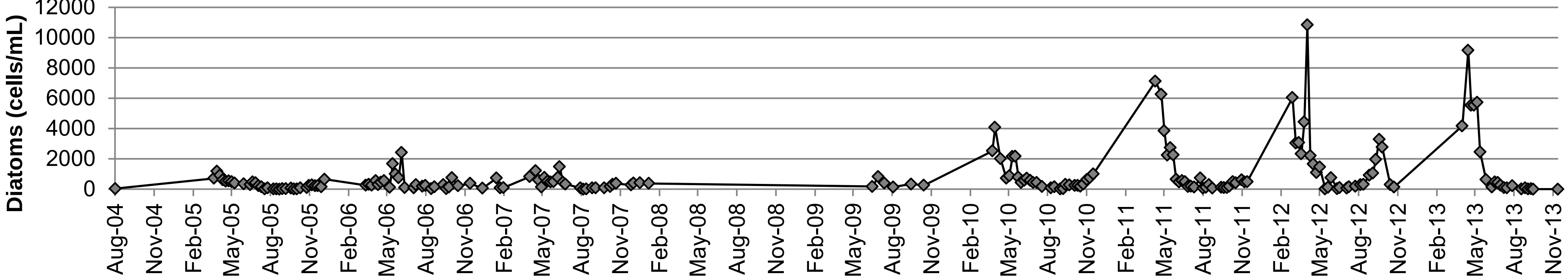
Before Aeration

Glendola Reservoir 8/25/92

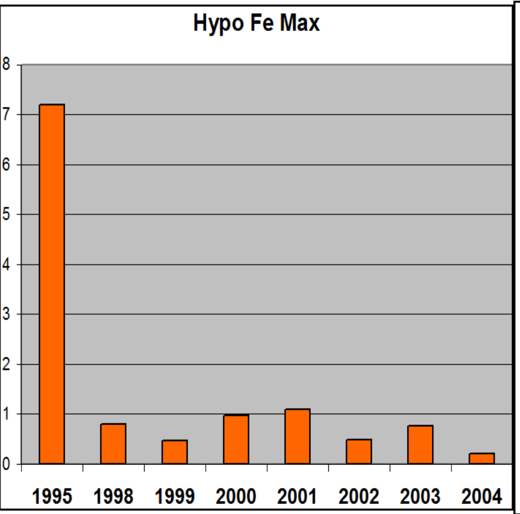
By managing to reduce raw water problems from Anaerobic Respiration Products in Deep Strata you can withdraw from under a bloom of Cyanobacteria.



