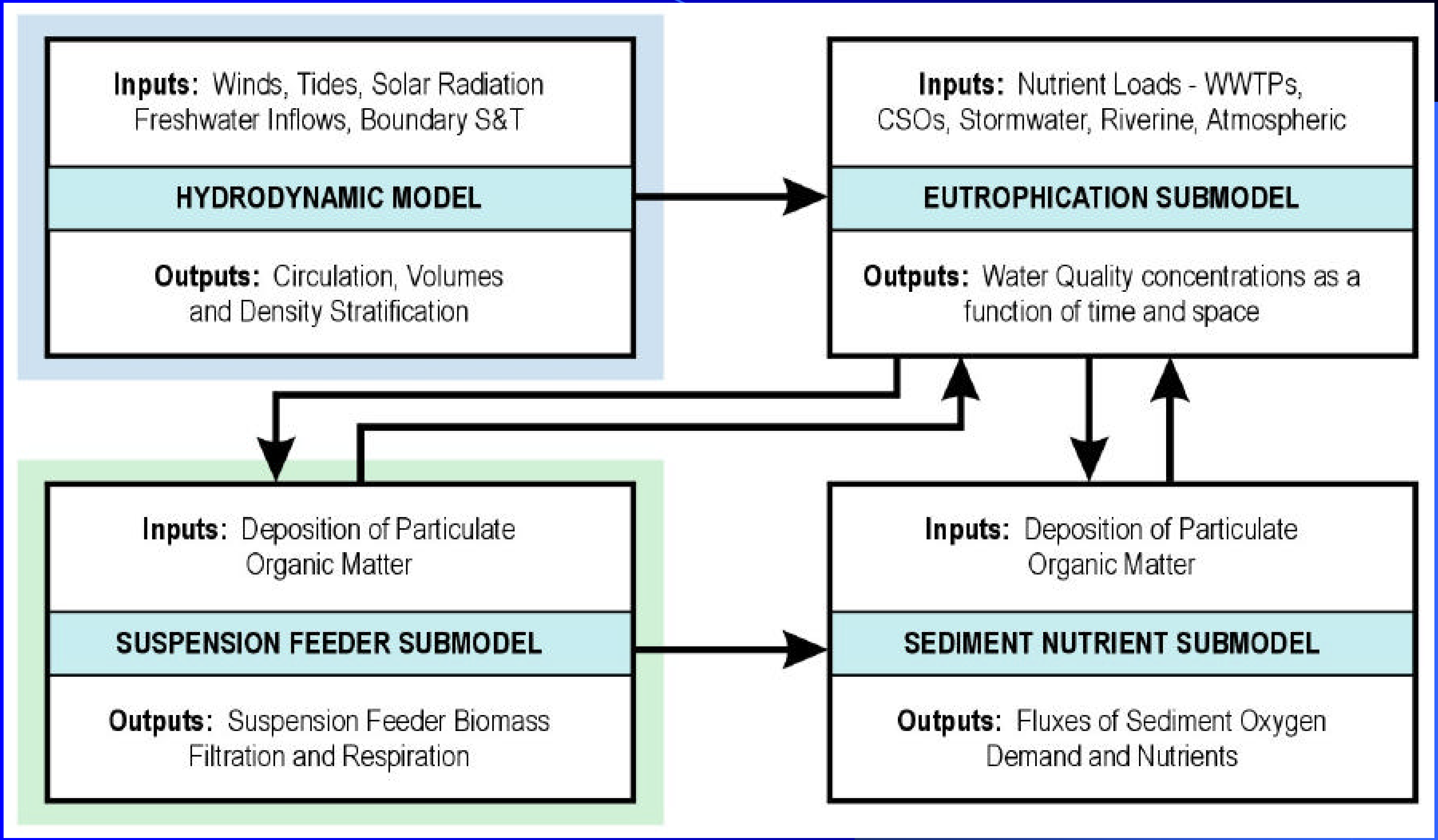
Eutrophication
And
Sediment Nutrient Flux
Modeling Primer

Science Advisory Panel Meeting

April 26, 2013

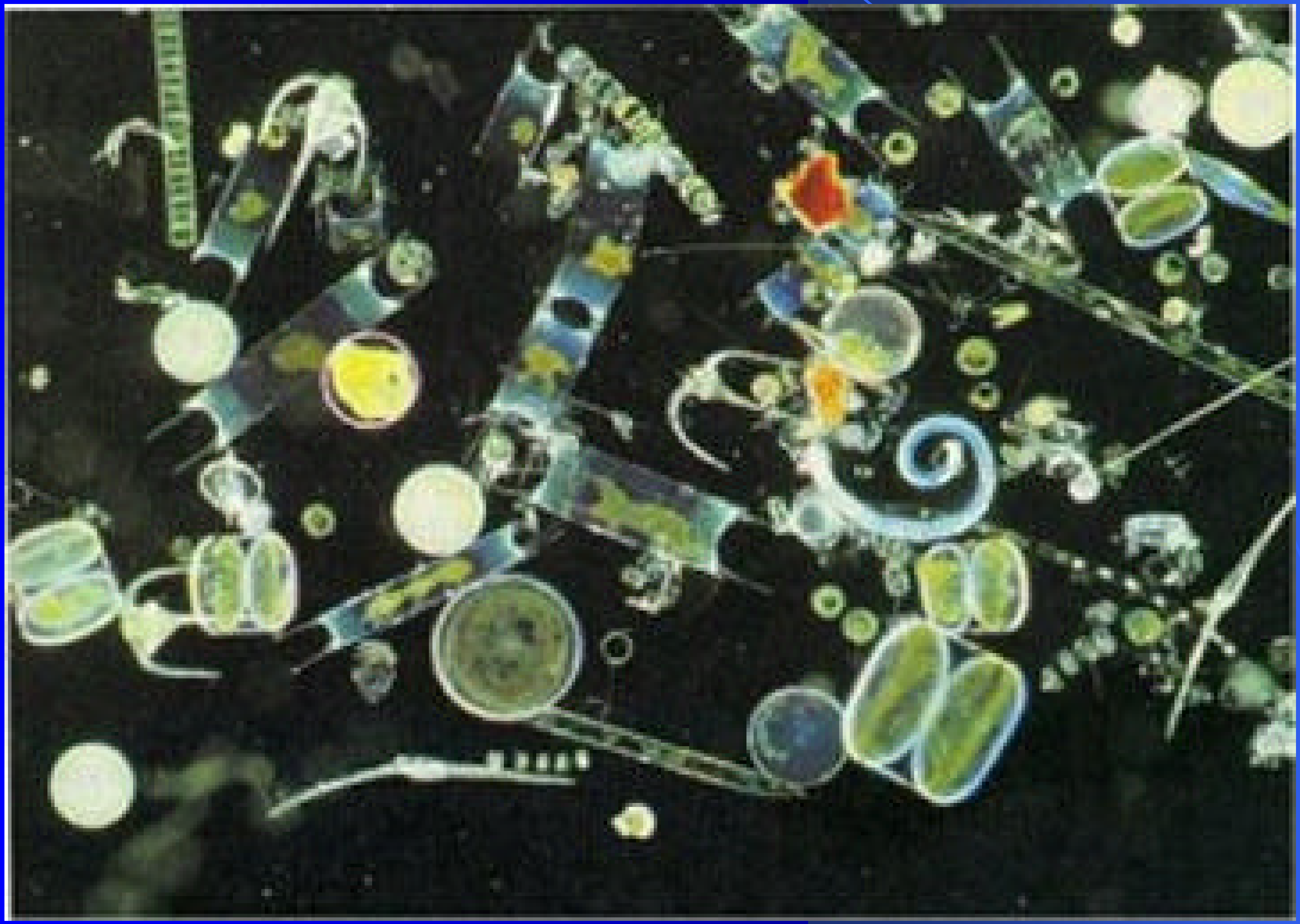
HDR | HydroQual

Overall Modeling Framework



Models based on continuity and mass balances

Phytoplankton, Light, Nutrients and Eutrophication Modeling



PHYTOPLANKTON GROWTH

- The time rate of change of algal biomass is a balance between phytoplankton growth and loss processes
- The latter of which include transport-related losses (settling or sinking and dispersion) and kinetic losses (respiration and predation)
- The growth rate itself is a function of environmental factors such as temperature, light, and nutrients

$$\frac{dP}{dt} = [u_{\max}(T, I, N) - r(T) - \frac{v_s}{H} - G_z]P$$

PHYTOPLANKTON GROWTH TEMPERATURE

- Different approaches: linear, Arrhenius (theta), optimal
  - –Linear

$$u_{\max,T} = 0 \qquad T \le T_{\min}$$

$$u_{\max,T} = u_{\max,ref} \frac{T - T_{\min}}{T_{ref} - T_{\min}} \qquad T > T_{\min}$$

