“Building the Perfect Beast”

Water-Quality Modeling of Lake Garda

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GARDEN 2018
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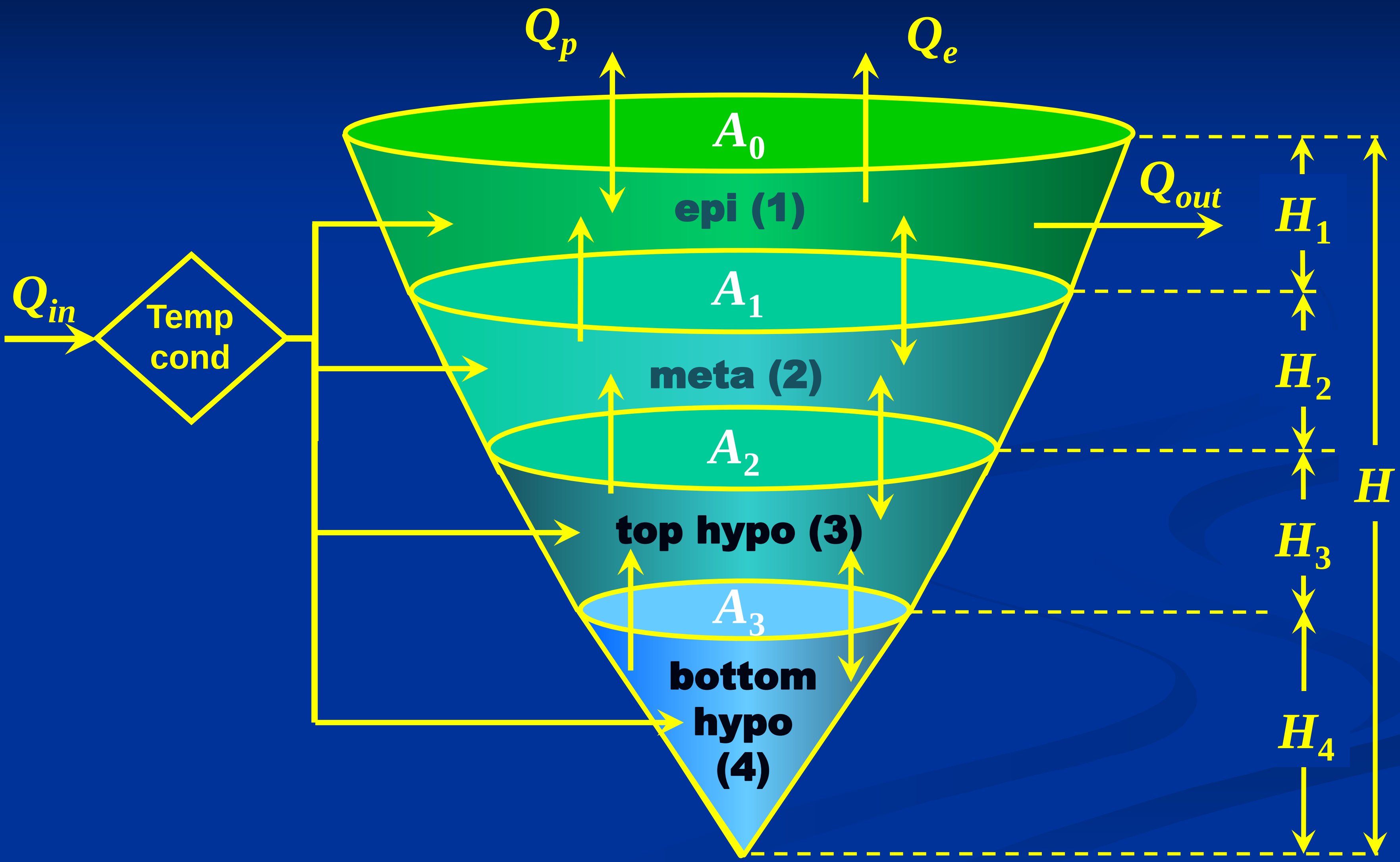
OUTLINE

- Assumptions
- Sediment-Water Interactions
- HABs
- Upper Food Web
- Chemistry
- The Po as a System
- Conclusions

