Modeling HABS with CE-QUAL-W2: Approaches and Future Challenges

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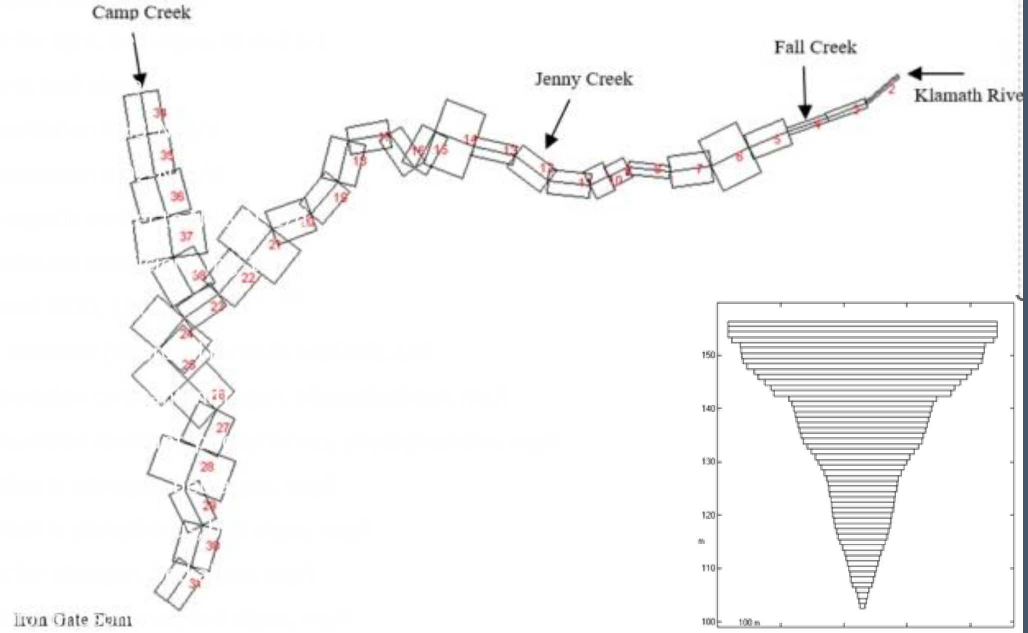
Cyanobacteria – Attributes

- Single celled, photosynthetic organisms with high reproduction rates
- Some cyanobacteria
  - Control their buoyancy and thus vertical position in the water column
  - Fix atmospheric nitrogen (N2)
  - Produce toxins (e.g., neurotoxins, hepatotoxins)
  - Form colonies that aid with mobility, reduced predation, and shade out competition
  - Have unique reproductive strategies
  - Other unique attributes.
- Harmful algal blooms (HABS) are typically related to blooms that include toxin producing strains, create public health hazards and/or environmental impacts
- Nuisance blooms of non-toxic species also occur

CE-QUAL-W2

- Two-dimensional laterally averaged model
- Hydrodynamic and water quality model
- Capable of modeling a wide suite of water quality constituents including detailed representation of multiple algae groups

ALP0	Chl a to algal biomass conversion factor, phytoplankton, mg Chl_a to mg-A	BMORT	Local respiration rate of algae, bed algae, 1/d
ALP1	Fraction of algal biomass that is nitrogen, phytoplankton, mg-N/mg A	KBLIGHT	Half-saturation coefficien
ALP2	Fraction of algal biomass that is phosphorous, phytoplankton, mg-P/mg A	PBREFN	Preference factor for NH3
MUMAX	Maximum specific growth rate, phytoplankton, 1/d	BET1	Rate constant: biological
RESP	Local respiration algae, phytoplankton, 1/d	BET2	Rate constant: biological
RESP	Local mortality rate of algae, phytoplankton, 1/d	BET3	Rate constant: hydrolysis
SIG1	Settling rate of algae, phytoplankton, 1/d	KNINH	First order nitrification in
KLIGHT	Half saturation coefficient for light, phytoplankton, KJ m-2 s-1	K1	Deoxygenation rate const
PREFN	Preference factor for NH3-N, phytoplankton	-	Minimum reaeration rate
ABLP0	Chl a to algal biomass conversion factor, bed algae, mg Chl_a to mg-A	KNITR	Michaelis-Menton half sa
BMUMAX	Maximum specific growth rate, bed algae, 1/d	KPHOS	Michaelis-Menton half sa
BRESP	Local respiration rate of algae, bed algae, 1/d	ABLP1	Fraction of algal biomass
GRAZE	Local respiration rate of algae, bed algae, 1/d	ABLP2	Fraction of algal biomass
BMORT	Local respiration rate of algae, bed algae, 1/d	KBNITR	Half-saturation coefficien
KBLIGHT	Half-saturation coefficient for light, bed algae, KJ m-2 s-1	KBPHOS	Half-saturation coefficien



Case Studies

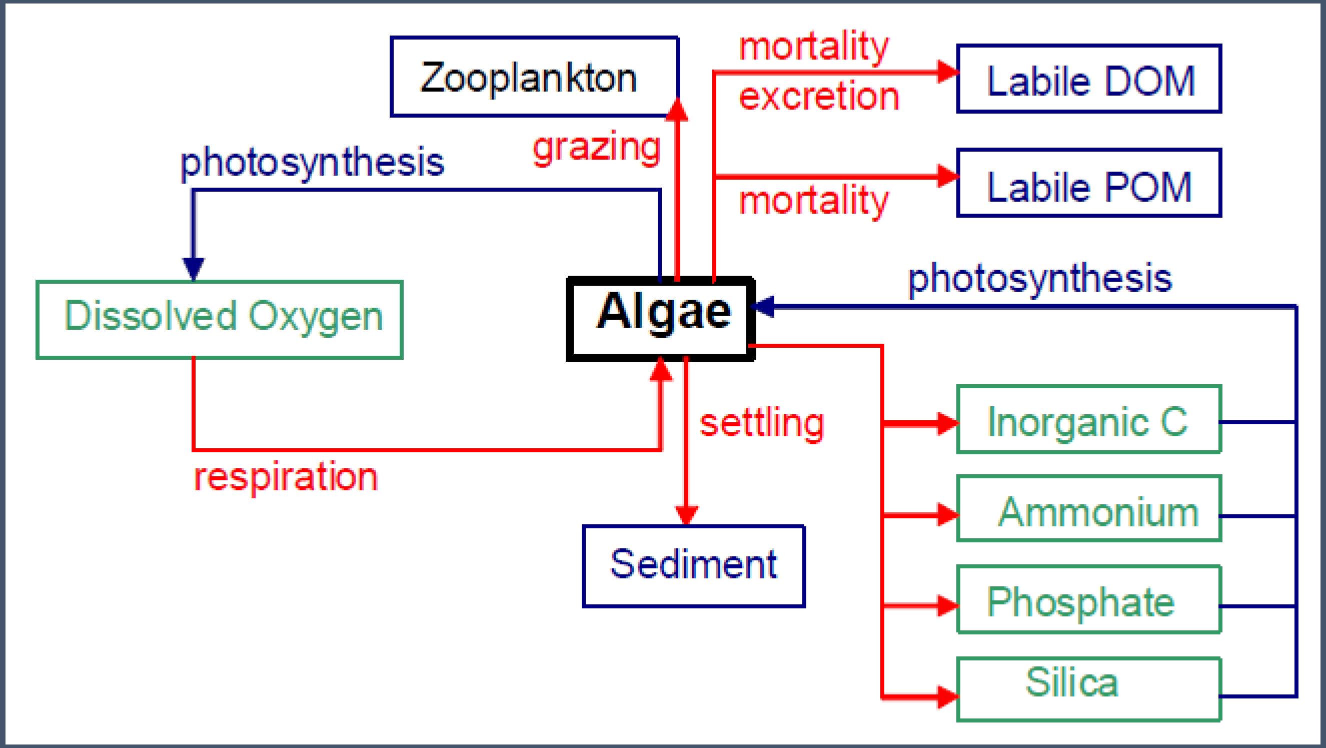
- CE-QUAL-W2 Modeling Approaches - Processes
  - Representing buoyancy compensating cyanobacteria
  - Representing nitrogen fixing cyanobacteria
  - Representing dissolved oxygen constraints on growth and mortality*
- CE-QUAL-W2 Modeling Approaches – Prescriptions
  - Enhanced mixing (cove)
  - Barrier Curtain*
  - Algaecide Treatment*
  - Reservoir Drawdown*
  - Hypolimnetic oxygenation*