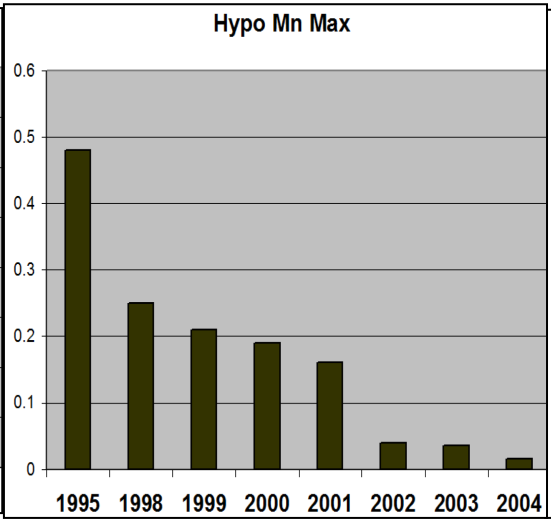
Glendola Site C 2005-2013 Cyanobacteria



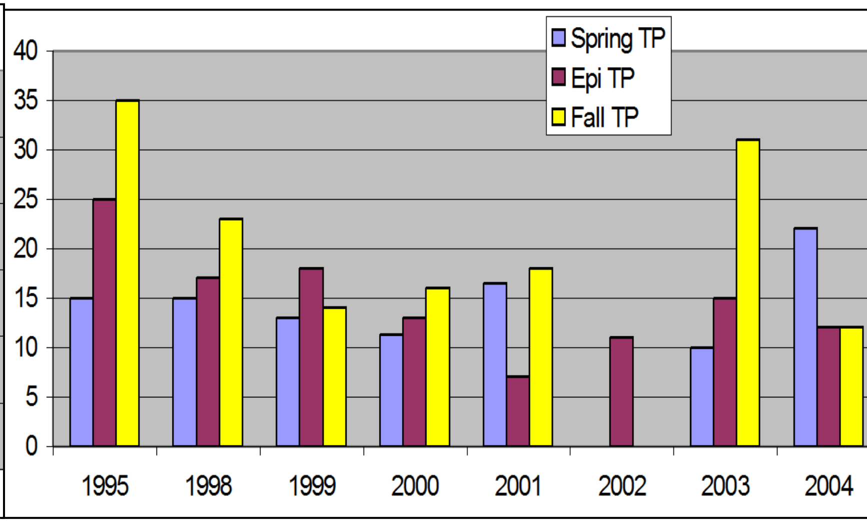
Glendola Site C 2005-2013 Diatoms



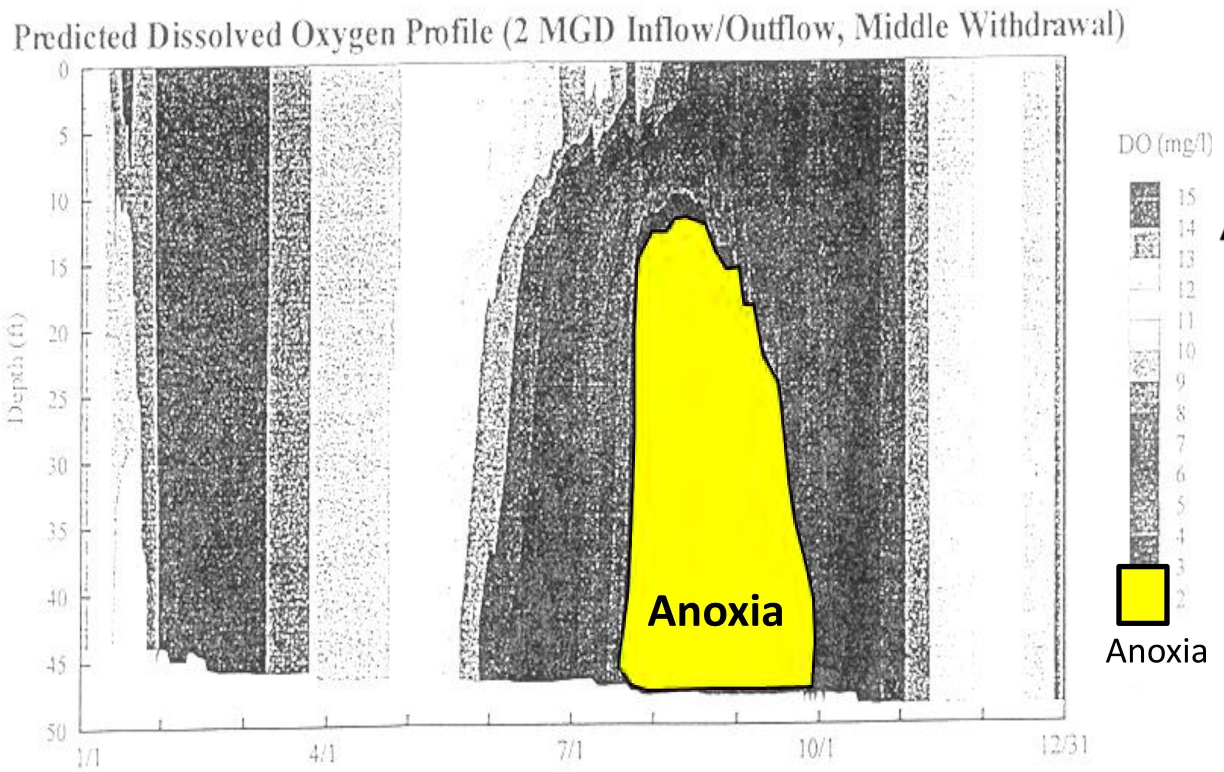
Hypo Fe Max

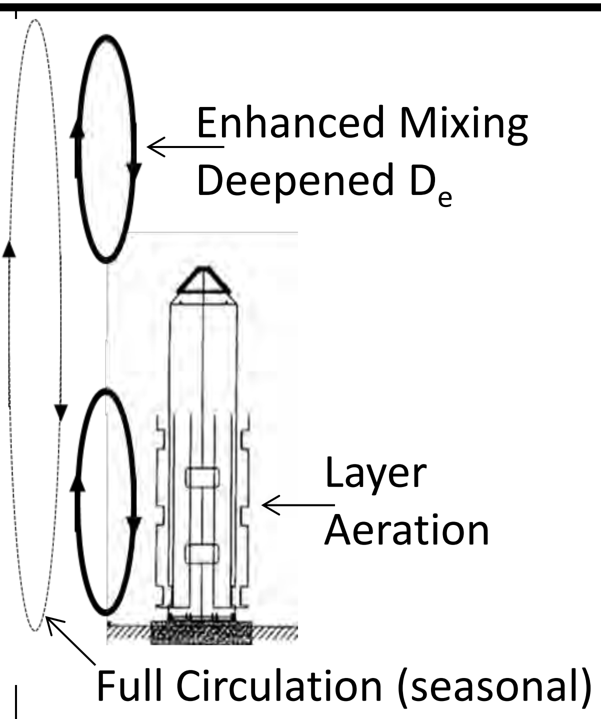


Hypo Mn Max



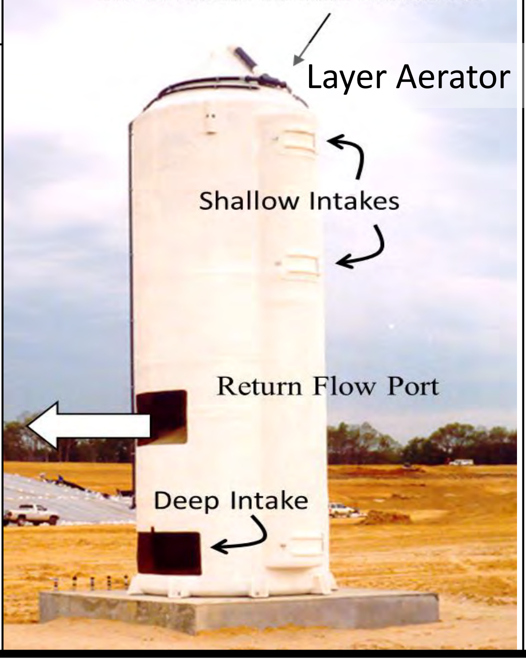
By eliminating Fe and Mn accumulation in deep strata, raw water can be withdrawn from below the thermocline during the summer (under Cyanobacteria).

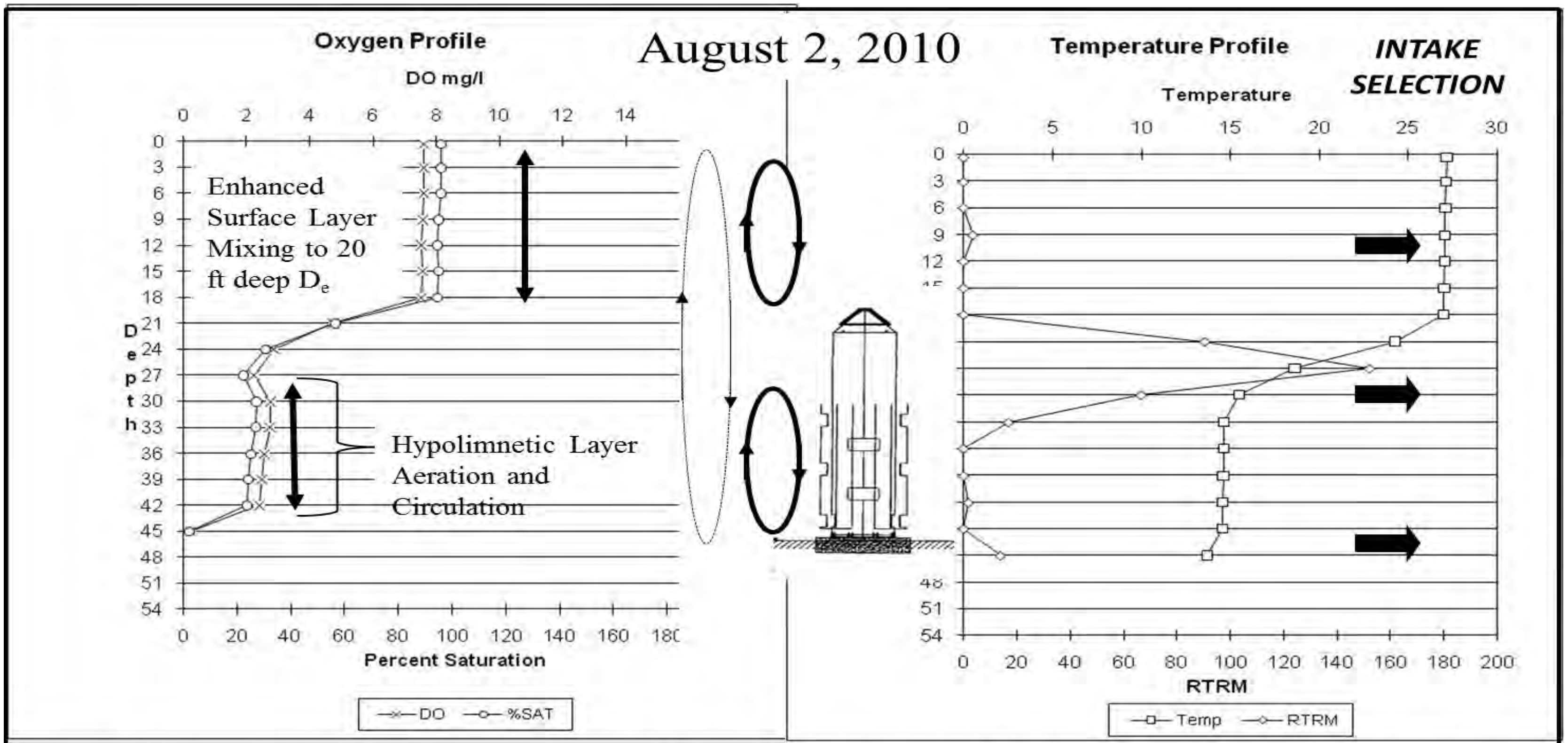

Predicted Dissolved Oxygen Profile (2 MGD Inflow/Outflow, Middle Withdrawal)