L2K: PHYSICAL MODEL



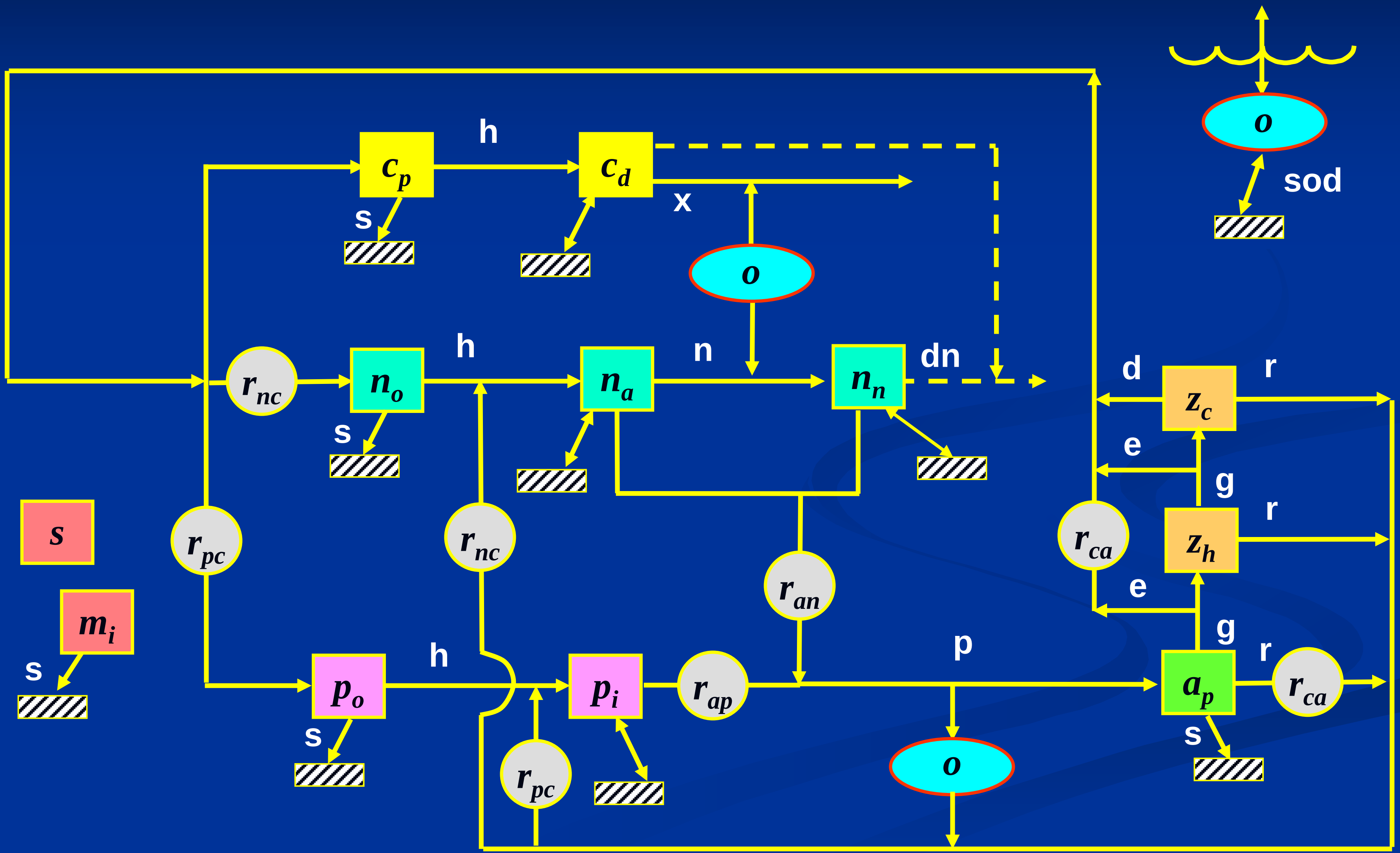
STATE VARIABLES (mass balances)