  - –Theta

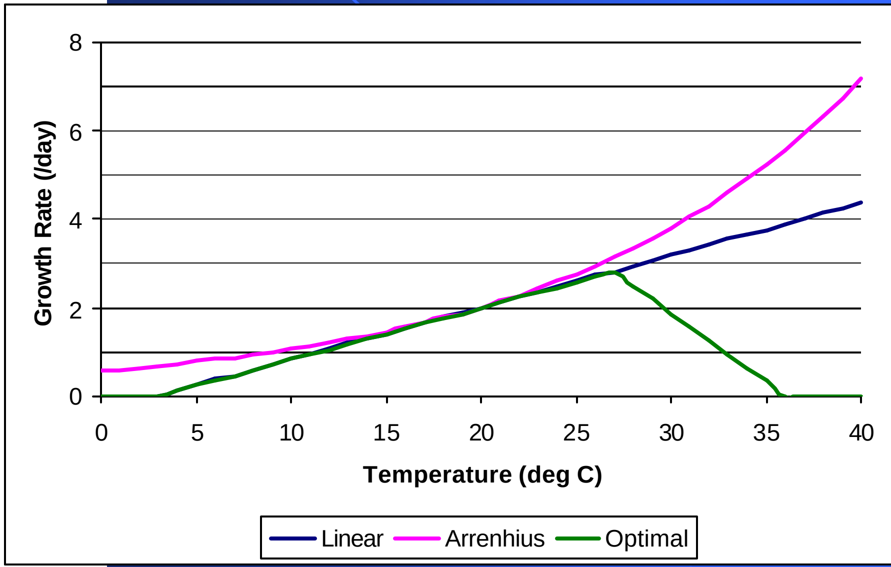
$$u_{\max,T} = u_{\max,20} \Theta^{T-20}$$

  - –Optimal

$$u_{\max,T} = 0 \qquad T \le T_{\min}$$

$$u_{\max,T} = u_{\max,opt} \frac{T - T_{\min}}{T_{opt} - T_{\min}} \qquad T_{\min} \le T \le T_{opt}$$

$$u_{\max,T} = u_{\max,opt} \frac{T_{\max} - T}{T_{\max} - T_{opt}} \qquad T_{\min} \le T \le T_{opt}$$

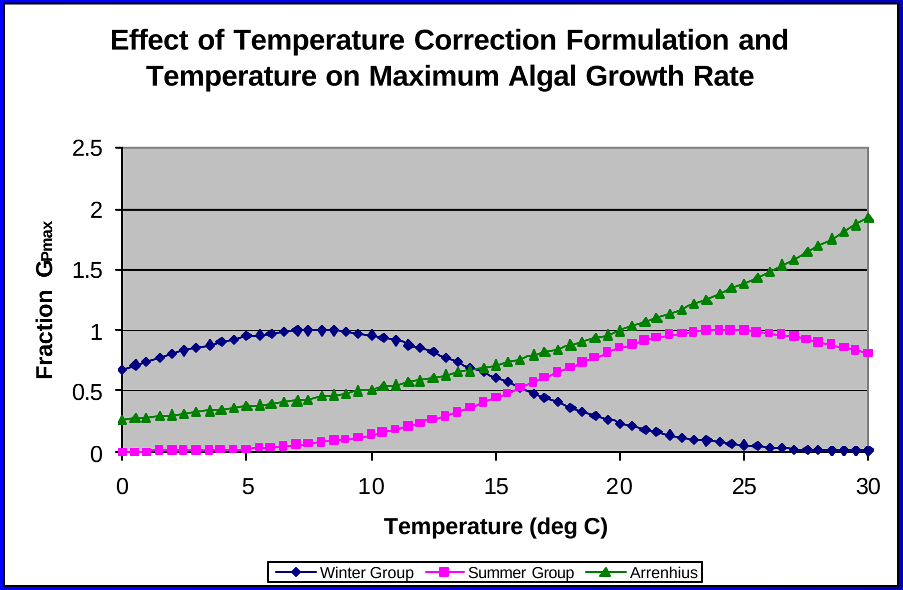


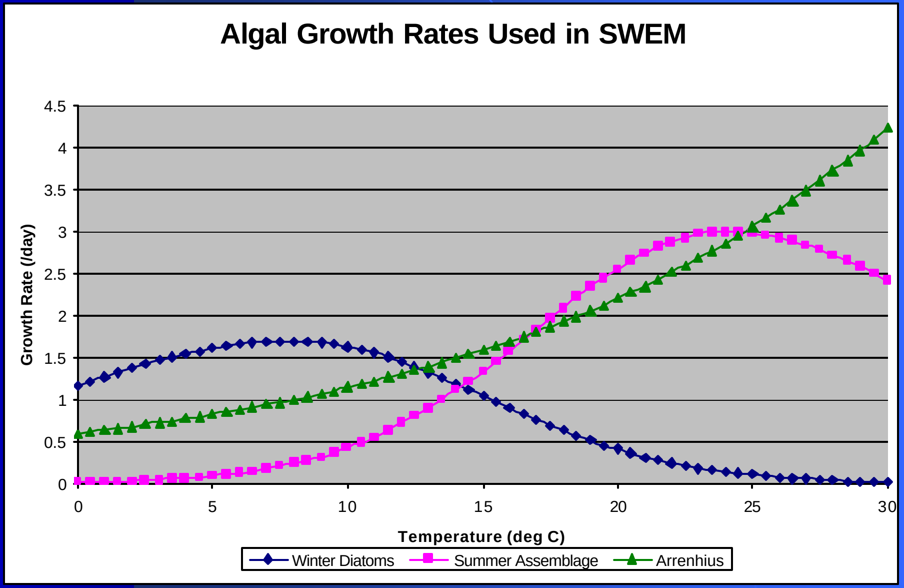
PHYTOPLANKTON GROWTH TEMPERATURE

- More than one functional algal group

$$u_{\max,T} = u_{\max,opt}\, e^{-b_1 (T - T_{opt})^2} \qquad T \le T_{opt}$$

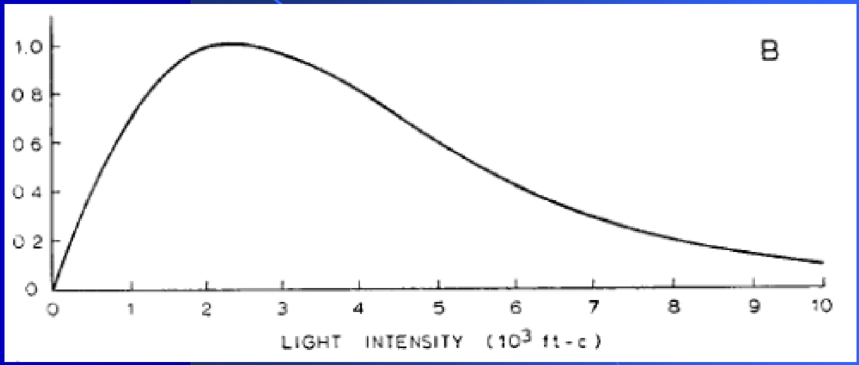
$$u_{\max,T} = u_{\max,opt}\, e^{-b_2 (T_{opt} - T)^2} \qquad T \ge T_{opt}$$