Brick Off-Line Storage Reservoir

Brick Township, NJ





August 2, 2010

INTAKE SELECTION

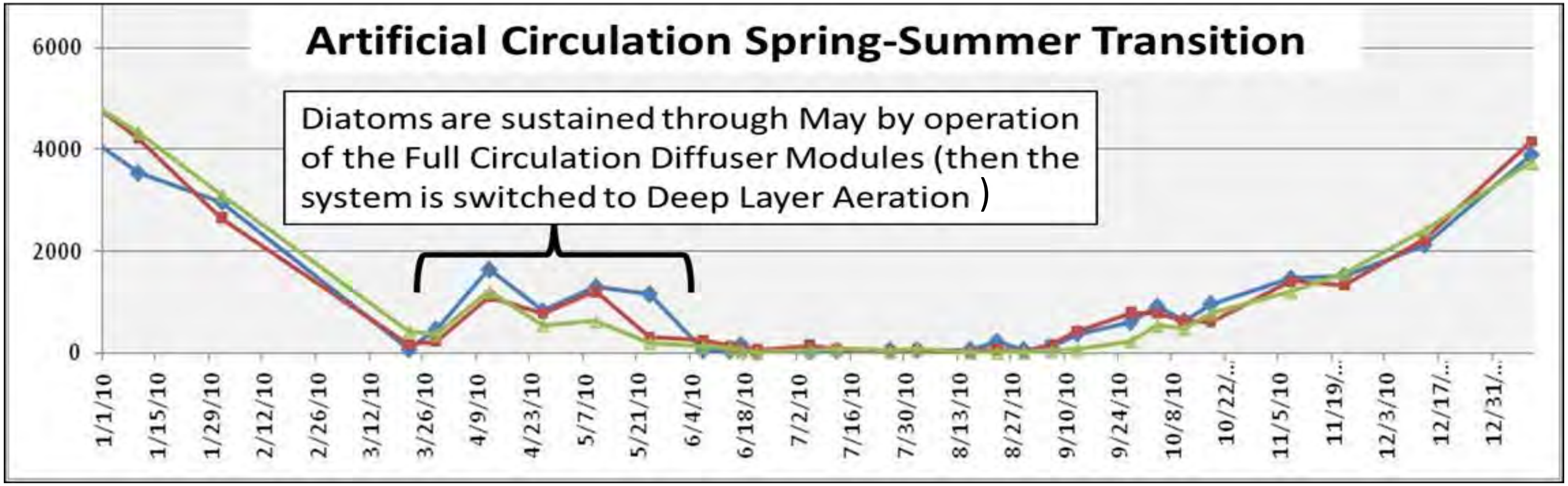
Enhanced Surface Layer Mixing to 20 ft deep D_e

Hypolimnetic Layer Aeration and Circulation

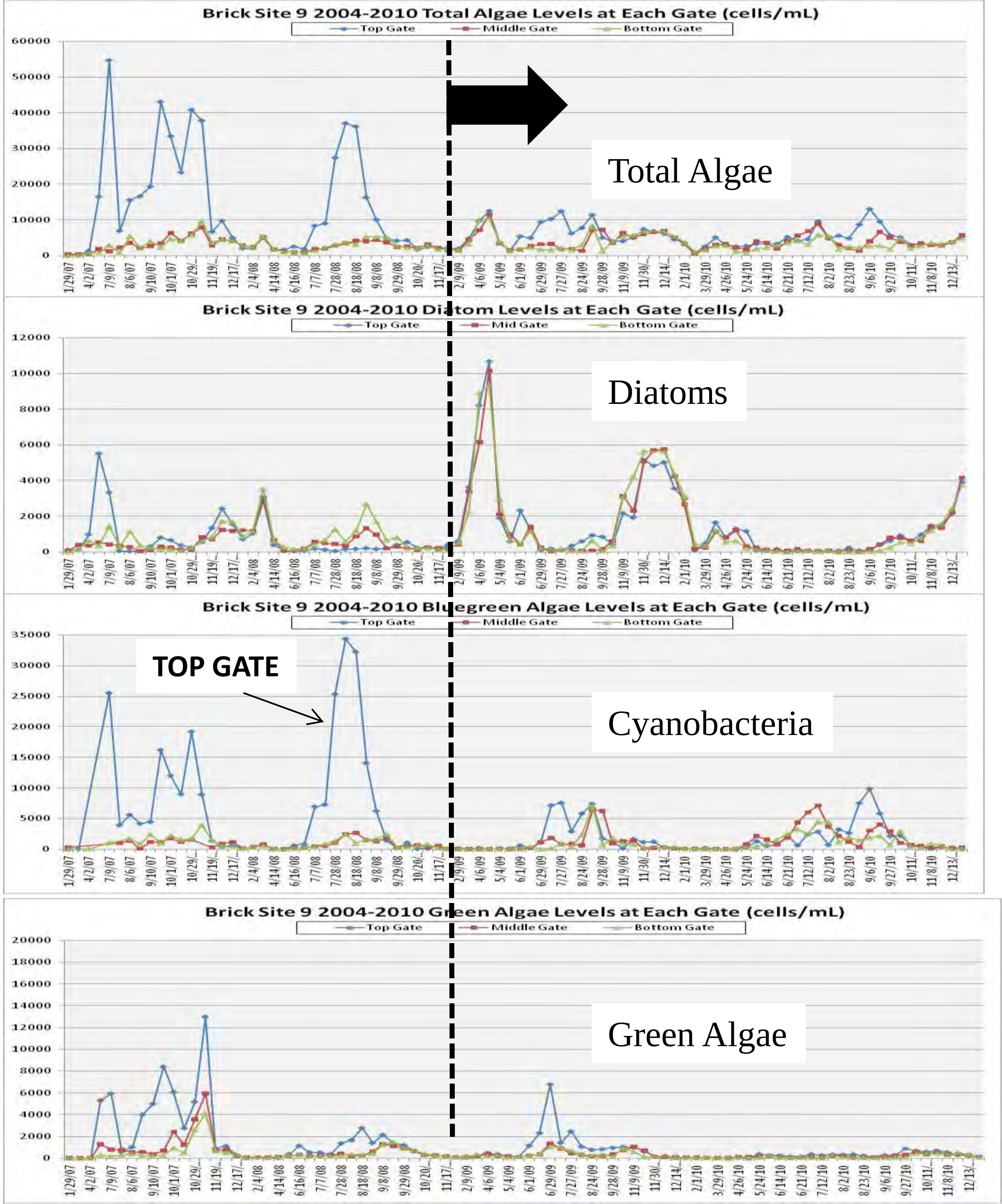
Summer Operation; BTMUA Reservoir Layer Aeration System

Kortmann and Karl, 2011

Artificial Circulation Spring-Summer Transition



Diatoms are sustained through May by operation of the Full Circulation Diffuser Modules (then the system is switched to Deep Layer Aeration)

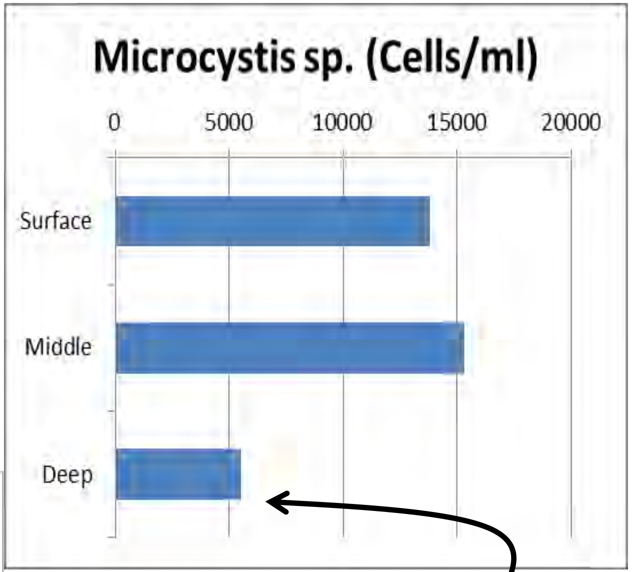


Enhancing Spring Diatoms

(by operating Full Circulation)