Variable	Units	Variable	Units
Temperature	C	Diatoms	mgC/L
Specific conductance	umhos	Greens	mgC/L
Inorganic suspended solids	mgD/L	Cyanobacteria fix	mgC/L
Particulate organic carbon	mgC/L	Cyanobacteria-non fix	mgC/L
Dissolved organic carbon	mgC/L	Nanoplankton	mgC/L
Organic nitrogen	mgN/L	Herbivorous zooplankton	mgC/L
Ammonia	mgN/L	Carnivorous zooplankton	mgC/L
Nitrate	mgN/L	Dissolved methane	$mgCH_4/L$
Organic phosphorus	mgP/L	Sulfate	$mgSO_4/L$
Bioavailable phosphorus	mgP/L	Hydrogen Sulfide	mgS/L
Detrital organic silica	mgSi/L	Calcium	mgCa/L
Bioavailable available silica	mgSi/L	Total inorganic carbon	mol/L
Dissolved oxygen	mgO_2/L	Alkalinity	$mgCaCO_3/L$

OTHER WATER-QUALITY OUTPUT

Derived variables	Sediment-water fluxes	Air-water gas fluxes
Carbonaceous BOD	Oxygen	Oxygen
Carbon dioxide	Total inorganic carbon	Carbon dioxide
Bicarbonate	Bioavailable phosphorus	Methane
Carbonate	Ammonia	Nitrous oxide
Total chlorophyll a	Nitrate	Hydrogen sulfide
Extinction coefficient	Sulfate	
Secchi depth	Hydrogen sulfide	
Turbidity	Nitrogen gas	
pH	Nitrous oxide	
Alkalinity	Dissolved organic carbon	
Specific conductance	Dissolved methane	
Total Kjeldahl N	Methane gas	
Total organic carbon		
Particulate organic carbon		