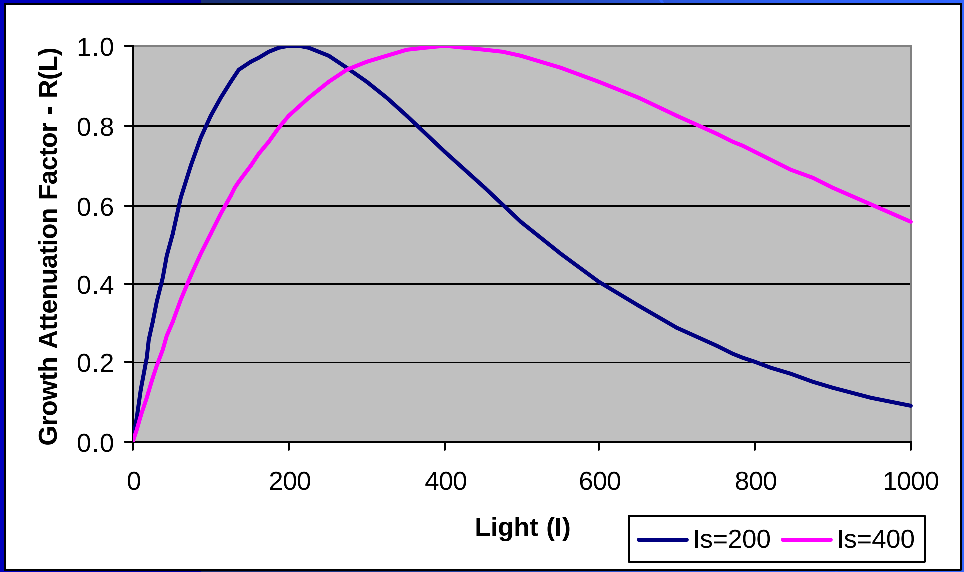
PHYTOPLANKTON GROWTH LIGHT

- Photoinhibition…



- Can be expressed mathematically …

$$F(I) = \frac{I}{I_s} \exp\{-\frac{I}{I_s} + 1\}$$



PHYTOPLANKTON GROWTH LIGHT

- How much light is available for growth …
  - seasonal patterns

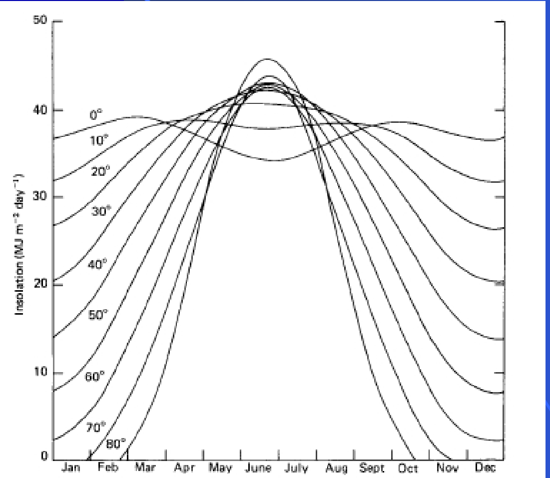
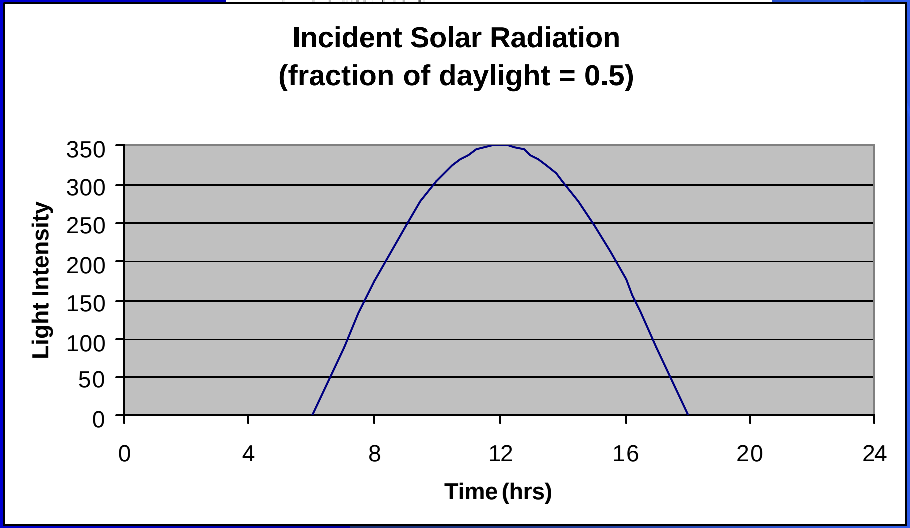


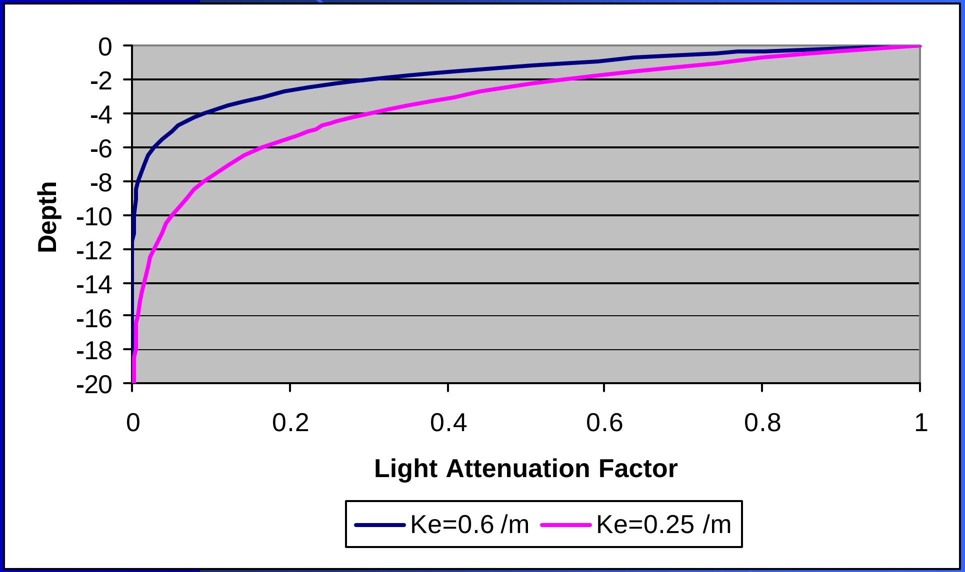
Fig. 2.8. Change in calculated daily insolation (ignoring the influence of the atmosphere) throughout the year at different latitudes in the northern hemisphere. The latitude is indicated above each curve. Plotted from data of Kondratyev (1954).

  - diurnal patterns



PHYTOPLANKTON GROWTH LIGHT

- How much light is available for growth …
  – vertical attenuation
- Vertical attenuation can be modeled by the Beer-Lambert law



$$I_z = I_0 e^{-k_e z}$$

where z = depth

K_e = light extinction coefficient

PHYTOPLANKTON GROWTH LIGHT

Extinction coefficient, K_e, is a function of phytoplankton biomass (chl-a), dissolved organic matter, and inert suspended solids

However, we usually just model it as a base value plus the algal component

$$K_{e-obs} = K_{e-base} + K_{e-algal}$$

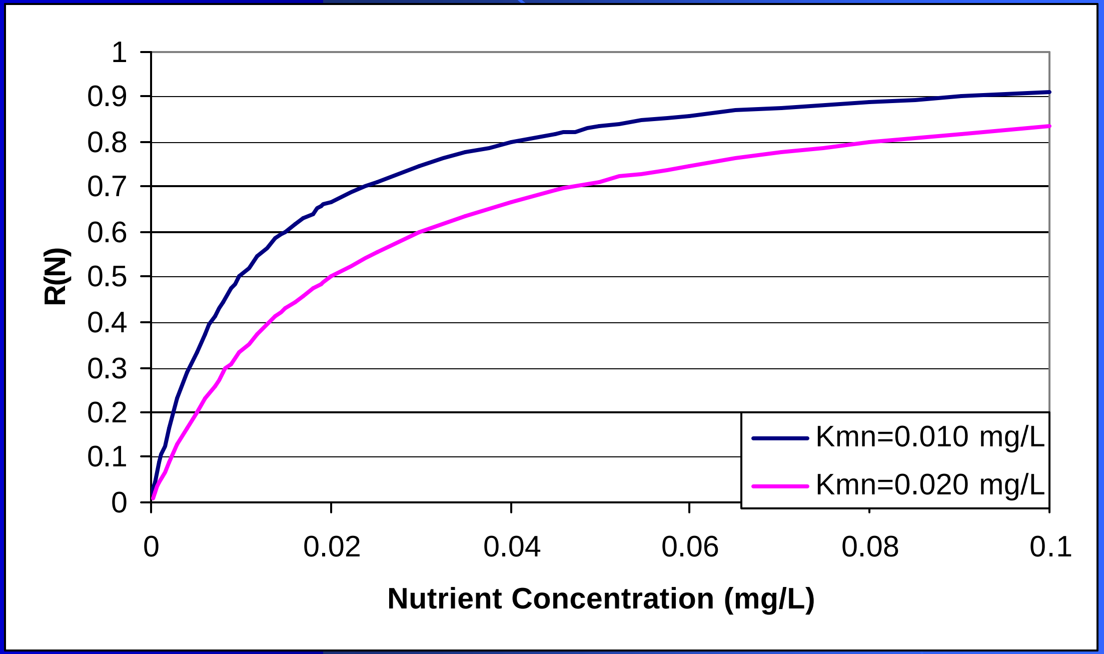
$$K_{e-obs} = K_{e-base} + a \cdot \mathrm{Chl\text{-}a}$$

Literature values of a range from 0.01 - 0.02 m^2/mg Chl-a

PHYTOPLANKTON GROWTH NUTRIENTS

- Michaelis-Menten kinetics

$$R(N) = \frac{C}{K_{MN} + C}$$



PHYTOPLANKTON GROWTH NUTRIENTS

- Early eutrophication models used fixed nutrient stoichiometry (usually based on Redfield ratio)
- However …