3x Increase in Diatoms

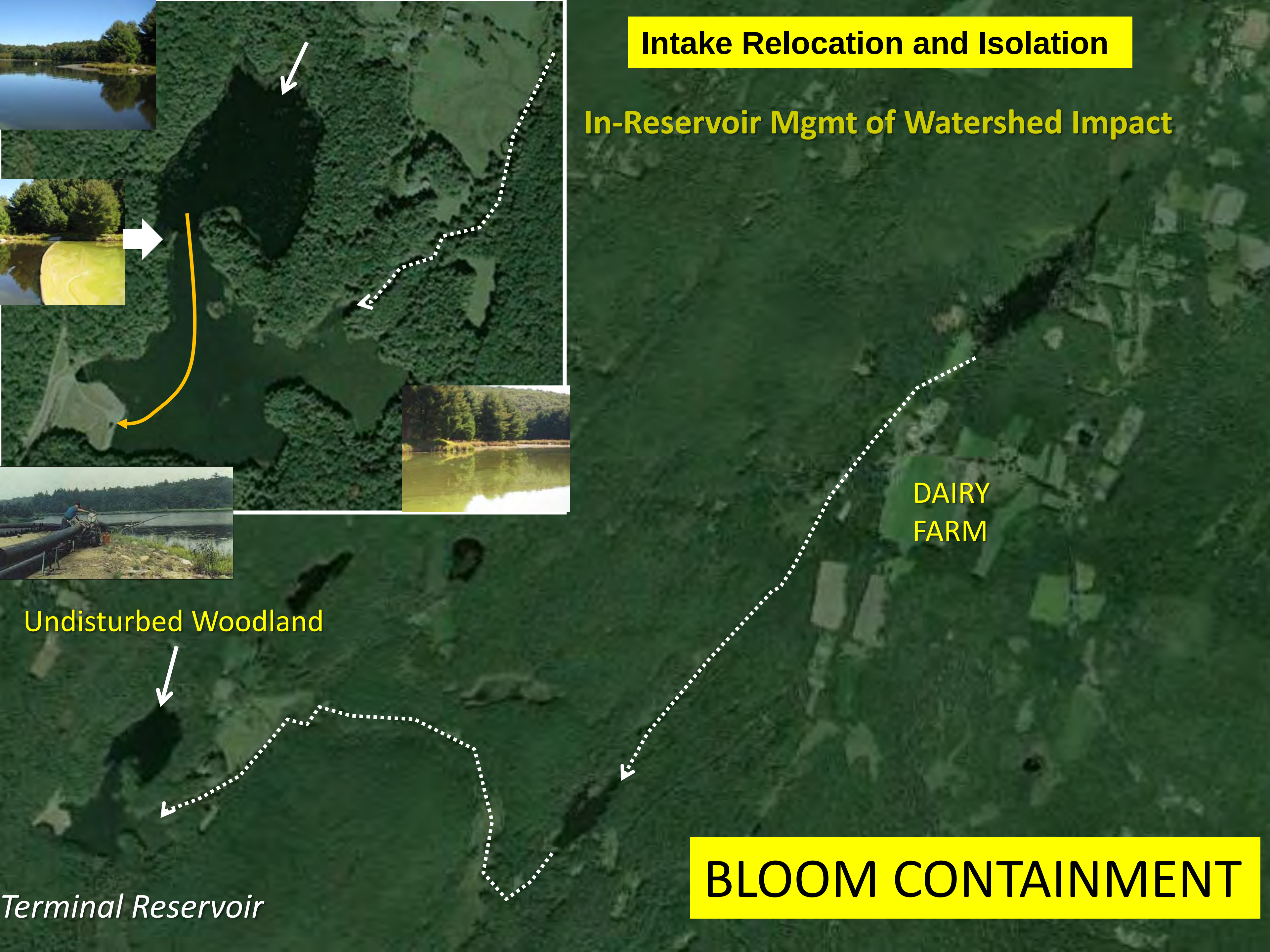
75% Decrease in Summer Cyanobacteria



DEEP INTAKE 2014:
< ½ Microcystis Surface Density

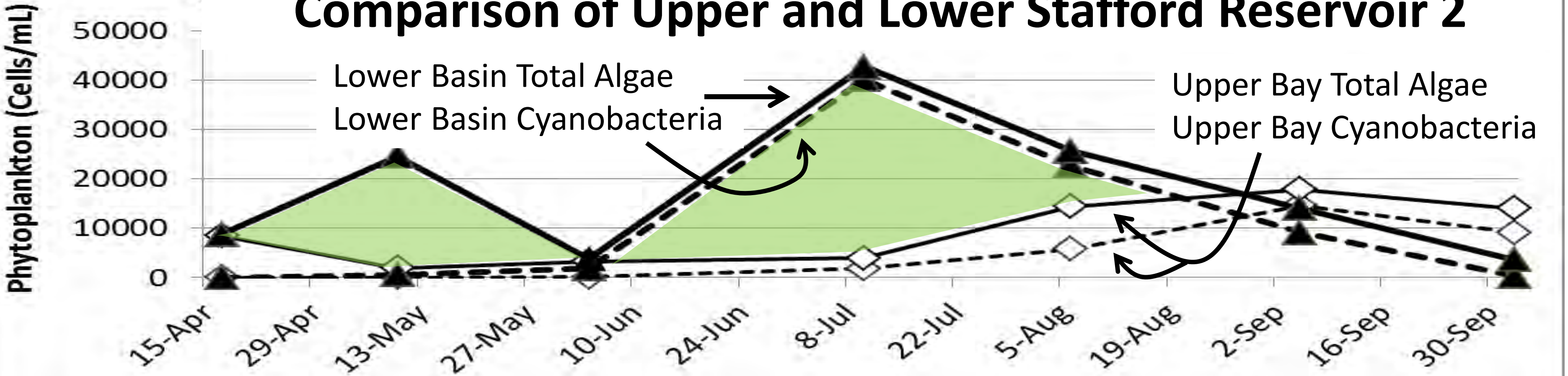
Intake Relocation and Isolation

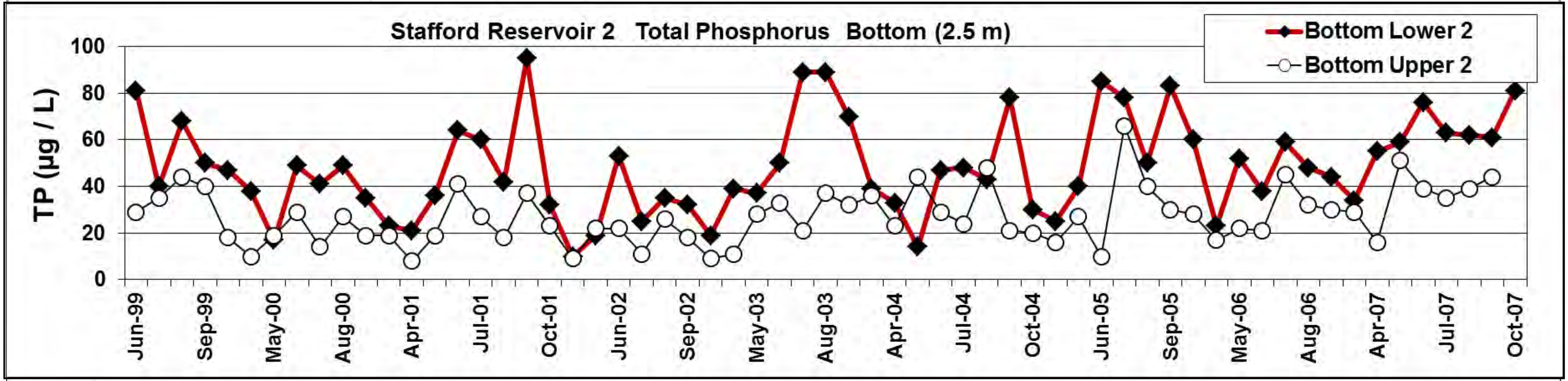
In-Reservoir Mgmt of Watershed Impact