WATER COLUMN KINETICS



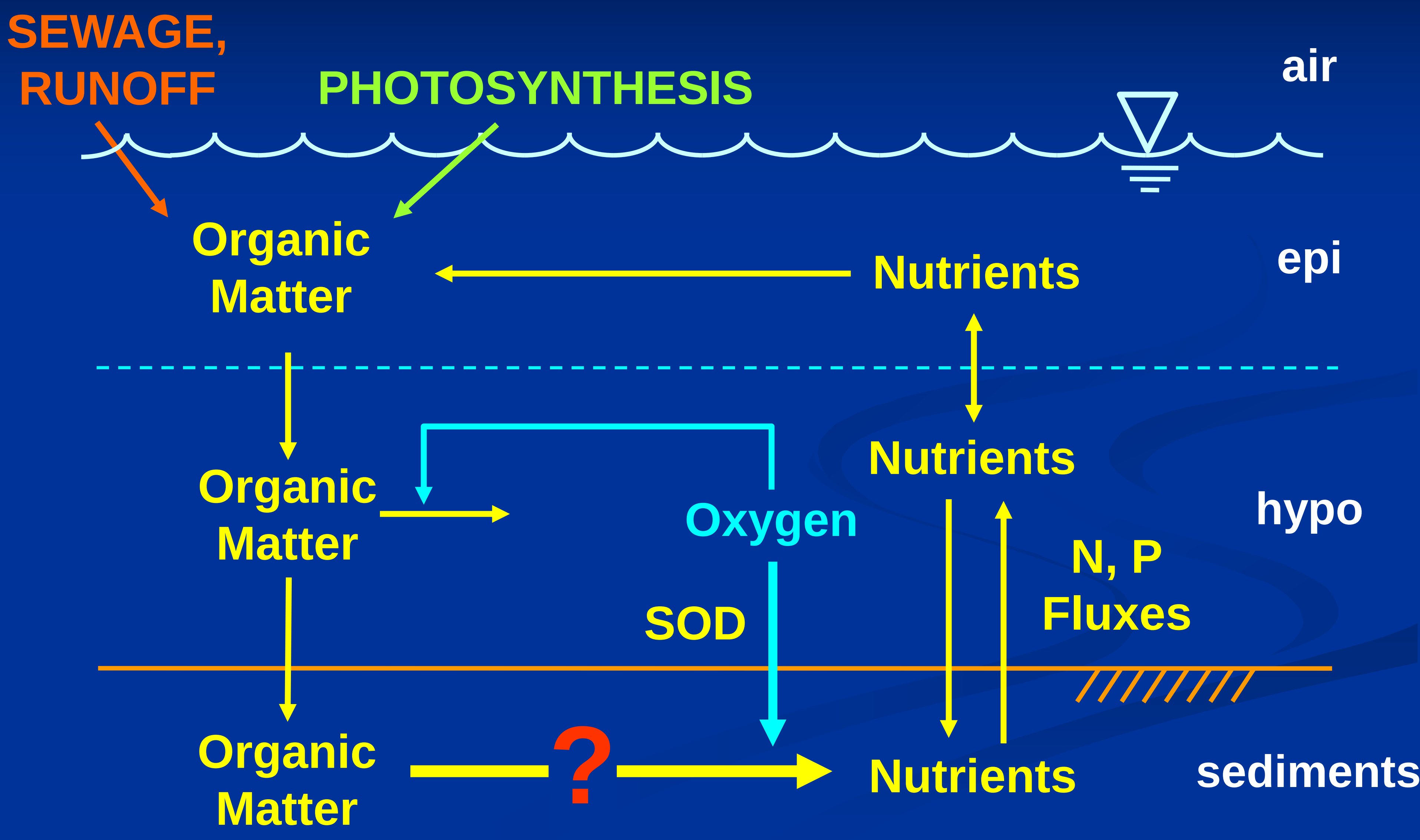
ASSUMPTIONS

- **State of the art physics**
  - ***Water motion***
  - ***Heat budget & temperature***
  - ***Boundary layers***
- **State of the art biology & chemistry**
  - ***Multiple algal groups (including HABs)***
  - ***Upper food chain (grazers)***
  - ***Macrochemistry (pH, major ions, calcite, etc.)***
- **Sediment-water interactions**