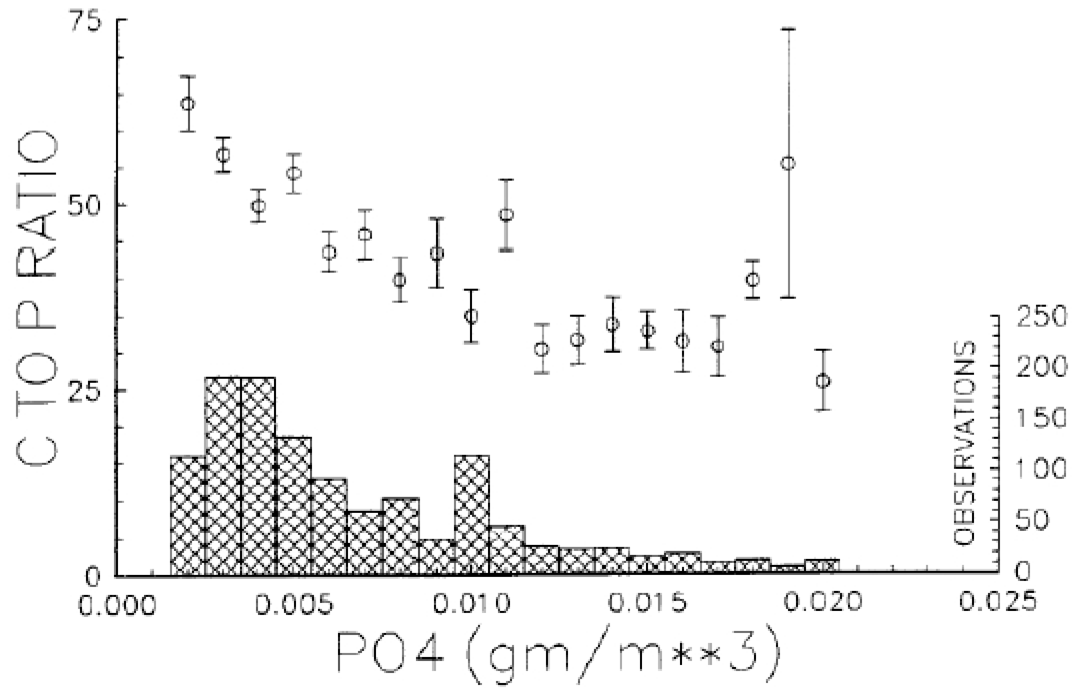
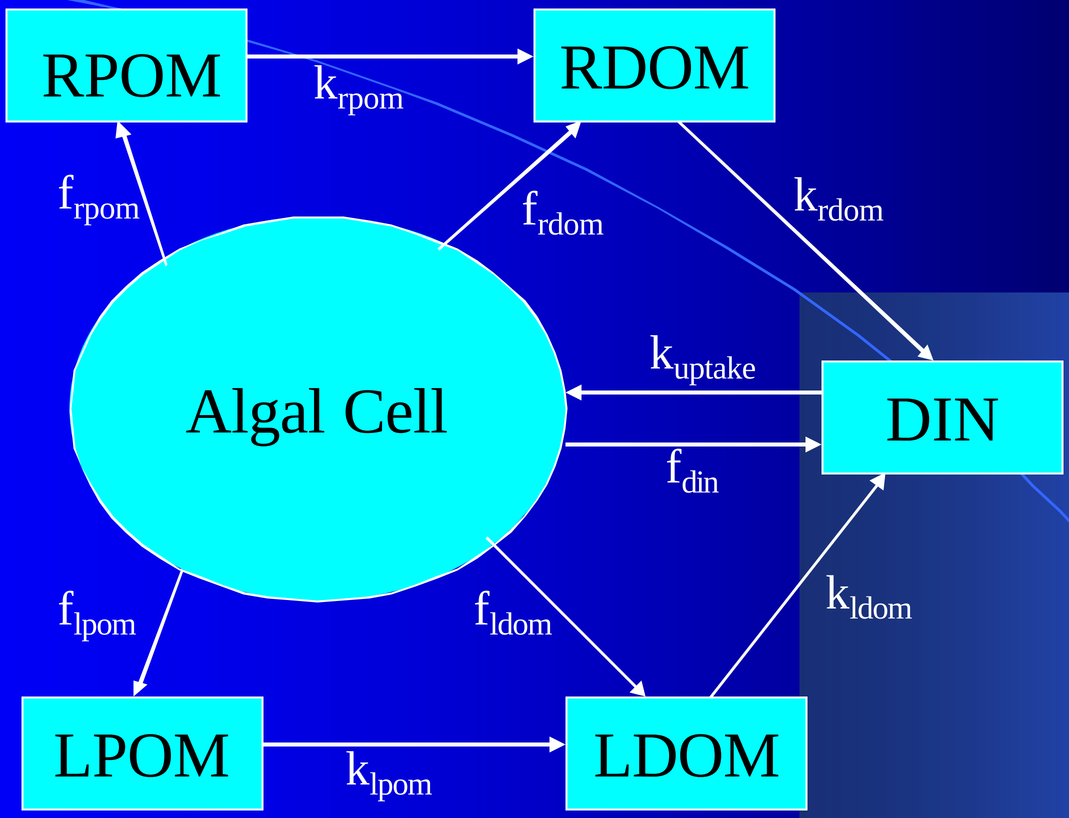


Figure 1-3. Carbon-to-phosphorus ratio (mean and standard error) of seston in Upper Chesapeake Bay. Bars show number of observations.

Nutrient Cycling

- Nutrients are utilized by phytoplankton for growth (nutrient uptake)
- As a consequence of respiration and death and grazing (fecal pellets or unassimilated particulate matter) nutrients are returned (in various forms) to the water column



RPOM – Refractory Particulate Organic Matter

LPOM – Labile Particulate Organic Matter

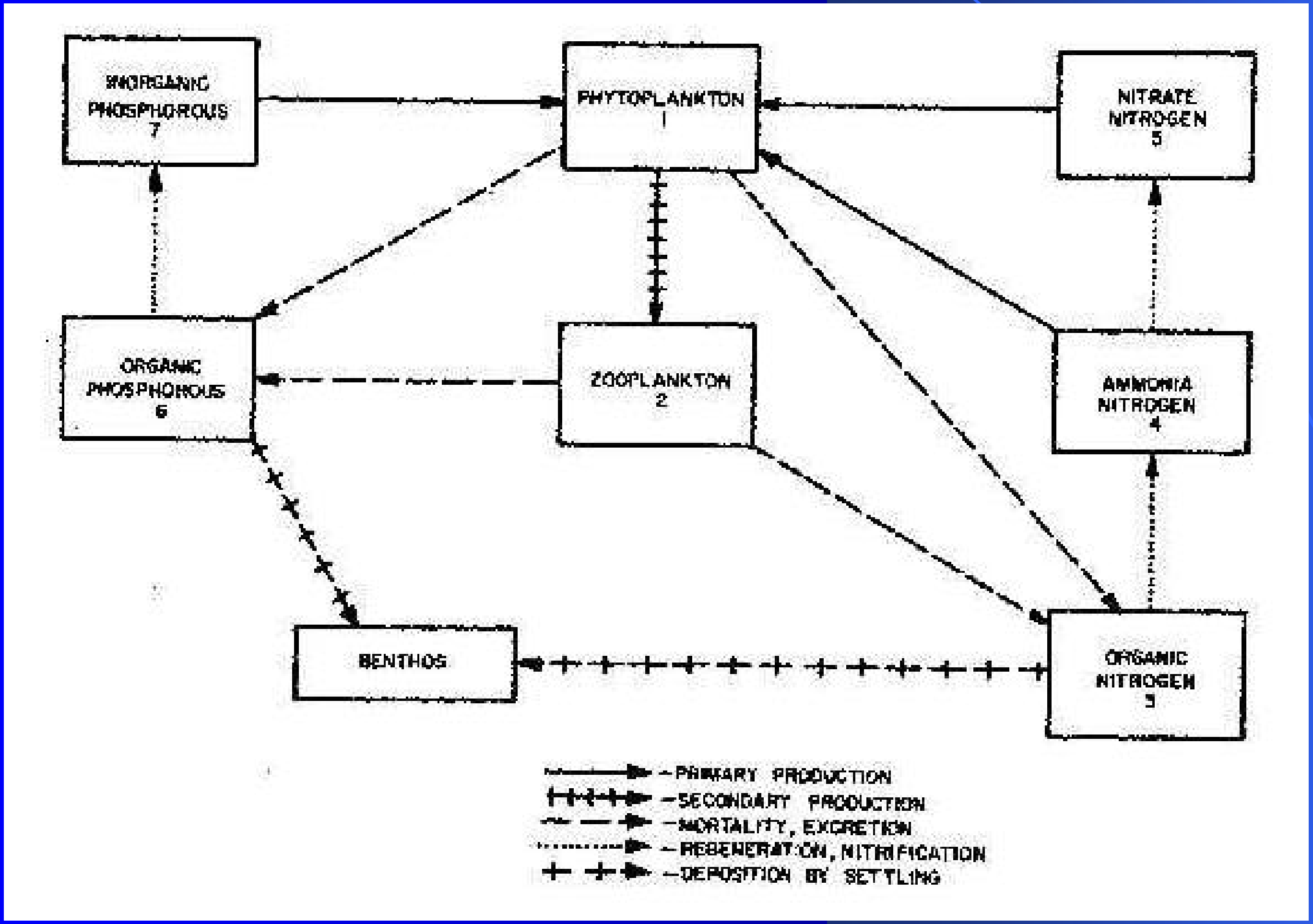
RDOM – Refractory Dissolved Organic Matter

LDOM – Labile Dissolved Organic Matter

DIN – Dissolved Inorganic Nutrient

Why So Complex?