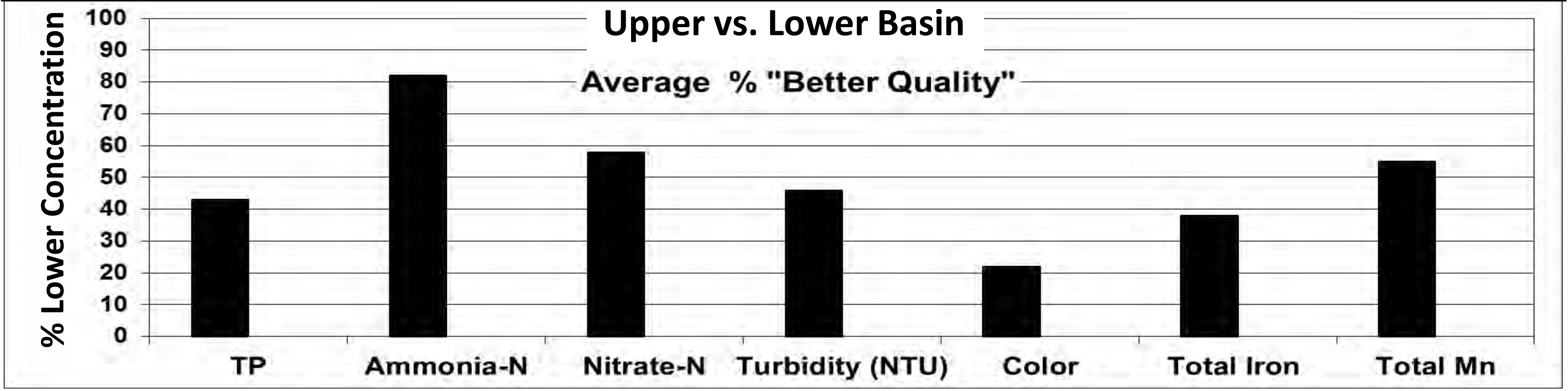


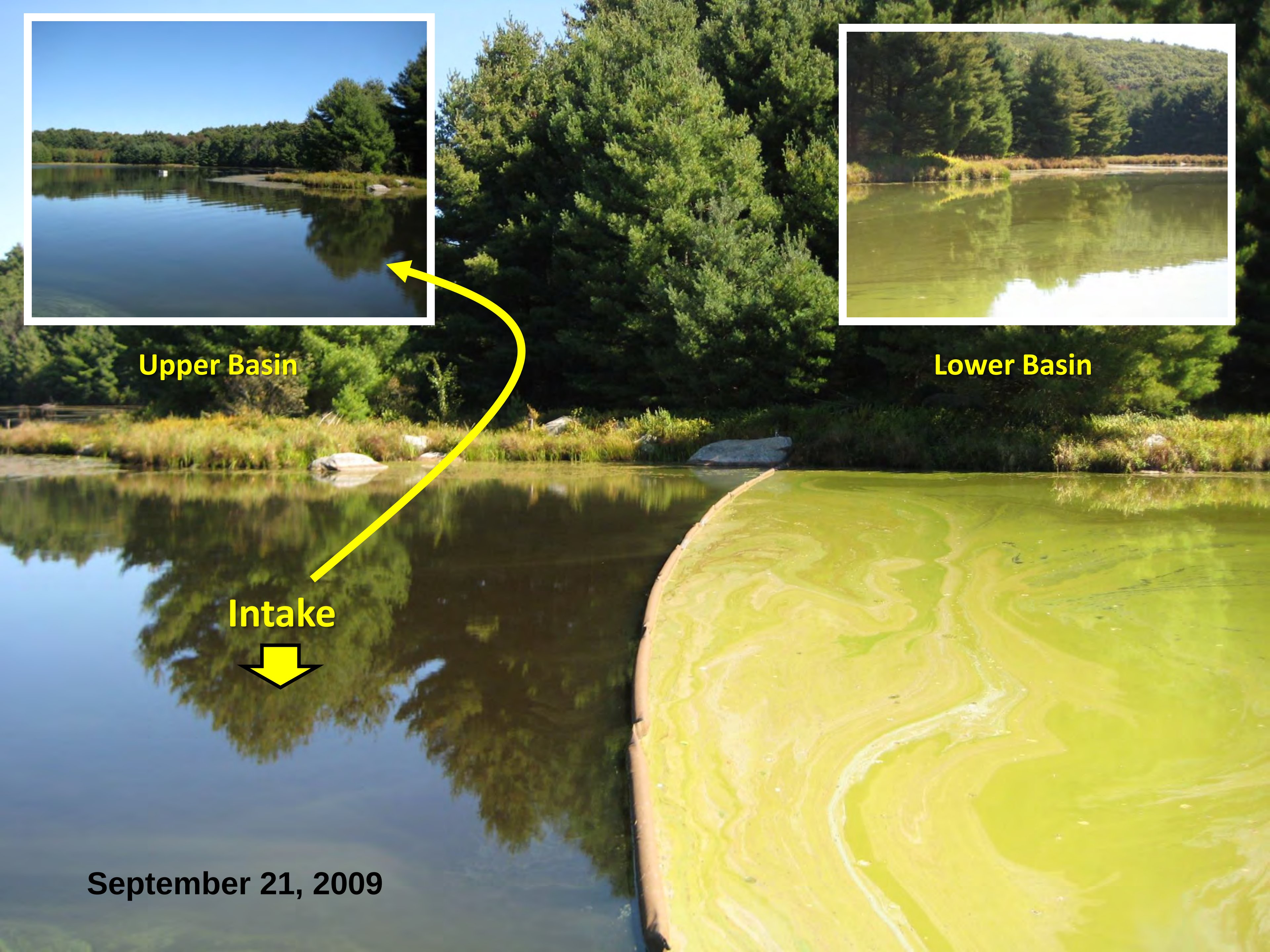
BLOOM CONTAINMENT

Comparison of Upper and Lower Stafford Reservoir 2









September 21, 2009

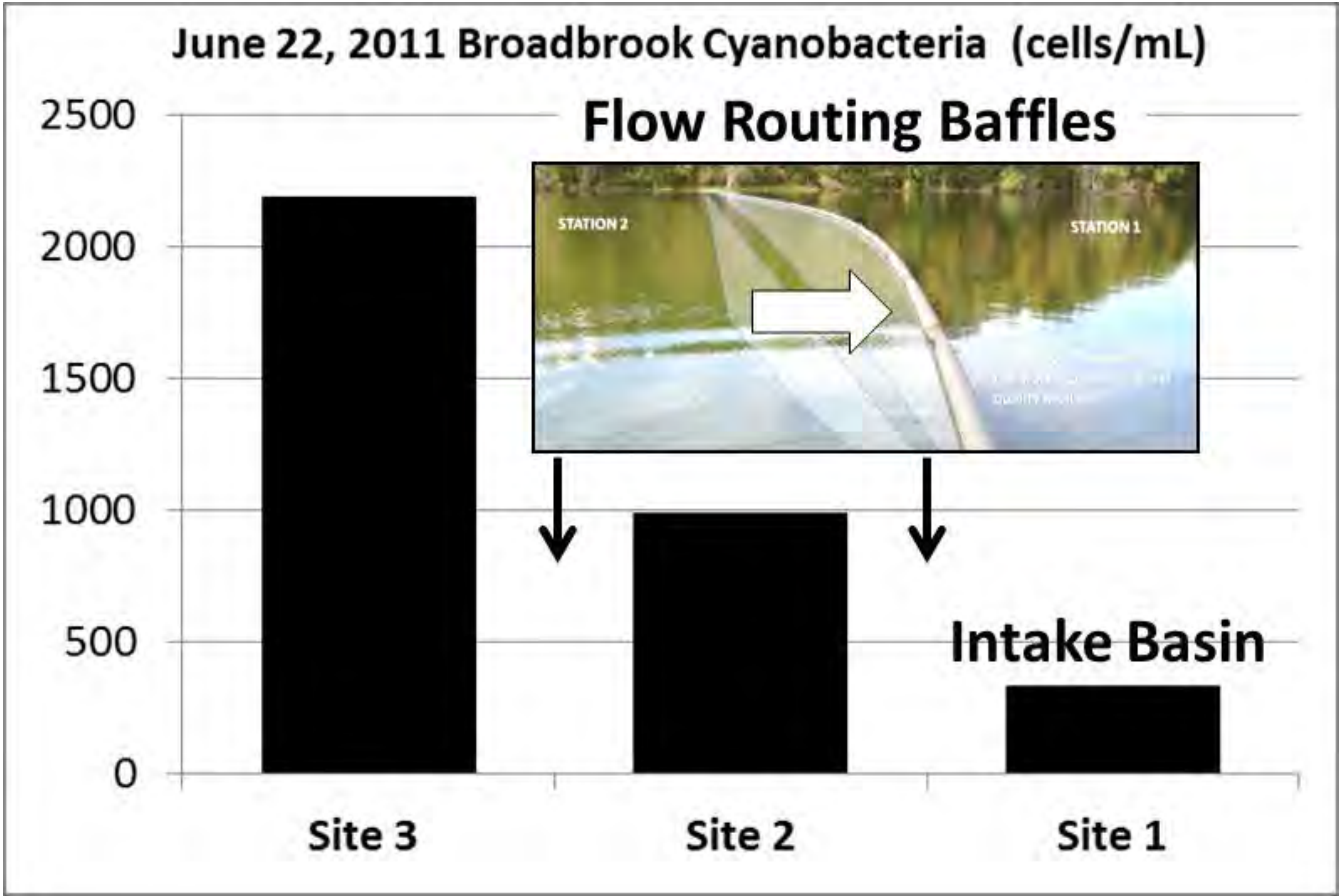
Cyanobacteria Blooms Initiate

Anaerobic
Respiration
Products