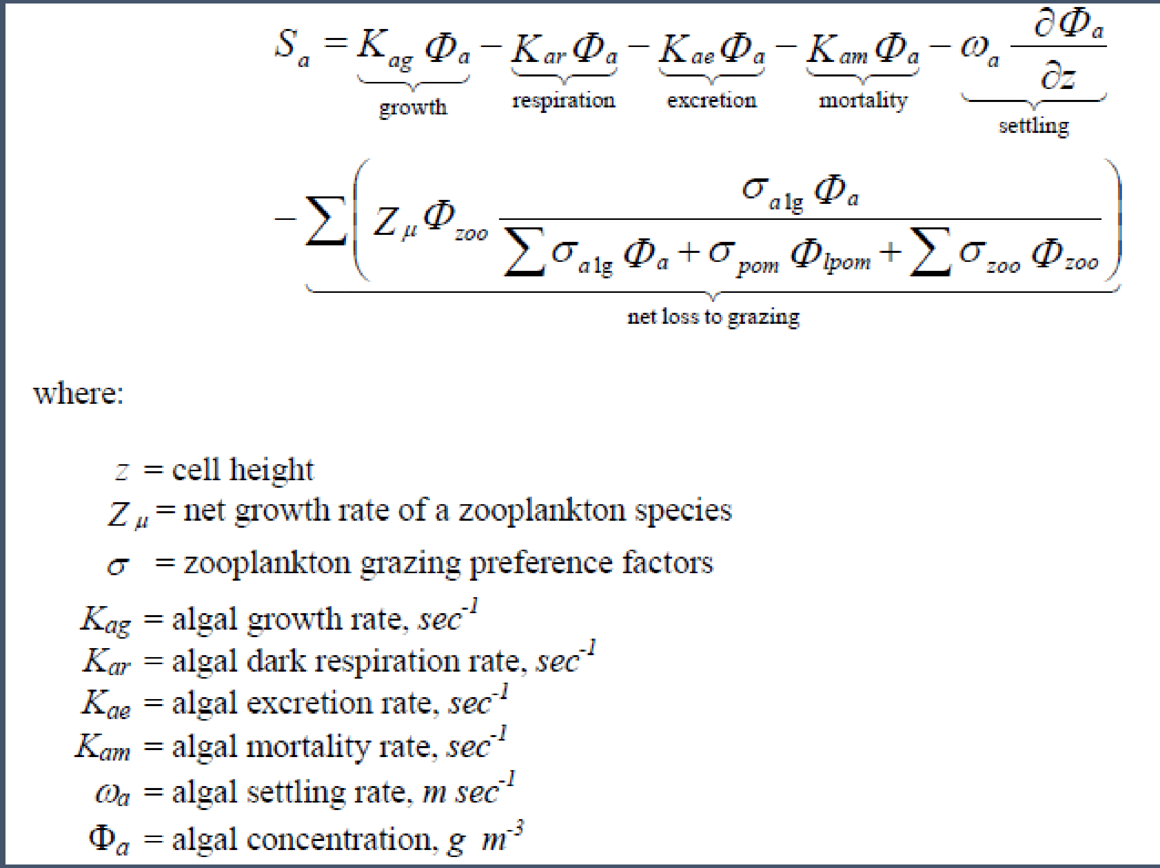
* Not covered herein

CE-QUAL-W2 Phytoplankton Logic

- Complex representation
- Multiple algae groups

- Other water quality interactions
- Temperature dependent





$$S_a = \underbrace{K_{ag}\,\Phi_a}_{\text{growth}} - \underbrace{K_{ar}\,\Phi_a}_{\text{respiration}} - \underbrace{K_{ae}\,\Phi_a}_{\text{excretion}} - \underbrace{K_{am}\,\Phi_a}_{\text{mortality}} - \underbrace{\omega_a \frac{\partial \Phi_a}{\partial z}}_{\text{settling}}$$

$$\underbrace{-\sum \left(Z_\mu \Phi_{zoo} \frac{\sigma_{a\lg}\,\Phi_a}{\sum \sigma_{a\lg}\,\Phi_a + \sigma_{pom}\,\Phi_{lpom} + \sum \sigma_{zoo}\,\Phi_{zoo}} \right)}_{\text{net loss to grazing}}$$

where:

z = cell height
Z_μ = net growth rate of a zooplankton species
σ = zooplankton grazing preference factors
K_{ag} = algal growth rate, sec^{-1}
K_{ar} = algal dark respiration rate, sec^{-1}
K_{ae} = algal excretion rate, sec^{-1}
K_{am} = algal mortality rate, sec^{-1}
ω_a = algal settling rate, $m\ sec^{-1}$
Φ_a = algal concentration, $g\ m^{-3}$