- Early eutrophication models were considerably less complex when it came to modeling nutrient pools

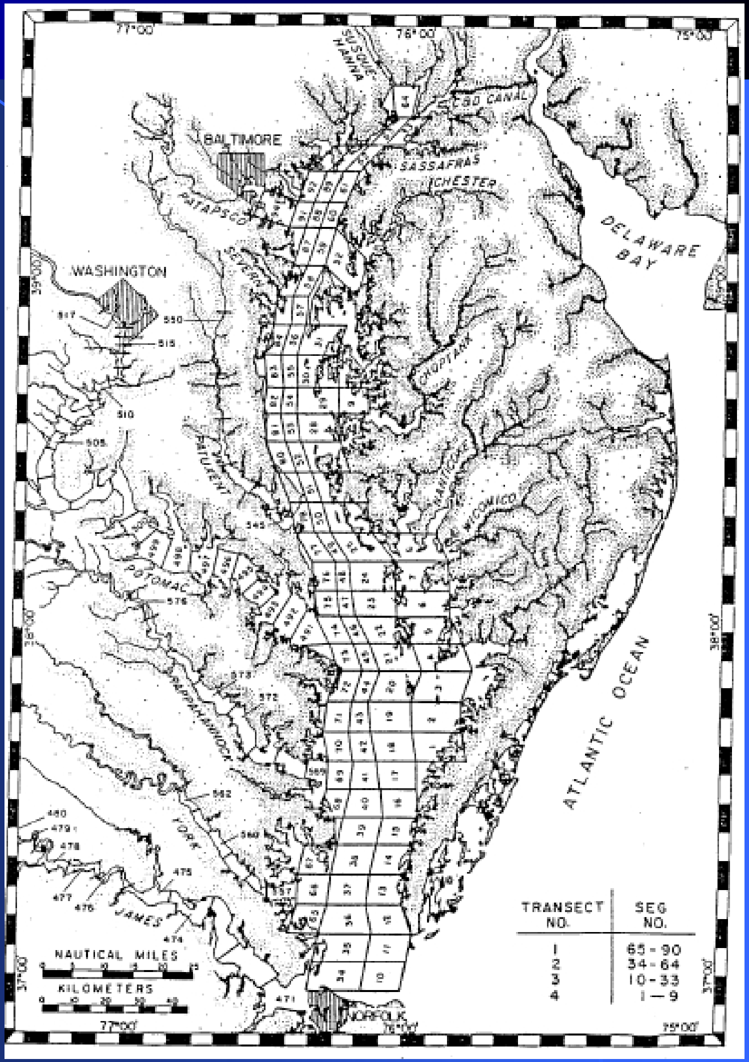


Why So Complex?

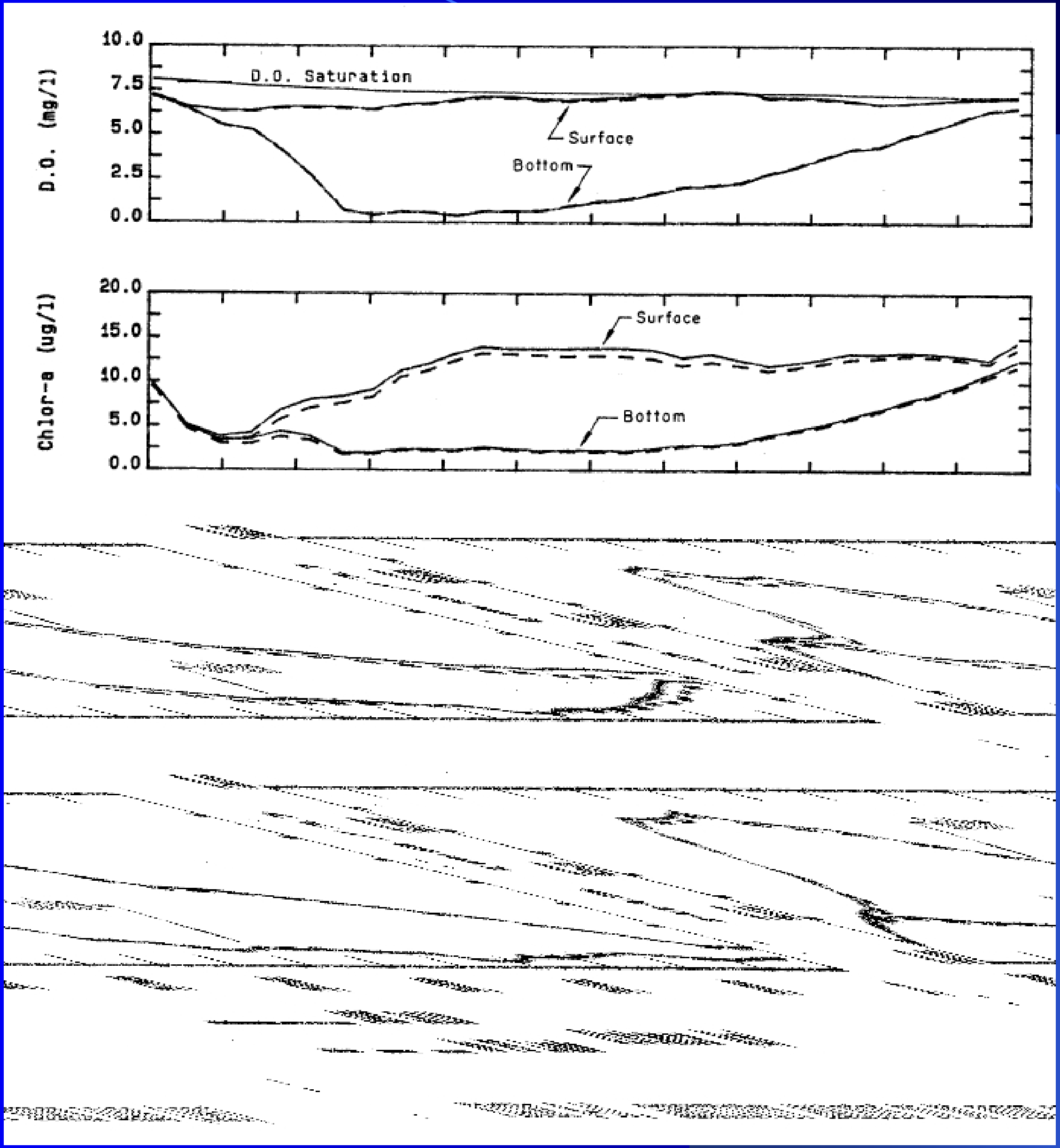
- While a portion of the organic matter was settled (representing the particulate fraction), it soon became obvious that just treating organic matter as a single state-variable would not work in many modeling applications ? initial split into particulate and dissolved pools
- With the development of the sediment flux model, which includes labile ("fast"), refractory ("slow"), and inert organic matter pools in the sediment bed, it became necessary to include labile and refractory particulate fractions in the water column
- With coastal applications and in systems that contain "tea-colored" waters (mangrove forests, bayous, etc.), it became necessary to partition dissolved organic matter into labile and refractory pools

Sediment Flux Modeling

- Why do it?
- Historically, the sediment bed was treated as a boundary condition, with sediment oxygen demand (SOD) and nutrient fluxes specified based on observed data
- Early modeling in Chesapeake Bay changed all that



Chesapeake Bay Projection Analysis



Chesapeake Bay Projection Analysis

- Oops! Not good to find out that reducing point source nutrient inputs has no effect on Bay water quality
- What went wrong?
- Model did not account for the fact that the input of particulate organic matter (POM) to the sediments would be reduced due to reduced levels of primary production associated with reduced nutrient inputs,
- Which in turn would reduce SOD and nutrient fluxes back to water column
- Developed an approach that adjusted SOD and nutrient fluxes either in proportion to reductions in the deposition of POM to the sediment