  - ***Gas transfer (SOD, methane flux, etc.)***
  - ***Nutrient fluxes***
  - ***Sediment chemistry (beyond nutrients)***

MODELLING
Sediment/Water Interactions in Lakes
(SOD and Nutrient Fluxes)

SEDIMENT-WATER PROCESSES

“THE MISSING LINK OF WATER-QUALITY MODELLING”



SEWAGE, RUNOFF

PHOTOSYNTHESIS

air

Organic Matter

Nutrients

epi

Organic Matter

Oxygen

Nutrients

hypo

N, P Fluxes

SOD

Organic Matter

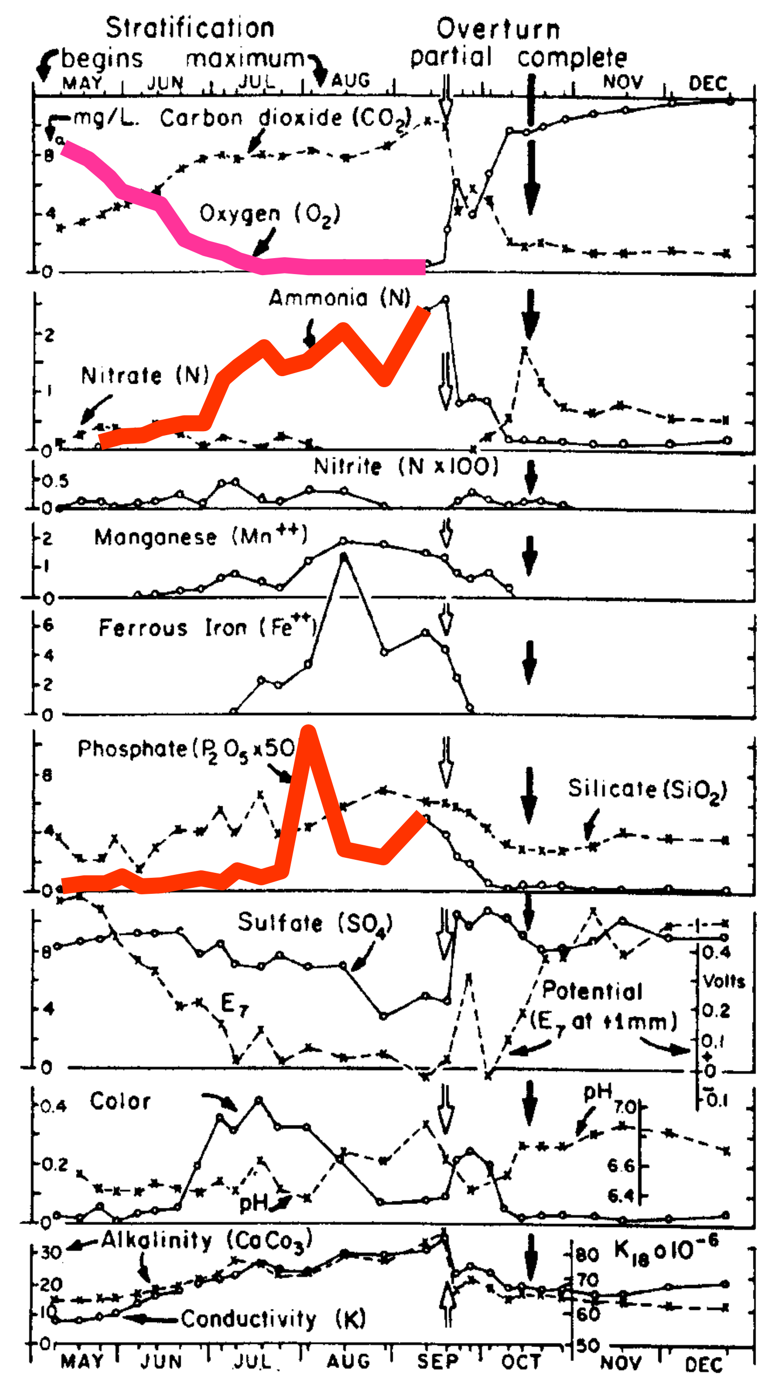
?