CE-QUAL-W2 Phytoplankton Logic

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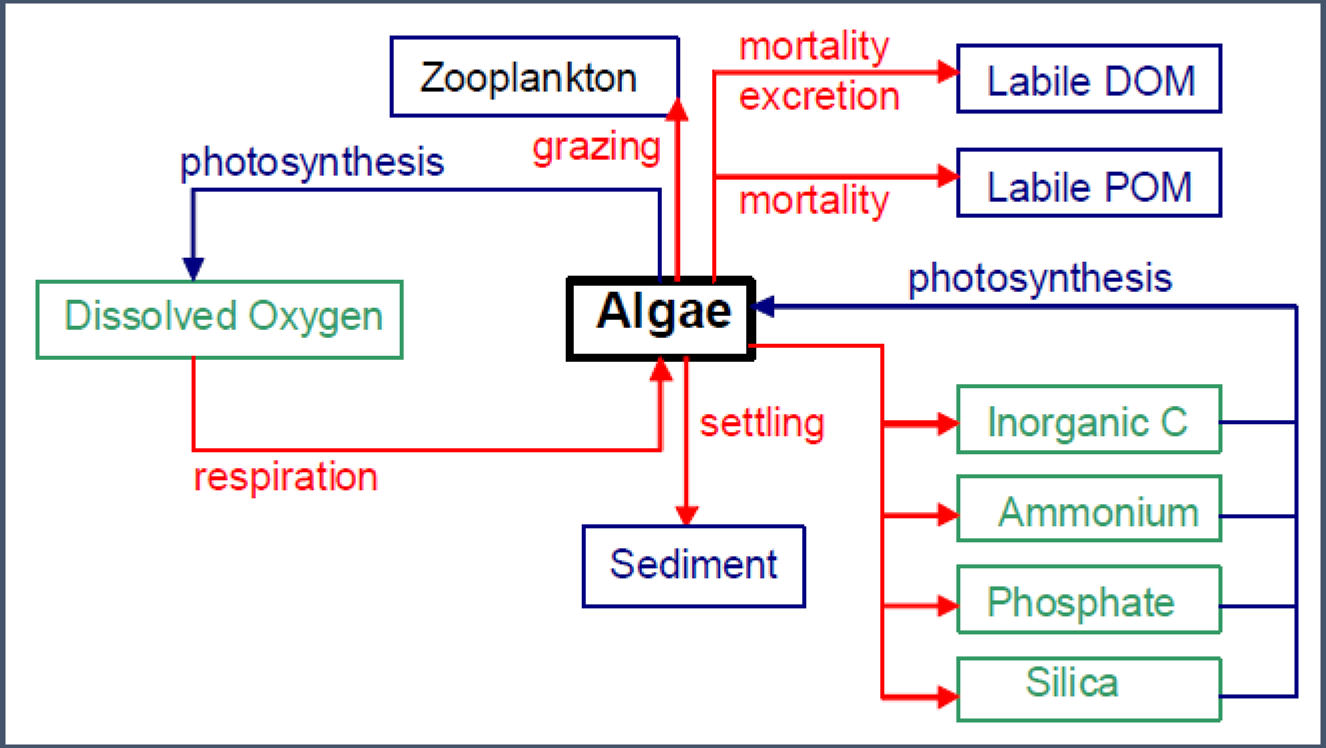