Chesapeake Bay Projection Analysis

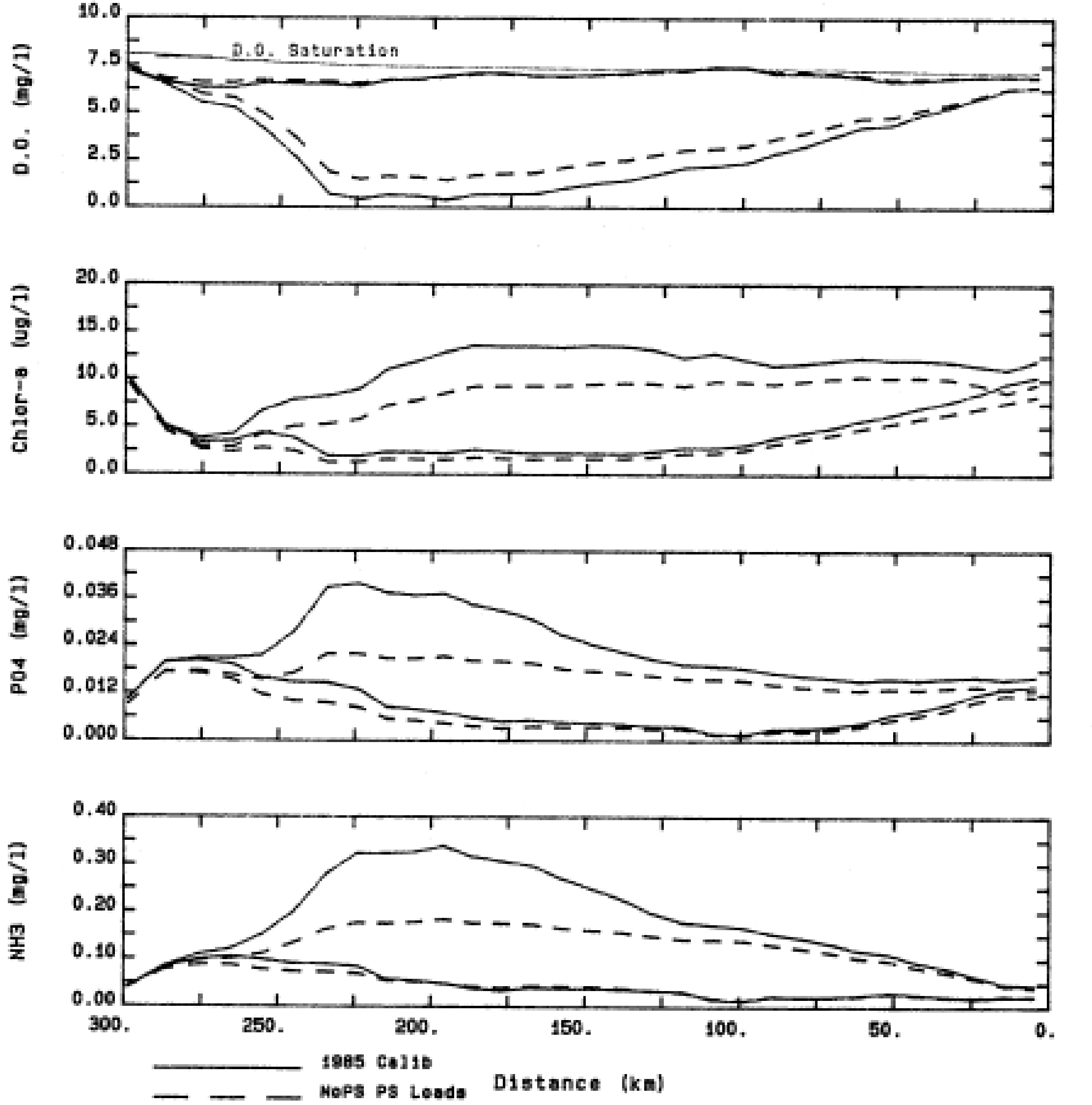


FIGURE 9. NO POINT SOURCE PROJECTION (1985) USING PERCENT REDUCTION METHODOLOGY

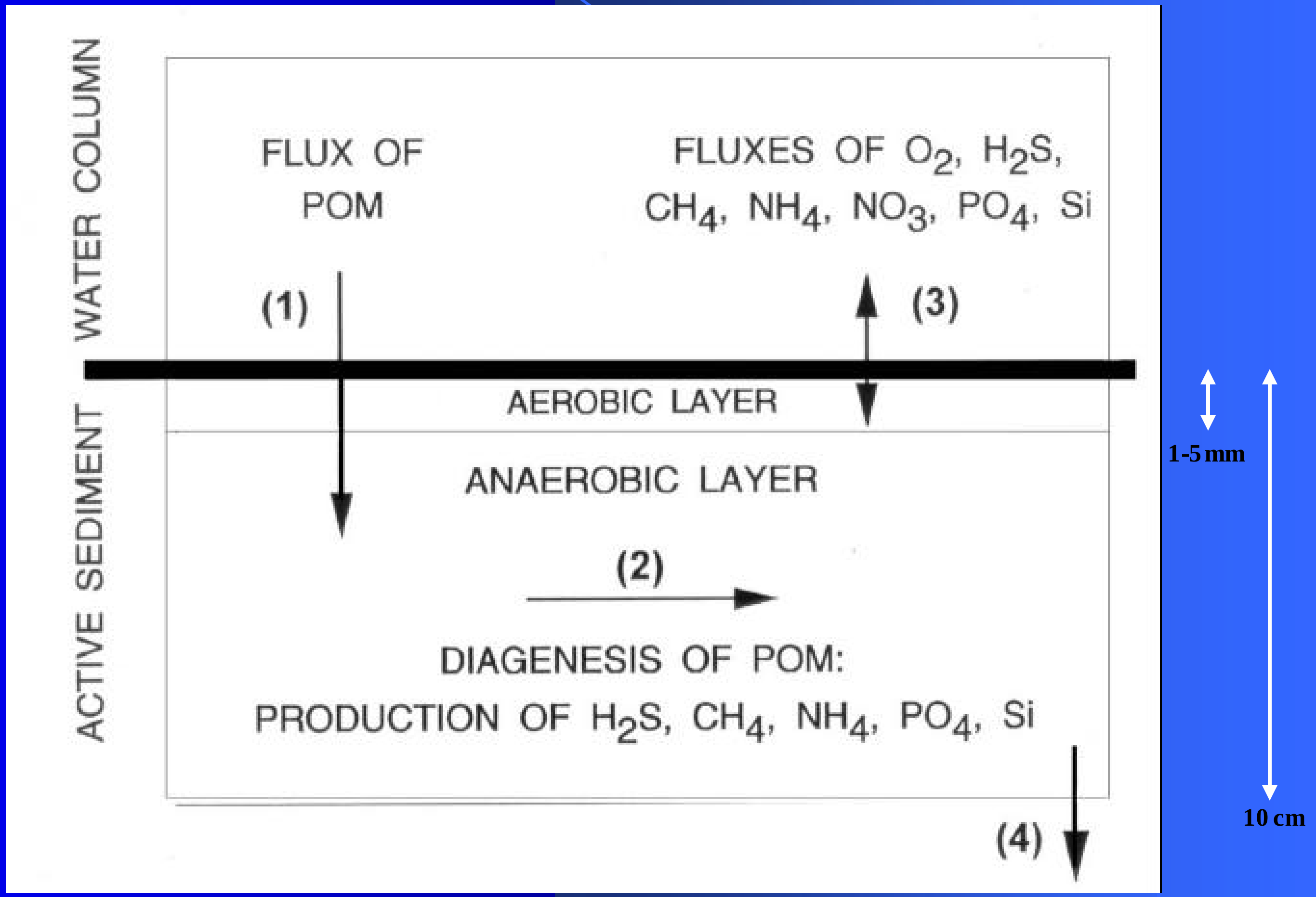
Sediment Flux Model (SFM) Framework

(1) Deposition of POM

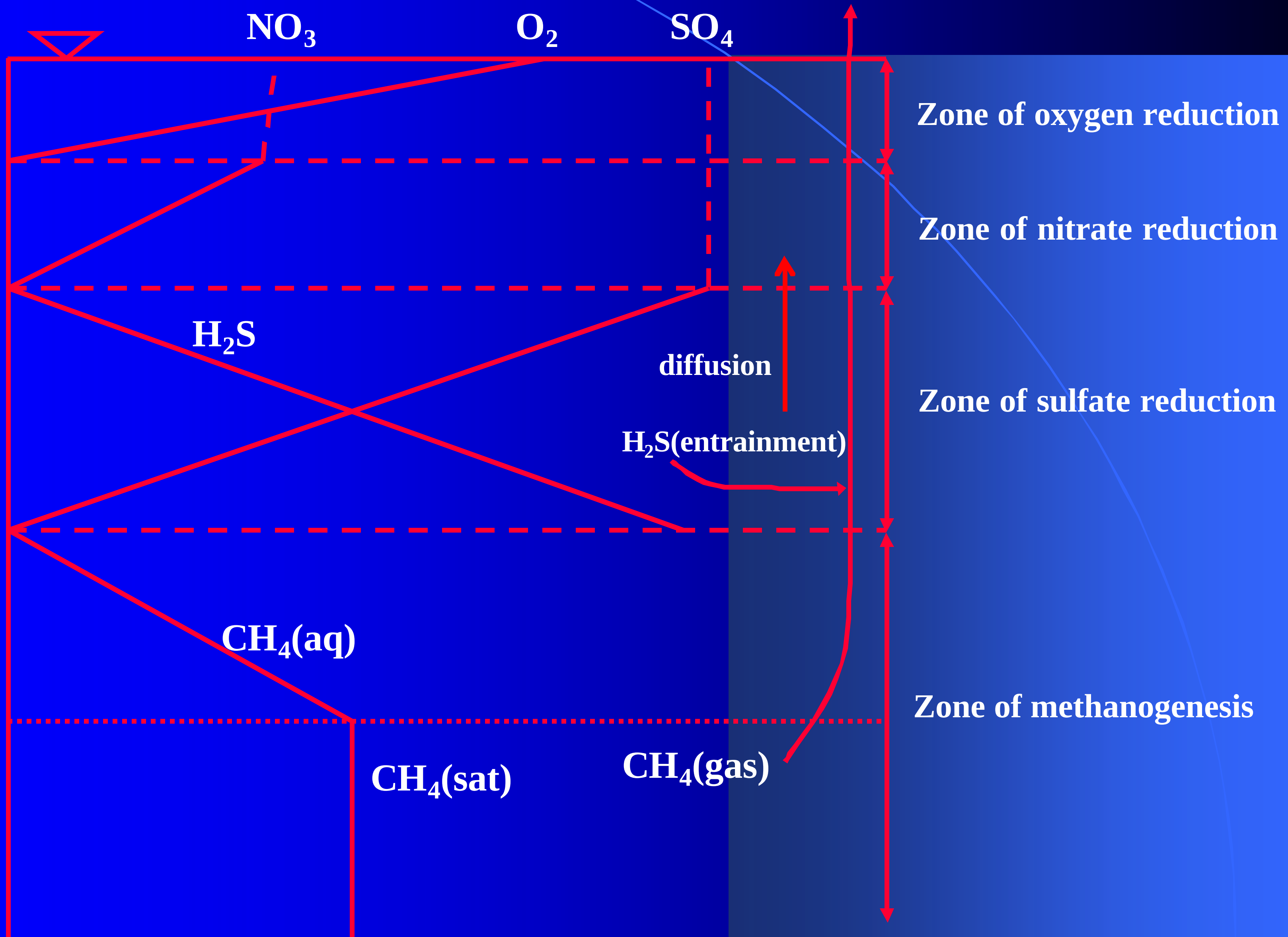
(2) Diagenesis – decomposition of POM

(3) Flux of SOD and inorganic end-products back to OWC

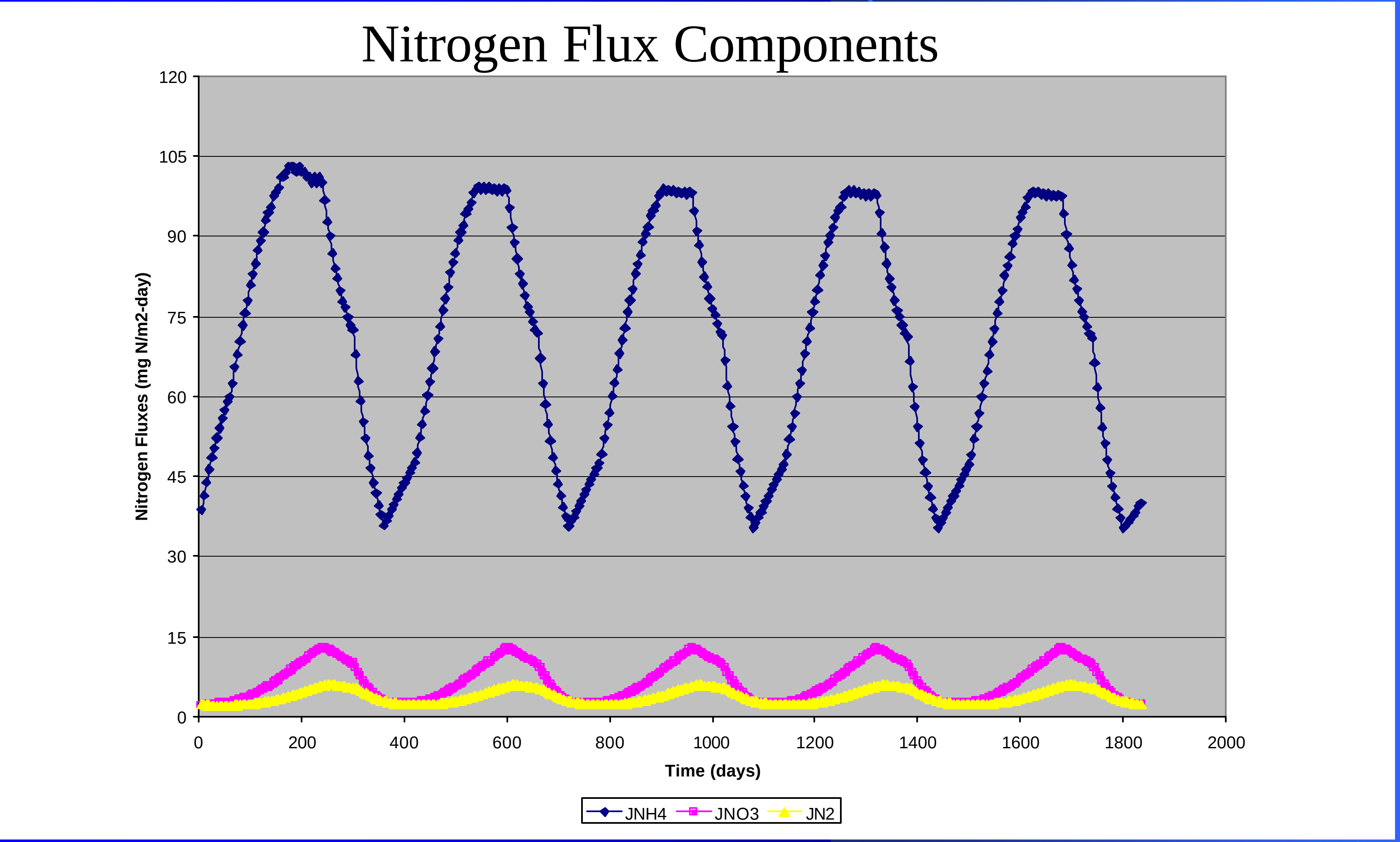
(4) Burial to deep sediments



Sediment Oxygen Demand

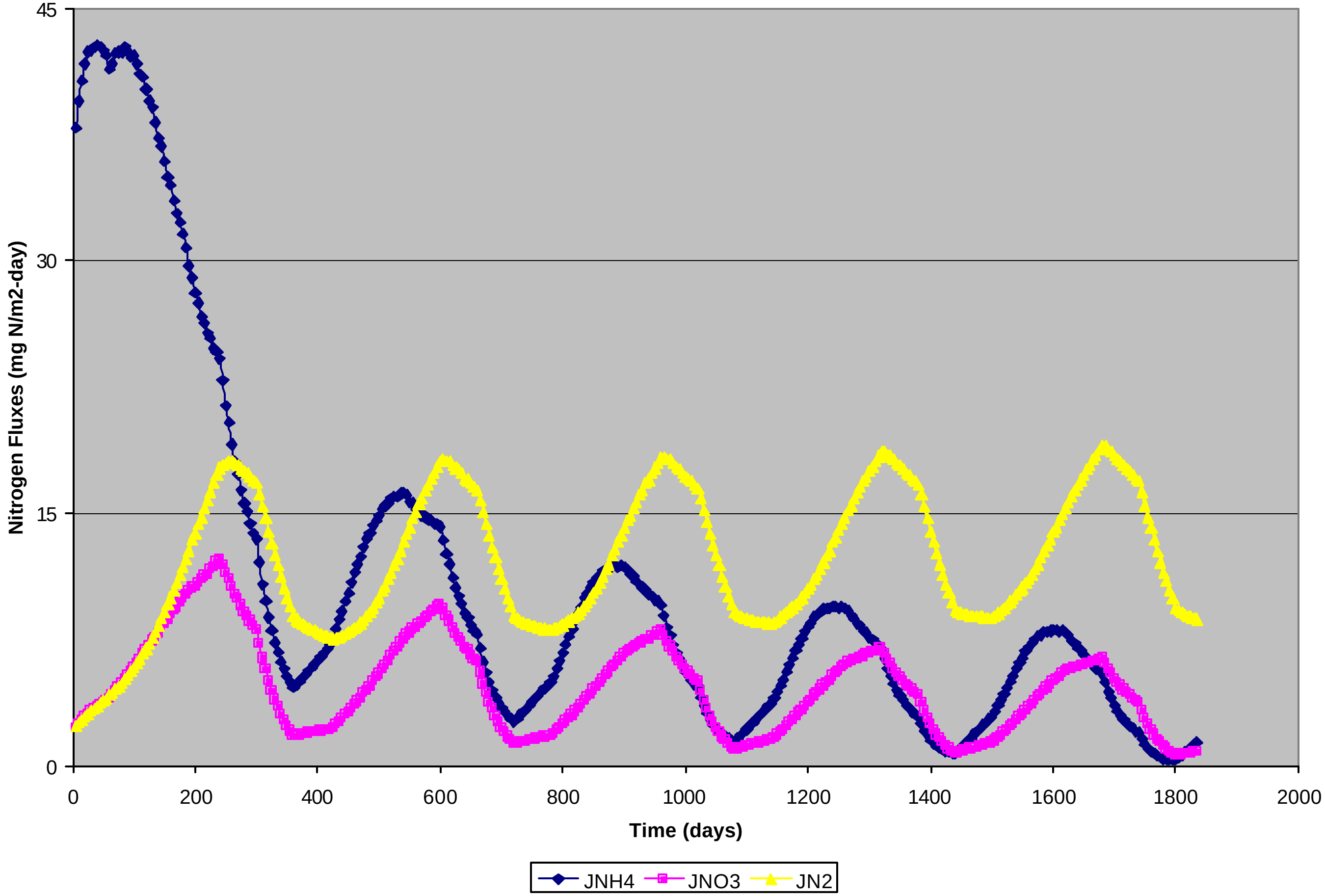


Examples of SFM Behavior

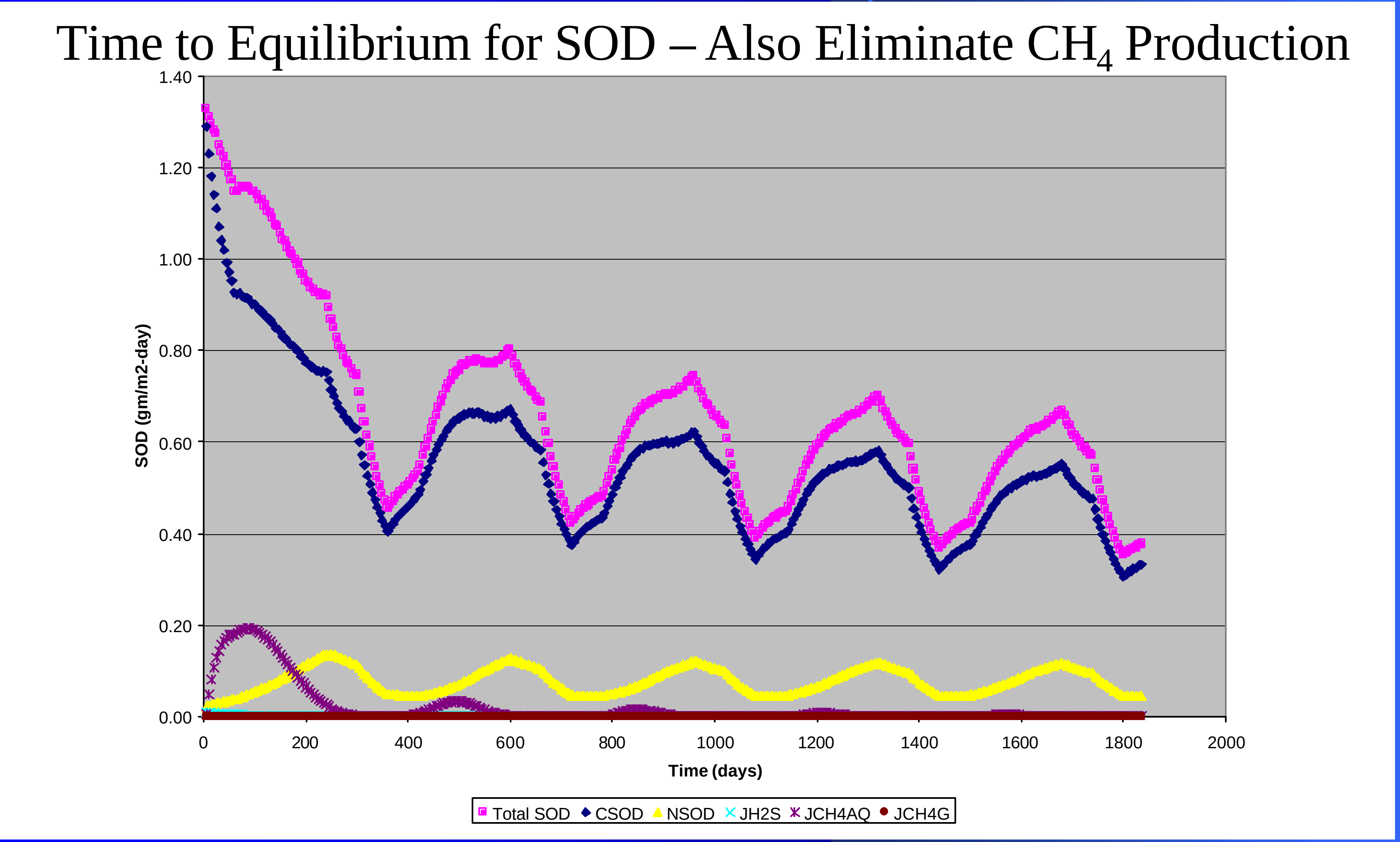


Reduce Loading 75%