Narrow Location
Flow Routing Baffle Curtains

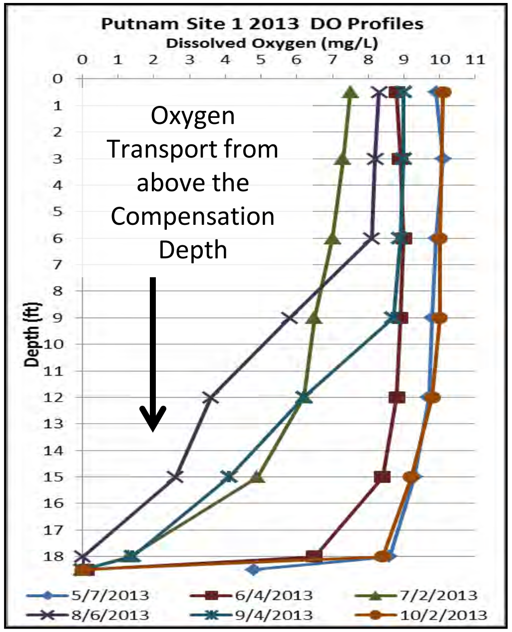
Sta1 ca. 30 ft; Sta 2 ca. 25 ft; Sta 3 ca. 20 ft deep

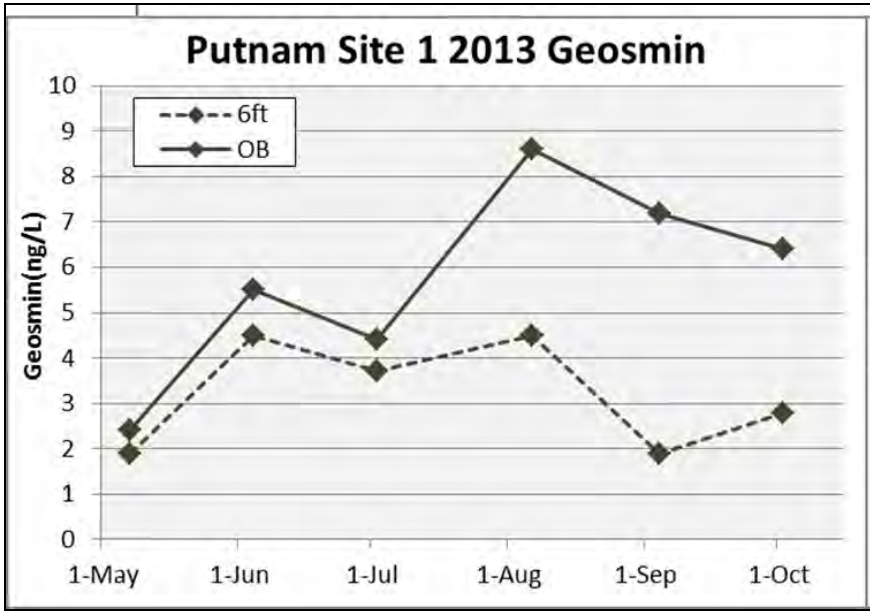
BLOOM CONTAINMENT

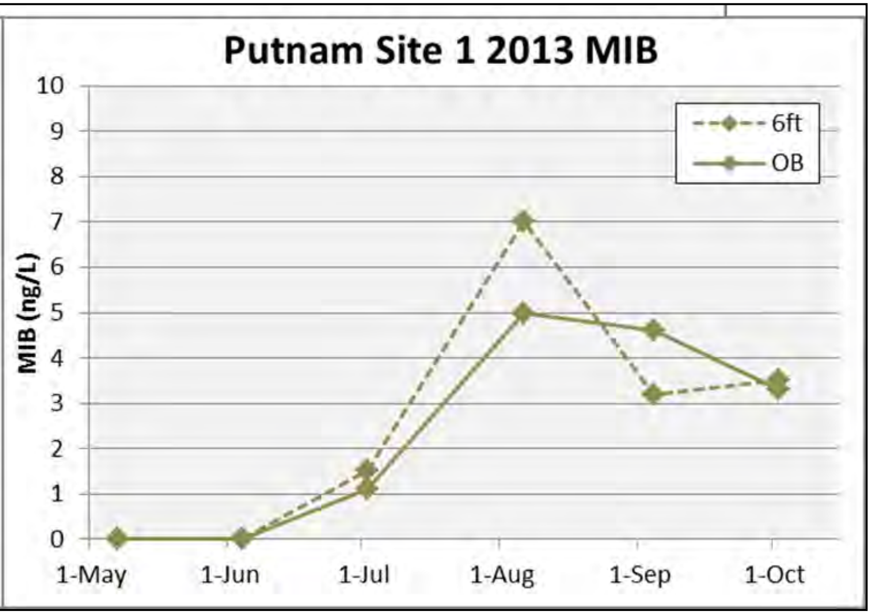


June 22, 2011 Broadbrook Cyanobacteria (cells/mL)