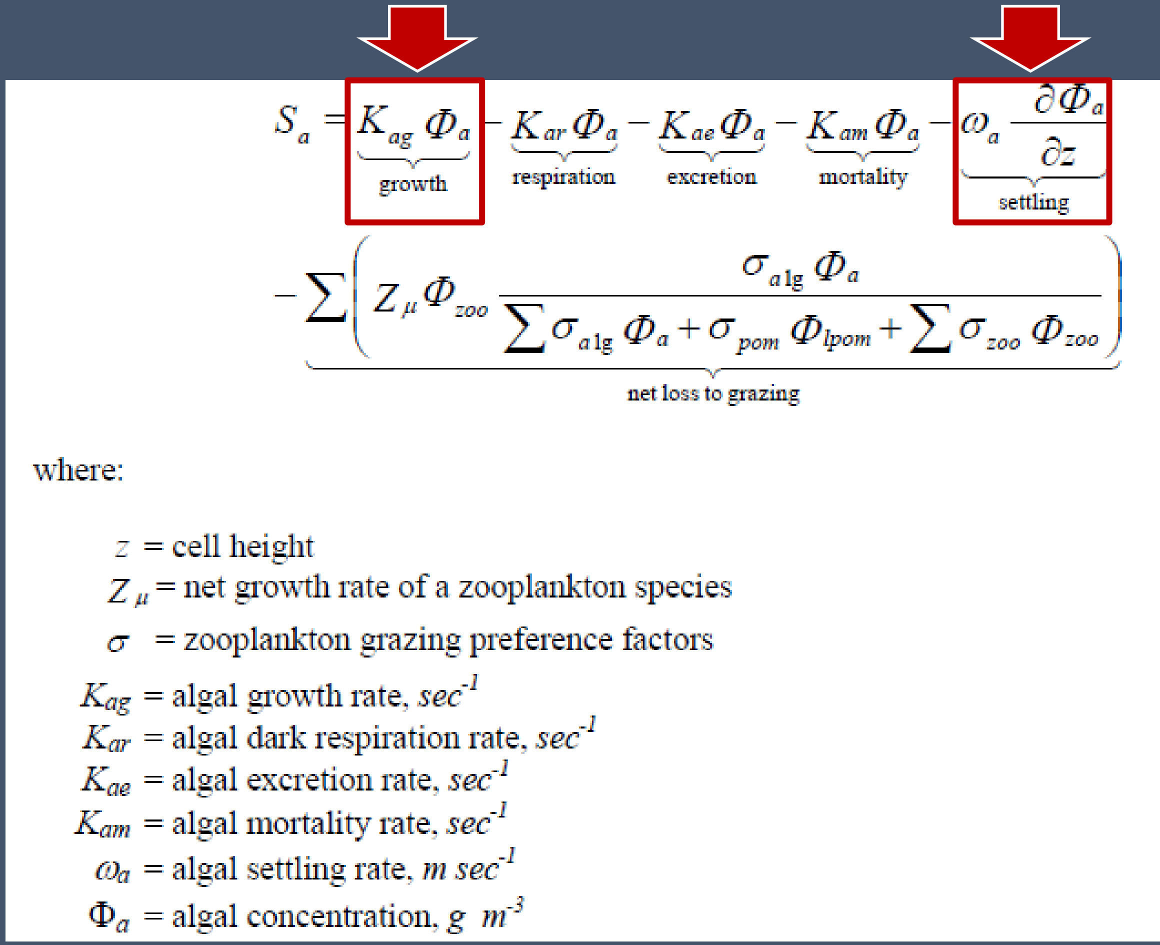

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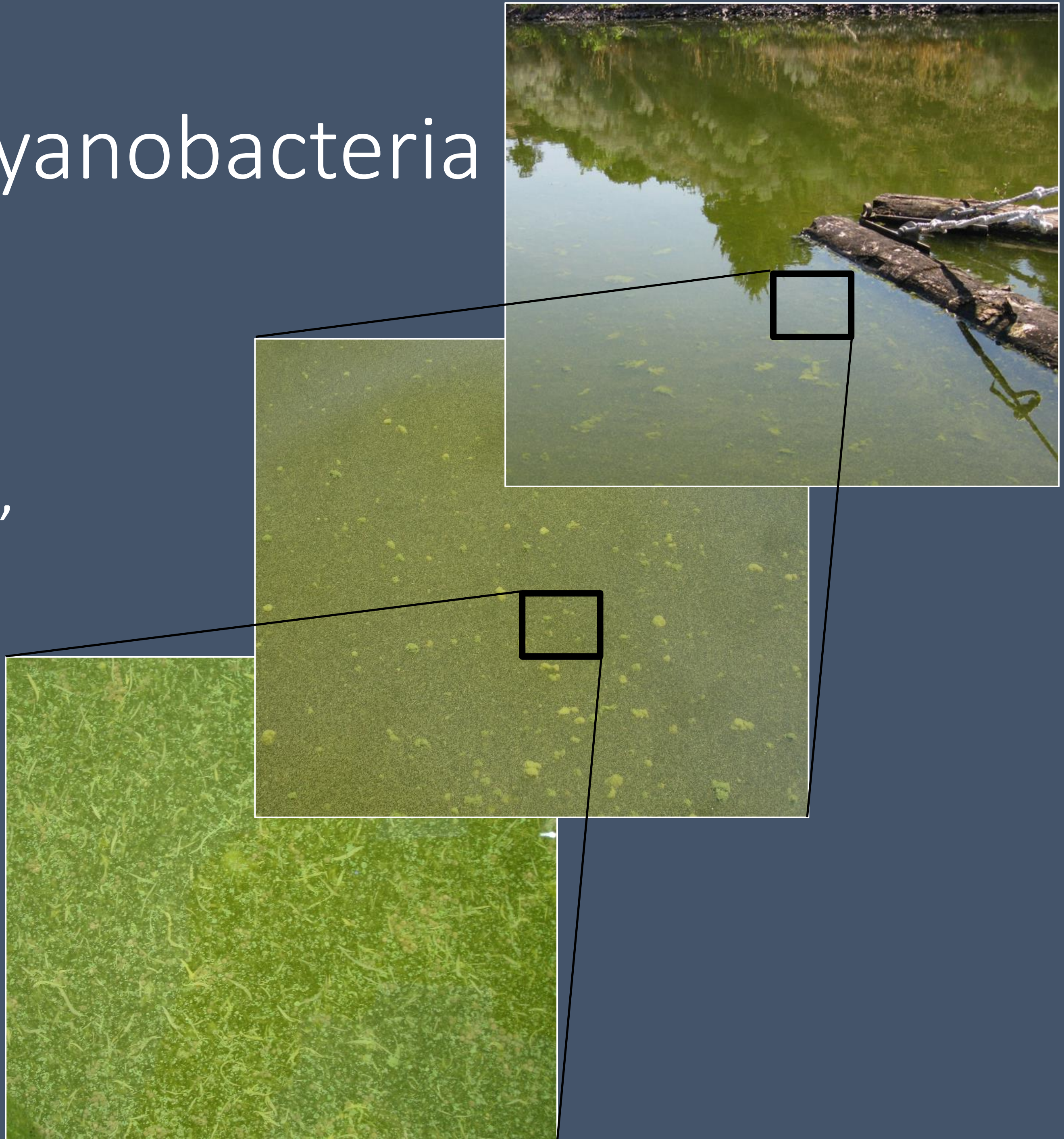
Vertical Movement of Cyanobacteria

- Gas Vesicles are used to "control" location in water column (formation, collapse, protein or carbohydrate content, environmental conditions, colony size/structure, other)
- Preferential position
    - Light
    - Nutrients
    - Competition
- Complex process



Settling Rate ($S_a = f(\omega_a \frac{\partial \Phi_a}{\partial z})$)

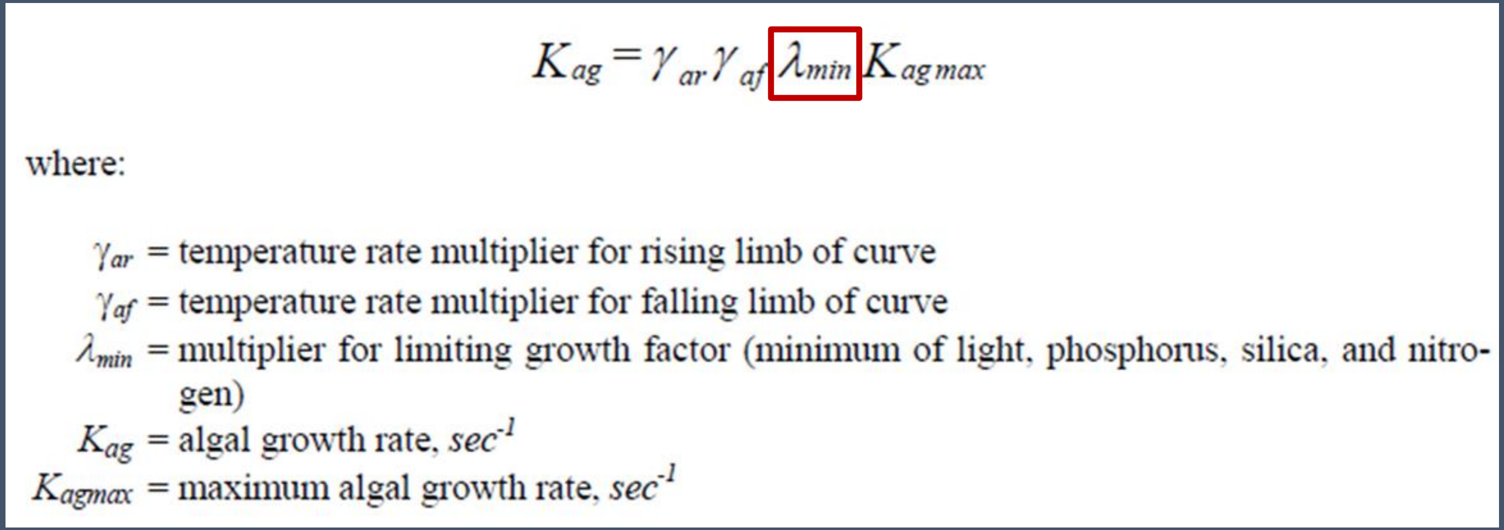
- Positive ω_a: negatively buoyant
- Negative or zero ω_a: positively buoyant or neutrally buoyant
- Subject to simulated aquatic system mixing processes

- CE-QUAL-W2 – Existing Formulation
  - Cyanobacteria or other floating phytoplankton: 0.0-0.05 m day-1 and can specify a negative settling velocity (CE-QUAL-W2 2021)
  - Settling rate = 0 (Smith and Kiesling 2019)
- CE-QUAL-W2 – Modified Formulation
  - Use specific logic to model vertical migration (Overman 2019*) – new code
  - Parameterization (field data) challenge

* Useful description of vertical migration models

Nitrogen Fixation Growth ($S_a = f(K_{ag}\Phi)$)

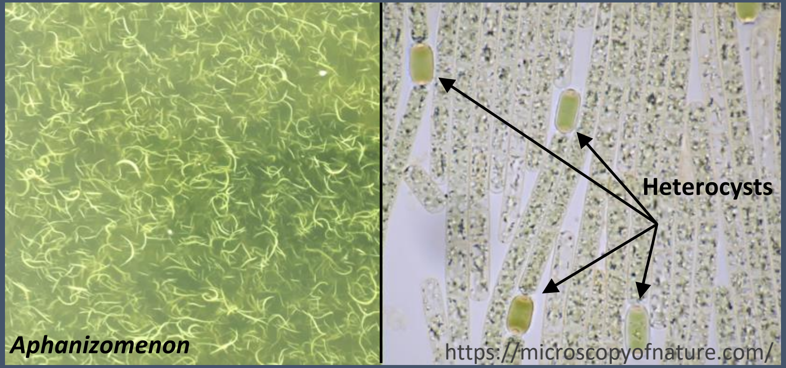
- Limiting growth factor
  - Light
  - Phosphorus
  - Nitrogen
  - Silica
- Heterocyst: specialized fix nitrogen (N2)



$$K_{ag} = \gamma_{ar}\gamma_{af}\boxed{\lambda_{min}}K_{ag\,max}$$

where:

γ_{ar} = temperature rate multiplier for rising limb of curve
γ_{af} = temperature rate multiplier for falling limb of curve
λ_{min} = multiplier for limiting growth factor (minimum of light, phosphorus, silica, and nitrogen)
K_{ag} = algal growth rate, sec^{-1}
K_{agmax} = maximum algal growth rate, sec^{-1}



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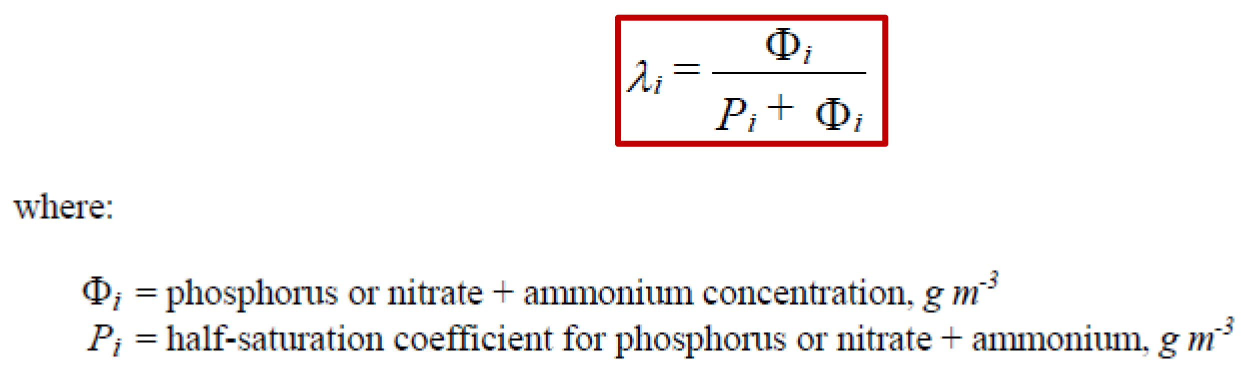


$$\boxed{\lambda_i = \frac{\Phi_i}{P_i + \Phi_i}}$$

where:

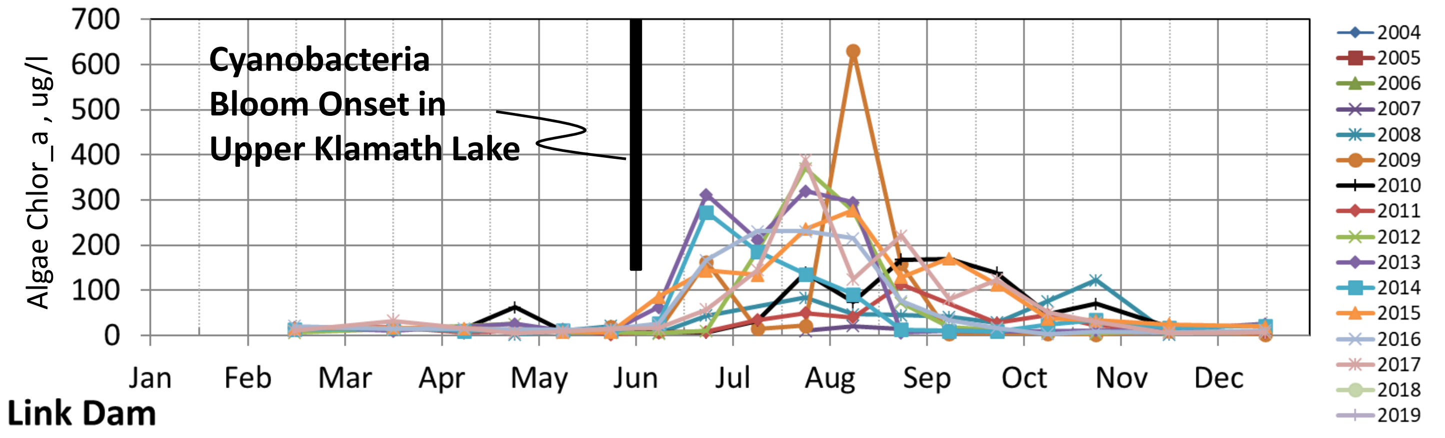
Φ_i = phosphorus or nitrate + ammonium concentration, $g\ m^{-3}$
P_i = half-saturation coefficient for phosphorus or nitrate + ammonium, $g\ m^{-3}$

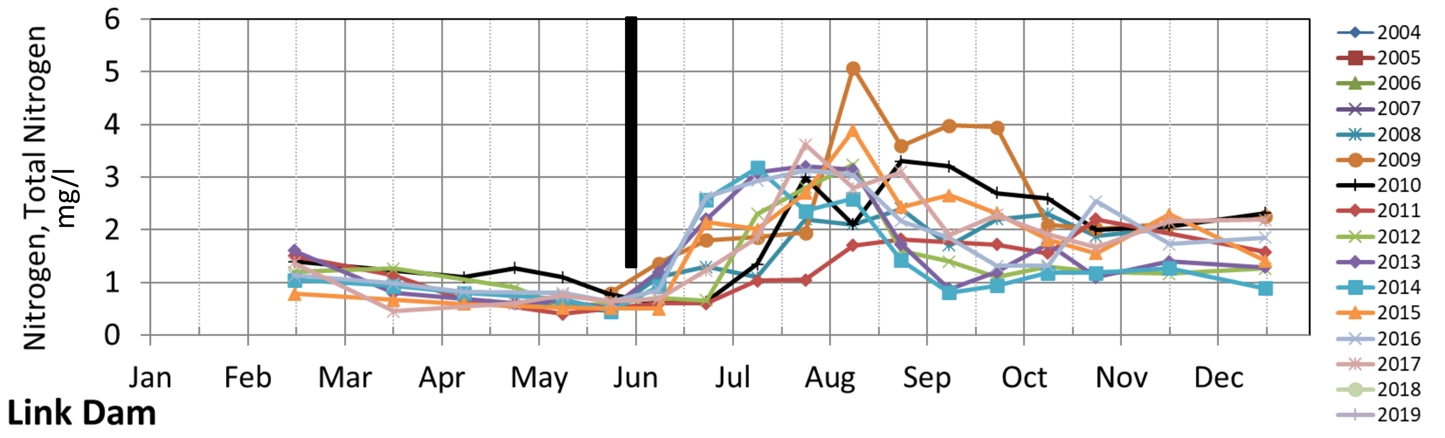
Nitrogen Fixation Growth ($S_a = f(K_{ag}\Phi)$)