Reduce NH_4 and NO_3 Fluxes and Enhance Denitrification (N_2) Flux



Reduce Loading 75%



James River HABs

- Modifications to phytoplankton kinetics:
- Addition of HAB groups
  - ✓ Diel migration for freshwater cyanobacteria and marine dinoflagellates
  - ✓ Cyanobacteria migration – buoyancy
  - ✓ Dinoflagellate migration – swimming
  - ✓ Both driven by light and nutrients
  - ✓ Dinoflagellates – heterotrophy – utilization of labile form of organic nitrogen as NH_4 and NO_3 are utilized
  - ✓ Reduced pelagic/benthic grazing pressure

James River HABs

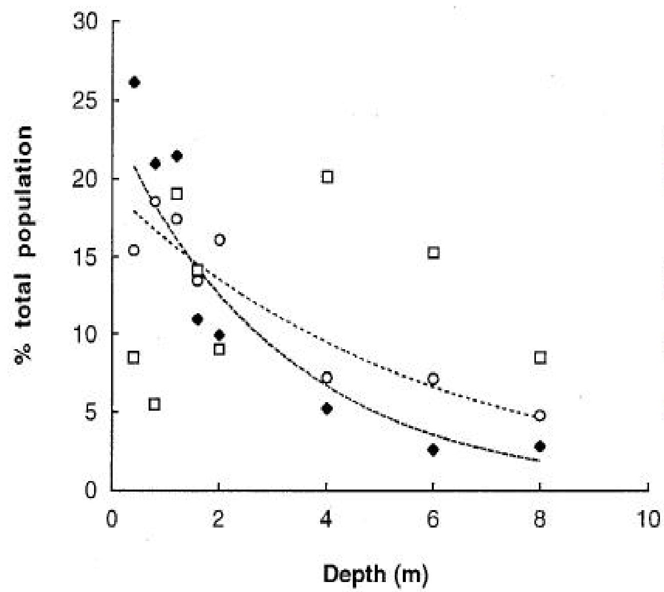


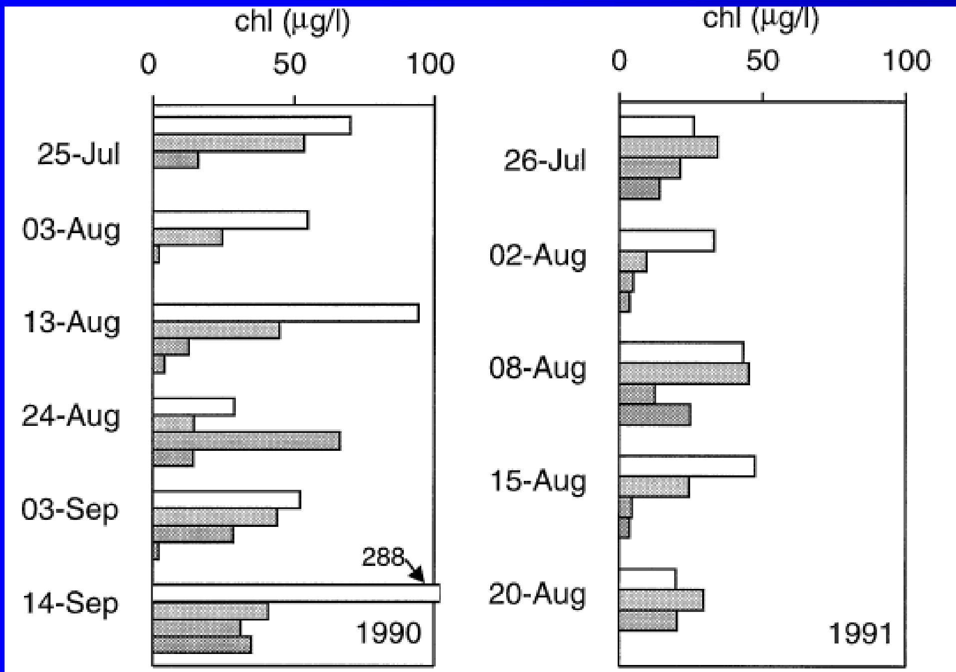
Fig. 3. Vertical distribution of *A.circinalis* as a percentage of the total population at 08:00 h (□), 13:00 h (◆, heavy dashed line) and 16:00 h (○, light dashed line).

Depth (m)	Control—no added nutrients		Nutrients added as nitrate and phosphate		Average light intensity (µmol m^{-2} s^{-1})
	07:30 h	17:00 h	07:30 h	17:00 h	
0.3	96	38 (9)	100	88 (1)	436
0.9	100	69 (12)	100	100	195
4.5	100	99 (1)	100	100	7

Brookes et al., 1999

James River HABs

Effect of Vertical Mixing on Microcystis



Visser et al., 1996

Vertical Depths: 0-2m, 2.5-4.5 m, 5-7 m, and 7-10 m

Vertical Depths: 0-2m, 2.5-4.5 m, 5-7 m, 7-10 m, 11-15m, 16-20m, 21-25m, and 27 m