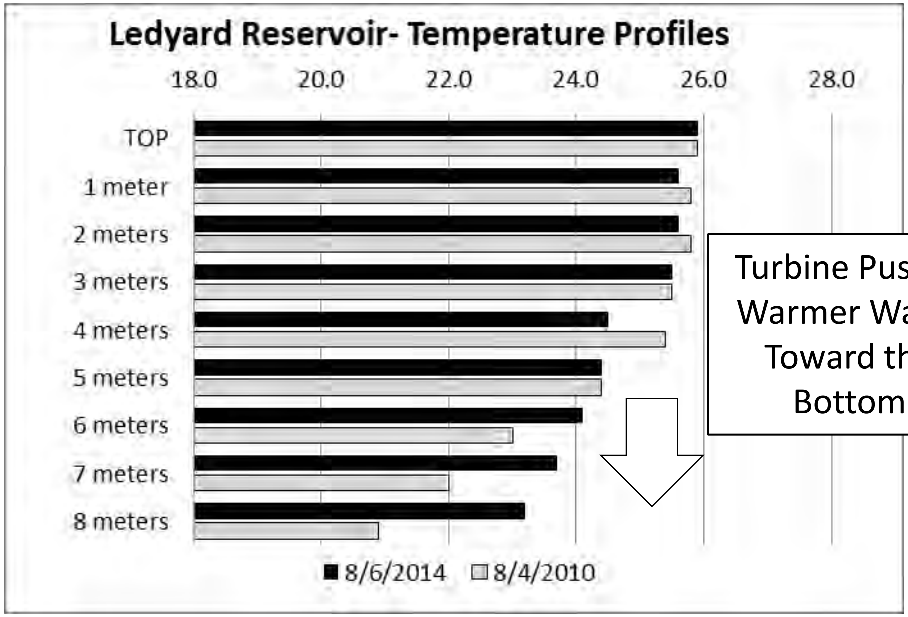
Putnam Reservoir: Solar Powered Layer Circulation System



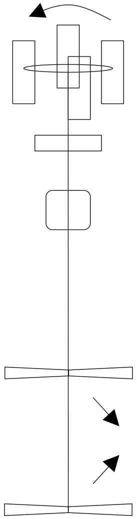


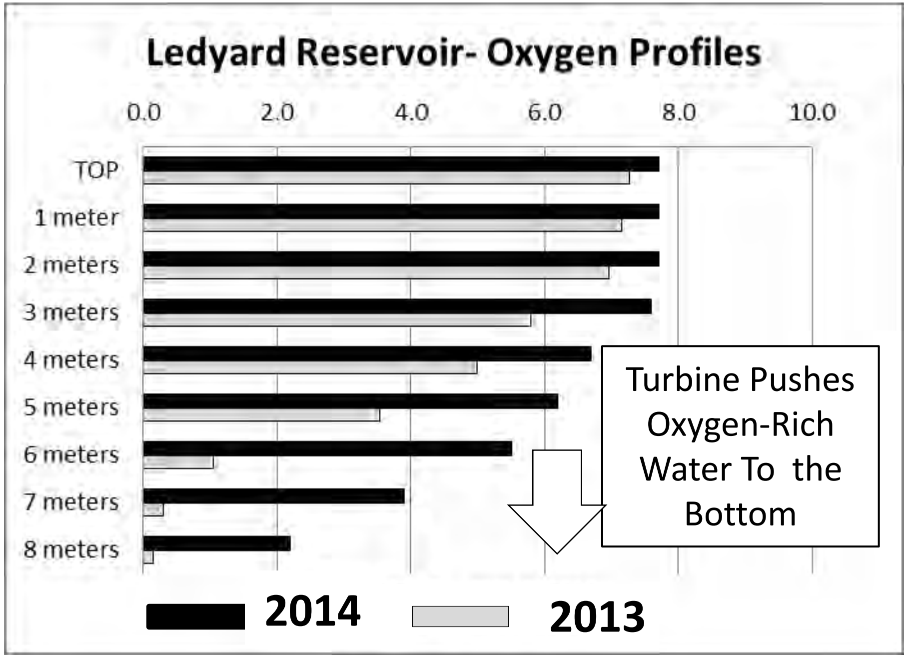


Ledyard Reservoir: Wind Powered Artificial Circulation System

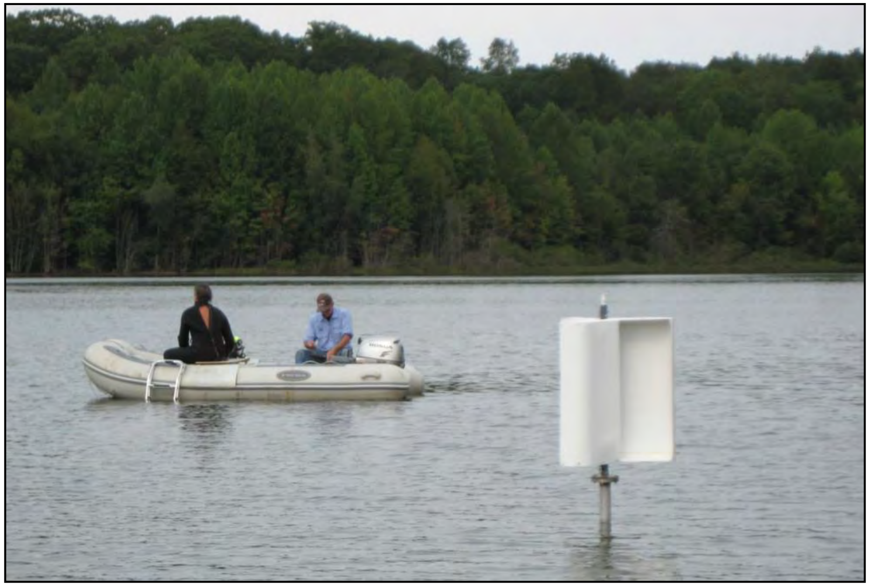


Turbine Pushes Warmer Water Toward the Bottom





Turbine Pushes Oxygen-Rich Water To the Bottom



US Pat 8,651,766

- Reduce TP (to < 25 µg/L as P)
- Bloom Containment
- Aeration or Oxygenation
  - Reduce Internal P Loading
  - Maintain Zooplankton Refuge
  - Piscivorous Habitat
- Maintaining Nitrate Availability
  - Import Nitrate
  - Enhance Nitrification
- Manage Stratification
  - e.g. Increase De, Depth-Selective Circulation
- Prolong the Diatom Maximum during Spring
- Carbonate Buffer System Management
  - Maintain pH< 8.3; CO_2 Availability
- Light Penetration Comp Depth >> D_e
- Enhance the Grazing Rate
  - Zooplanktivore Reduction (e.g. Alewife)

Sometimes this is very difficult, if possible

- Sonic Devices
- Depth-Selective Outflow
- P Inactivation
  - Al Based Coagulants
  - Use of the Iron Cycle
  - Decalcification
- Algaecides
  - Cu
  - Oxidant

- Source Selection and Sequencing
- Depth-Selective Withdrawal and Release

(and other Water Supply Specific Approaches)

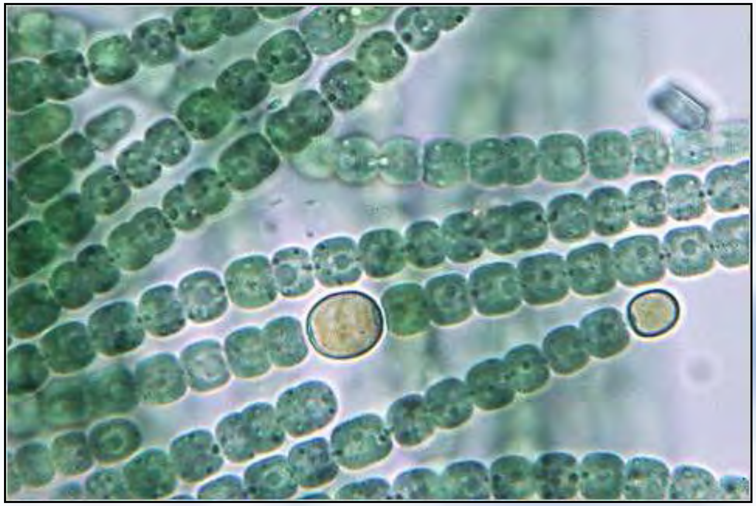
Nature is our foremost teacher! The task of technology is not to correct Nature…but to imitate her!