- CE-QUAL-W2 – Existing Formulation
  - Set half saturation coefficient for nitrate and ammonia to zero

$$\lambda_i(\mathrm{P}_i = 0) = \frac{\Phi_i}{\Phi_i} = 1.0$$

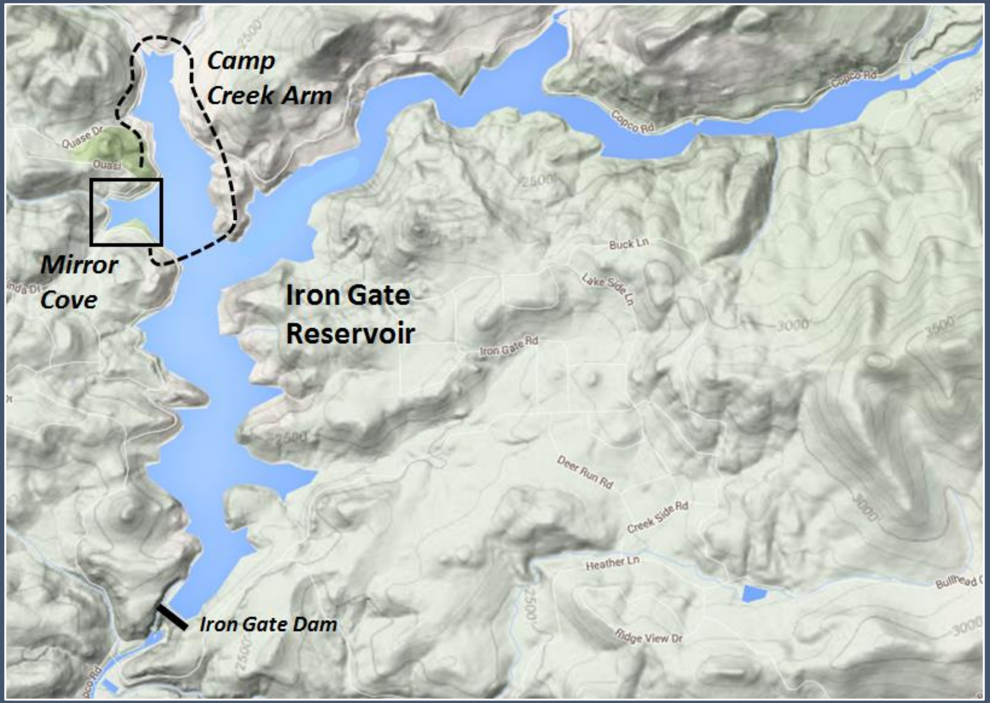
  - No nutrient limitation
  - Allows
    - Cyanobacteria to reproduce under low inorganic nitrogen concentrations
    - Effectively incorporates “load” due to N-fixation consistent with algae stoichiometry (≈0.08)

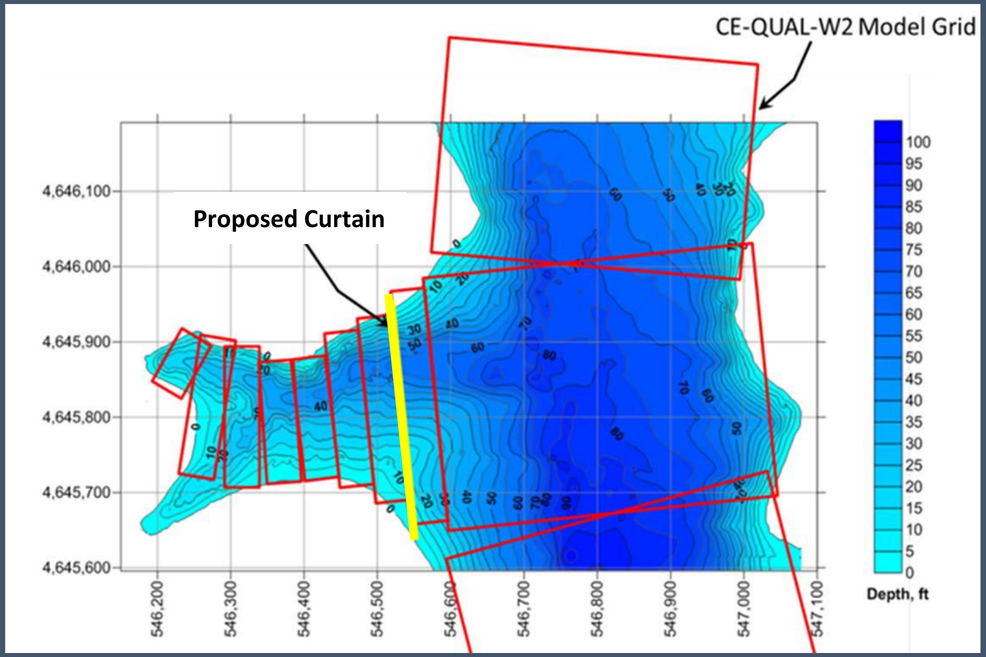




Prescription: Mixing a Cove

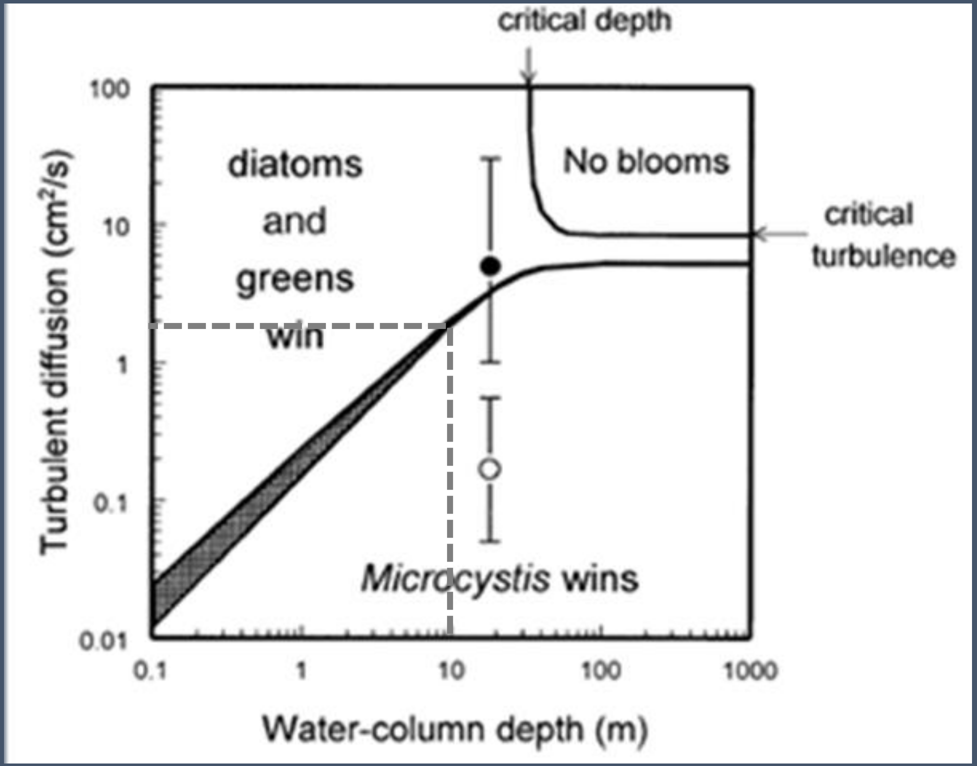
- Conceptualized isolating a cove using a barrier curtain
- Used CE-QUAL-W2 to assess mixing required to disrupt cyanobacteria
- Used vertical turbulent diffusion coefficient as a metric after Huisman et al. (2004)





Mixing Impacts on Microcystis

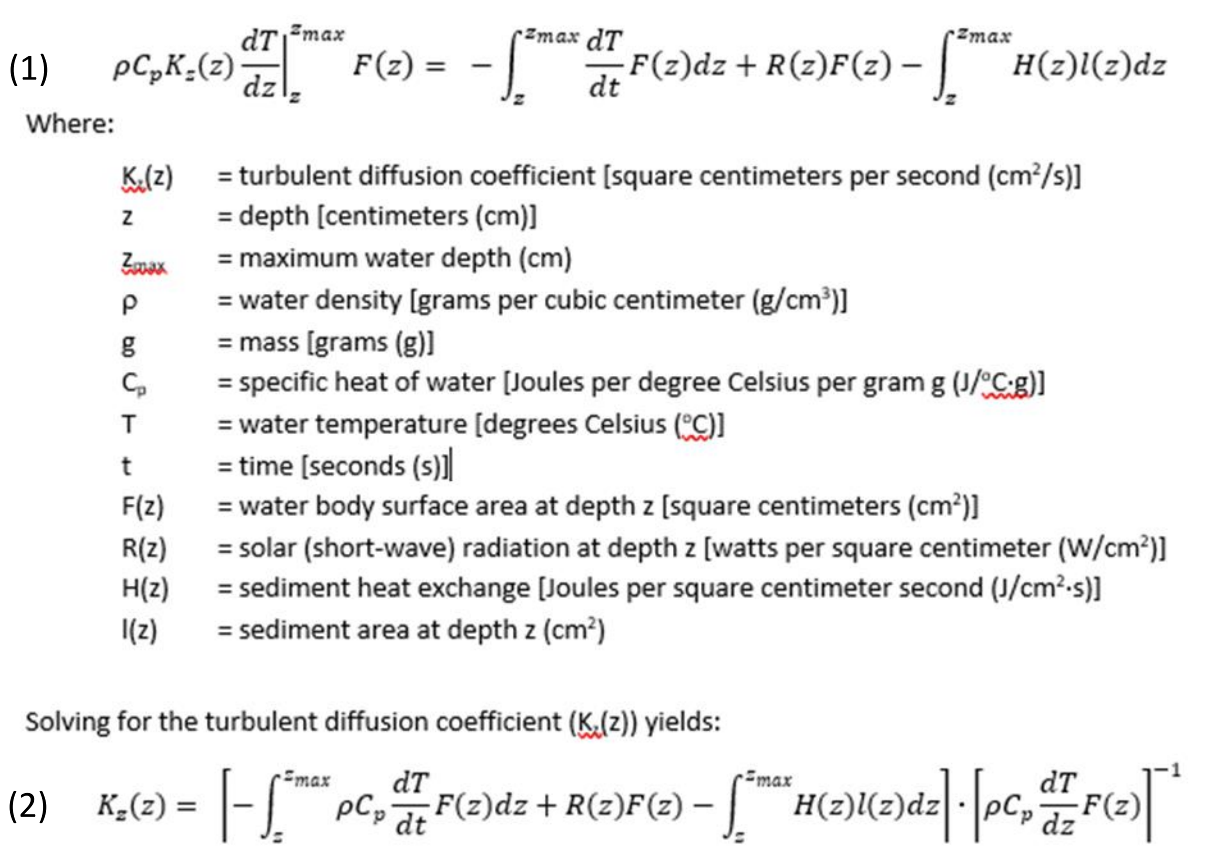
- Vertical mixing in the water column reduces the advantages of colonization and buoyancy compensation by vacuolated cyanobacteria
- If mixing is sufficient and depth great enough, other species can outcompete cyanobacteria



Predicted response of *Microcystis*, diatoms, and green algae as a function of water-column depth and turbulent diffusion (from Huisman et al. 2004).

Leveraging CE-QUAL-W2

- Using the temporal and spatial distribution of heat in the cove (eqtn 1))...
- Calculate eddy diffusivity values (eqtn 2) using simulated CE-QUAL-W2 vertical temperature profiles
- Three conditions
  - No curtain
  - Curtain with no circulation
  - Curtain with circulation
- Calculate turbulent diffusion coefficient (eqtn 2) and compare with Huisman



(1) $$\rho C_p K_z(z) \frac{dT}{dz}\bigg|_z^{z_{max}} F(z) = -\int_z^{z_{max}} \frac{dT}{dt} F(z)dz + R(z)F(z) - \int_z^{z_{max}} H(z)l(z)dz$$

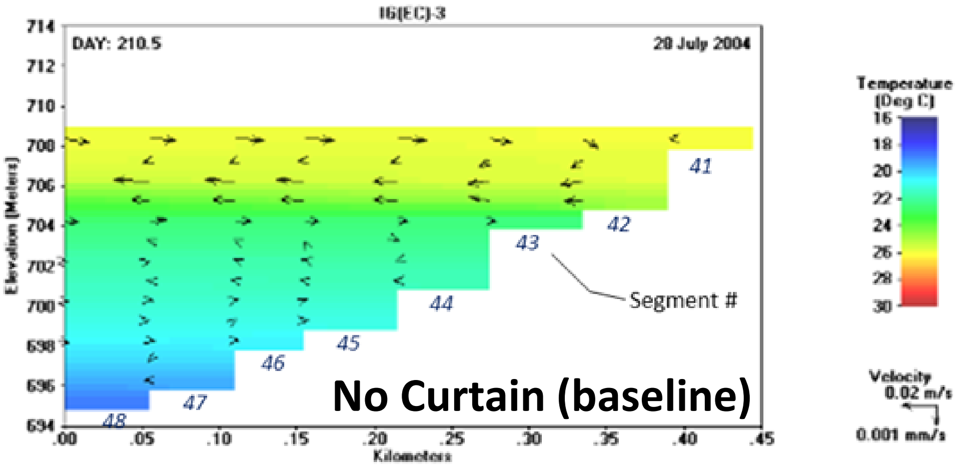
Where:

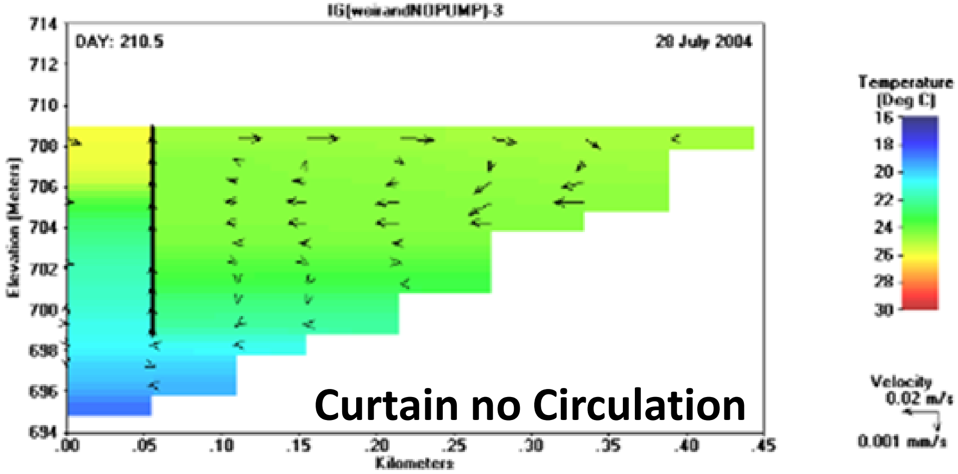
$K_z(z)$ = turbulent diffusion coefficient [square centimeters per second (cm^2/s)]
z = depth [centimeters (cm)]
Z_{max} = maximum water depth (cm)
ρ = water density [grams per cubic centimeter (g/cm^3)]
g = mass [grams (g)]
C_p = specific heat of water [Joules per degree Celsius per gram g ($J/^{o}C{\cdot}g$)]
T = water temperature [degrees Celsius (^{o}C)]
t = time [seconds (s)]
F(z) = water body surface area at depth z [square centimeters (cm^2)]
R(z) = solar (short-wave) radiation at depth z [watts per square centimeter (W/cm^2)]
H(z) = sediment heat exchange [Joules per square centimeter second ($J/cm^2{\cdot}s$)]
l(z) = sediment area at depth z (cm^2)