To avoid Cyanobacteria Blooms…

….prevent the conditions which provide them a competitive advantage!

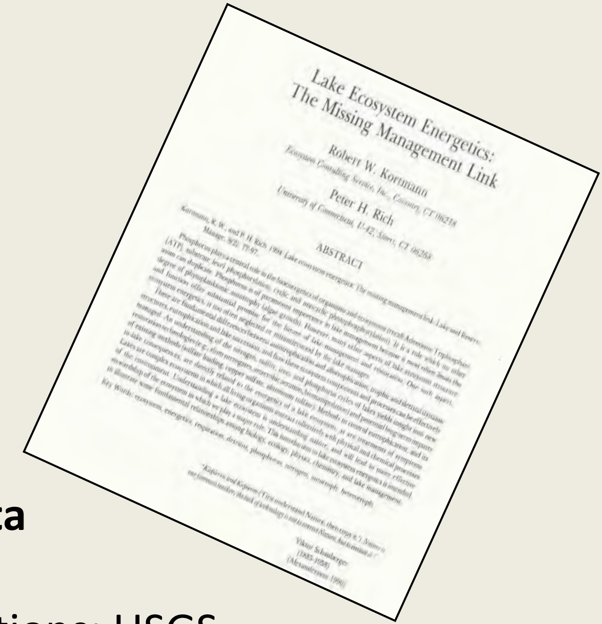
Prevent their Dominance…

Avoid Them by Withdrawal Strategies.



Nitrate, Nitrification Enhancement
Epilimnetic Mixing Depth
Prolonged Diatom Maximum
Carbonate Buffer System…pH
Light Penetration
Enhance Grazing Rate

Publication Resources


Lake Ecosystem Energetics:
The Missing Management Link

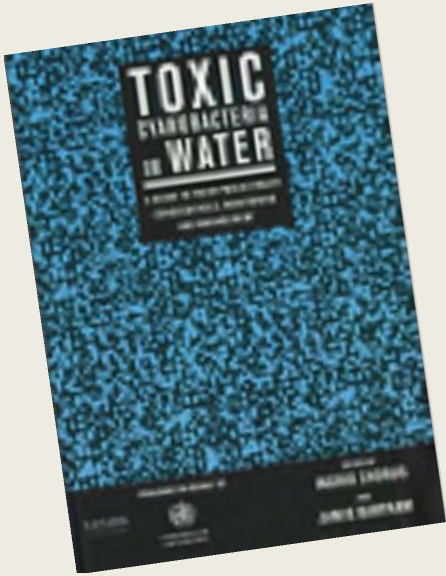
Robert W. Kortmann
Ecosystem Consulting Service, Inc., Coventry, CT 06238

Peter H. Rich
University of Connecticut, U-42, Storrs, CT 06268

ABSTRACT

Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring, and management
Edited by Ingrid Chorus and Jamie Bartram, © 1999 WHO;
ISBN 0-419-23930-8
(http://apps.who.int/iris/bitstream/10665/42827/1/0419239308_eng.pdf)

National Field Manual for the Collection of Water-Quality Data
Techniques of Water-Resources Investigations
Book 9-Chapter 7.5, Handbooks for Water-Resources Investigations; USGS
(http://www.jlakes.org/web/national-field-manual-collection-water-quality-data.htm)


TOXIC CYANOBACTERIA IN WATER

Kortmann, R.W. and P.H. Rich, 1994. **Lake Ecosystem Energetics: The missing management link.** *Lake and Reservoir Management Journal*, 8(2):77-97.
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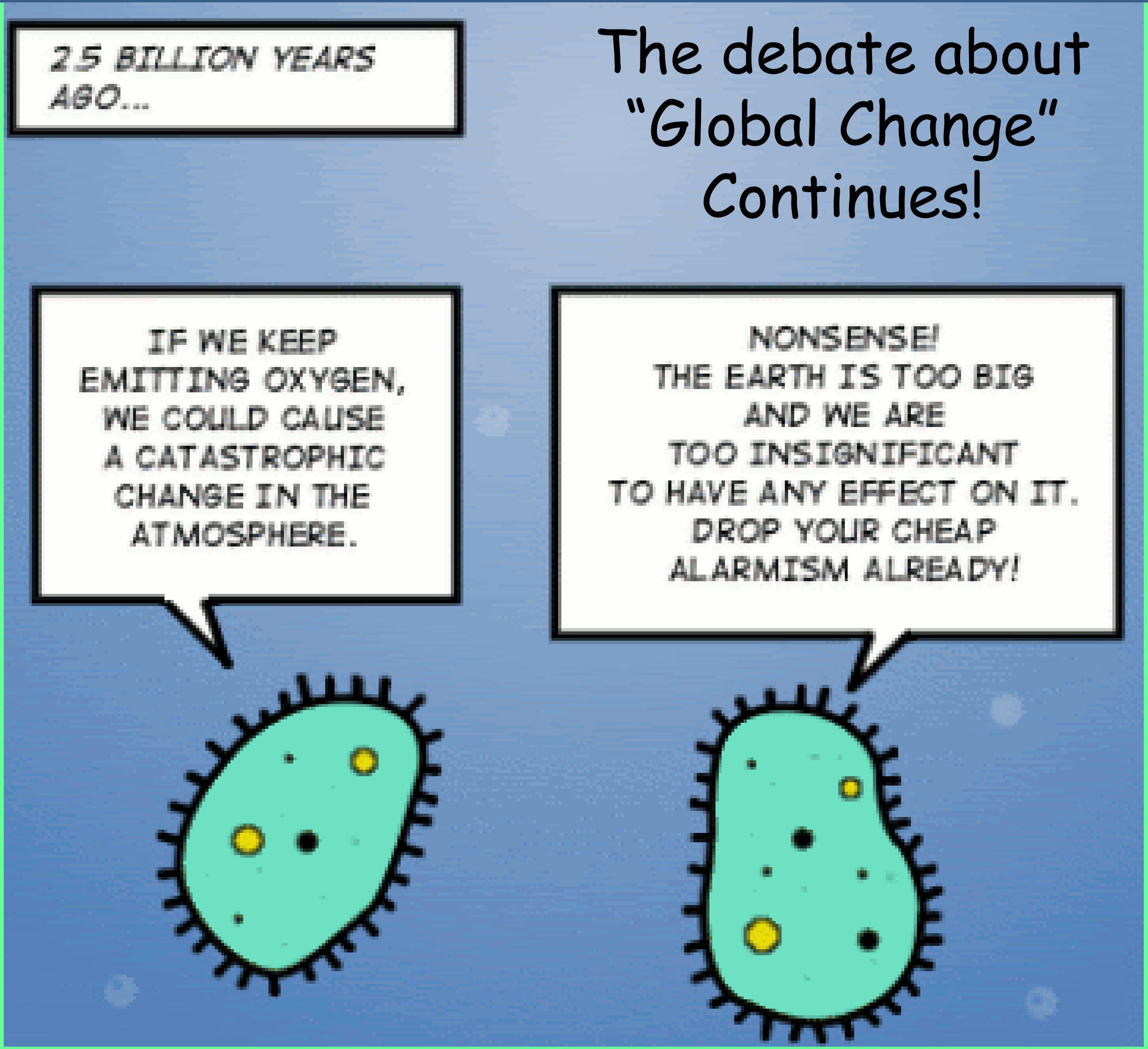
Wetzel, R.G., 1975. **Limnology.** W.B. Saunders Co., Philadelphia, PA

The debate about "Global Change" Continues!



Questions?