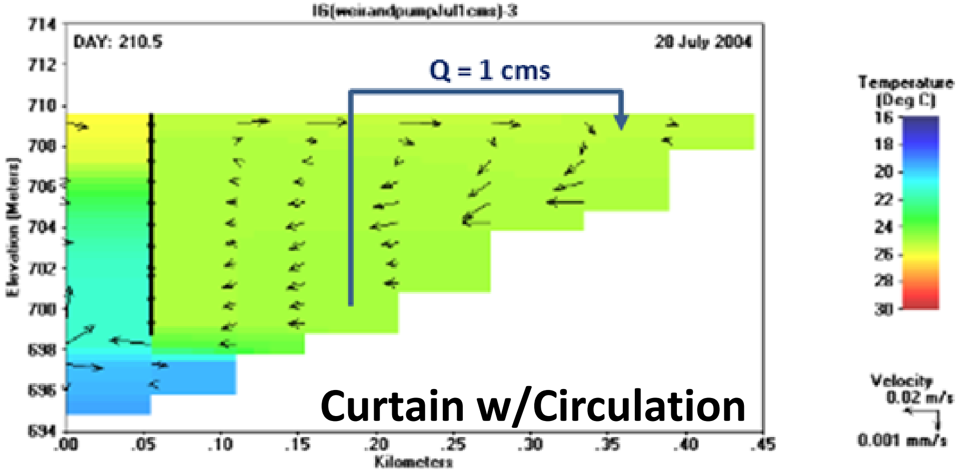
Solving for the turbulent diffusion coefficient ($K_z(z)$) yields:

(2) $$K_z(z) = \left[-\int_z^{z_{max}} \rho C_p \frac{dT}{dt} F(z)dz + R(z)F(z) - \int_z^{z_{max}} H(z)l(z)dz\right] \cdot \left[\rho C_p \frac{dT}{dz} F(z)\right]^{-1}$$

(see Jassby and Powell (1975) and Benoit and Hemond (1974)

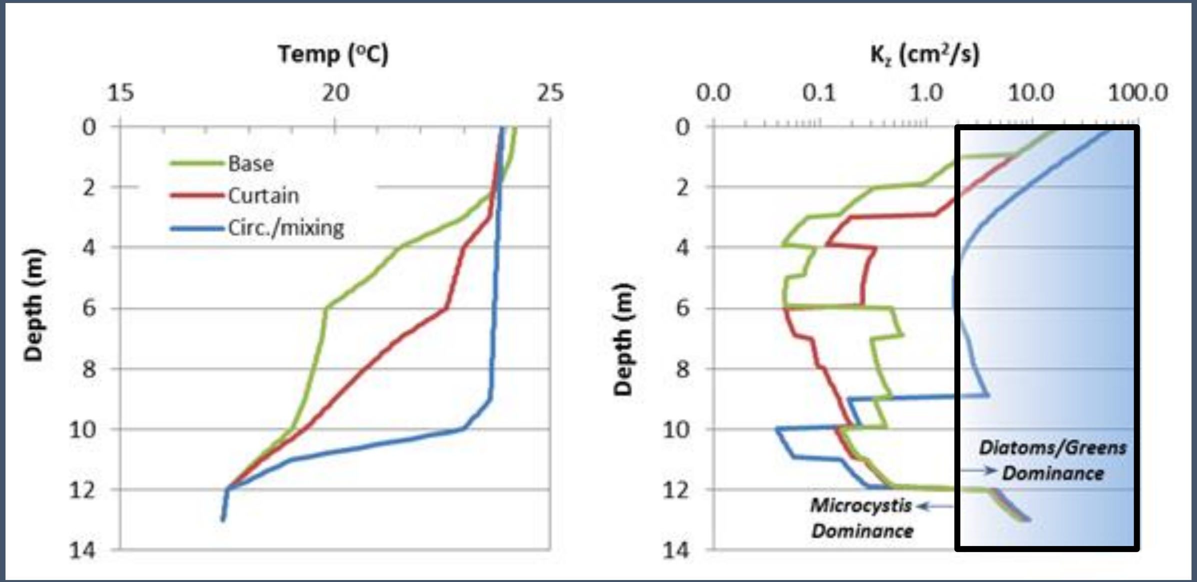






Results

- Curtain with 1 cms (35.3 cfs) circulation produces K_z from 2 cm^2/s to >50 cm^2/s in top 8 m of cove (Secchi 1.0-1.5m)
- Hydraulic residence time <5 days
- Results suggest viable control measure in this 10 m cove



Cyanobacteria Representation in CE-QUAL-W2: Considerations

- Blooms are often spatially heterogeneous (x-y-z) and dynamic through time
- Grid resolution is a key consideration, depending on objective
- Thermal stratification -> effectively modeled
- Water quality dynamics -> effectively modeled
- Species/group competition is challenging
- Can require considerable field observations to parameterize and test model for cyanobacteria simulation

- Recommend starting big (seasonal responses) and refine as needed

Discussion

Citations

- Benoit, G. and F.F. Hemond. 1996. Vertical eddy diffusion calculated by the flux gradient method: Significance of sediment-water heat exchange. Limnology and Oceanography. 41(1). Pp 157-168.
- Huisman, J., J. Sharples, J. M. Stroom, P. M. Visser, W. E.A. Kardinaal, J. M. H. Verspagen, and B. Sommeijer. 2004. Changes in turbulent mixing shift competition for light between phytoplankton species. Ecology 85:2960–2970.
- Jassby, A., and T. Powell. 1975. Vertical patterns of eddy diffusion during stratification in Castle Lake, California. Limnol. Oceanogr. 20: 530-543.
- Overman, Corina Christina Mae, "Modeling Vertical Migration of Cyanobacteria and Zooplankton" (2019). Dissertations and Theses. Paper 5178. https://doi.org/10.15760/etd.7054
- Smith, E.A., and Kiesling, R.L., 2019, Updates to the Madison Lake (Minnesota) CE-QUAL-W2 water-quality model for assessing algal community dynamics: U.S. Geological Survey Open-File Report 2019–xxxx, xx p., http://dx.doi.org/10.3133/XXXXX
- CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.5. Part 3 Input and Output Files - User Manual. 2021. Ed. S. Wells. Department of Civil and Environmental Engineering, Portland State University. August.