Nutrients

sediments

Short-term Effects:

O_2 Depletion and Internal Loading

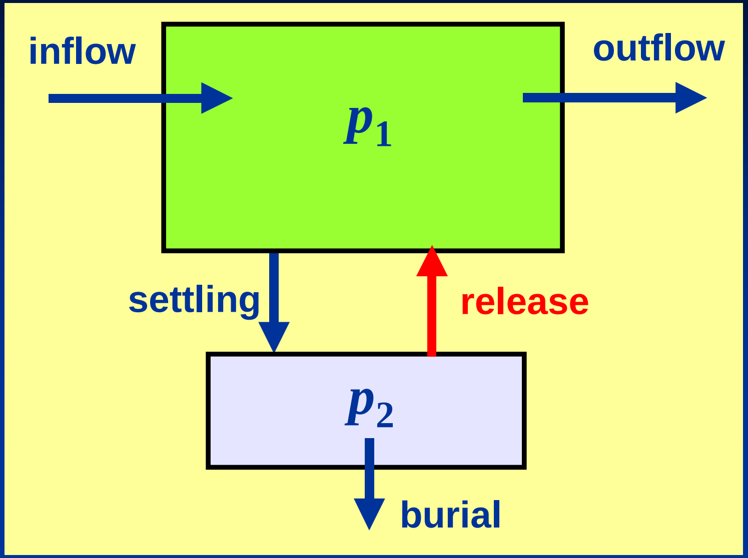


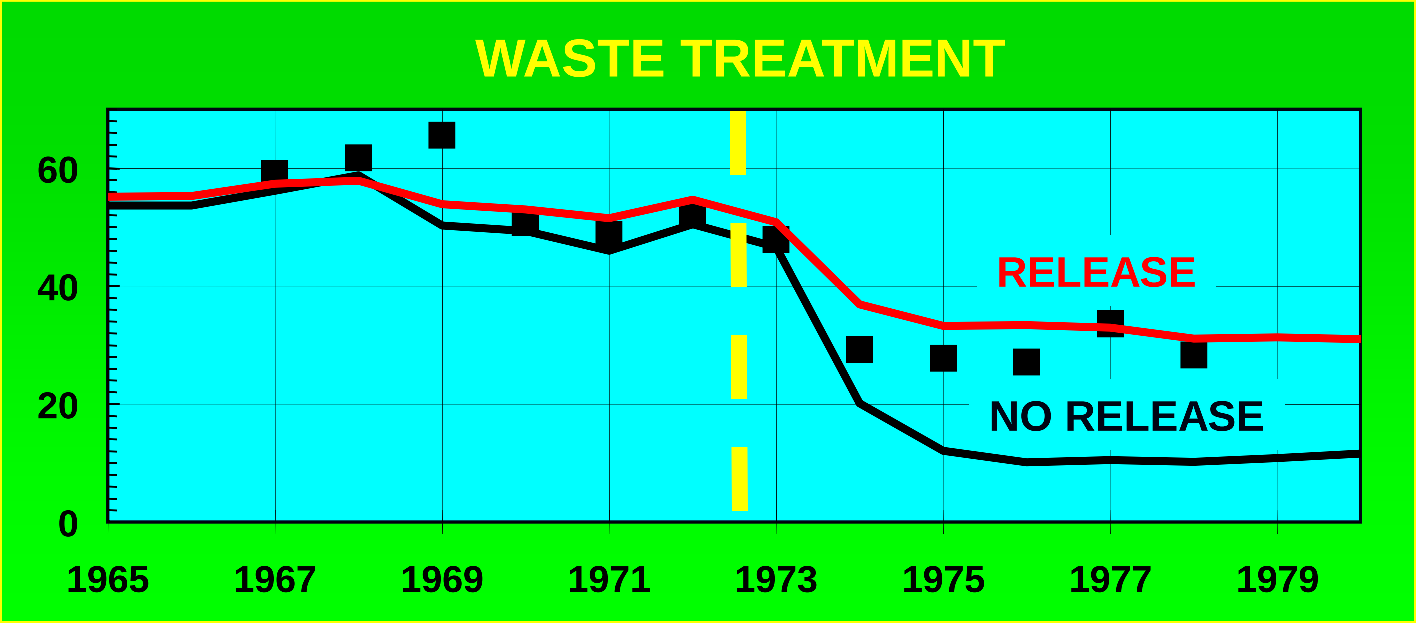
Esthwaite Water, England

Mortimer (1971)

Long-term Effects:

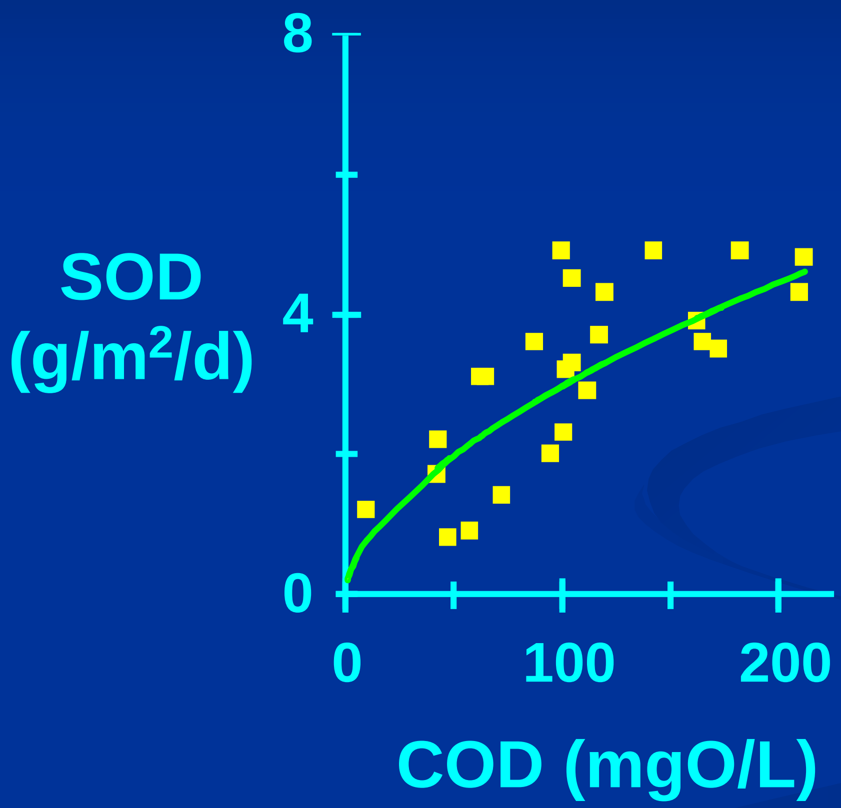
Retarded Recovery





SHAGAWA LAKE, MINNESOTA

THE “SQUARE-ROOT” RELATIONSHIP OF SEDIMENT OXYGEN DEMAND AND OVERENRICHMENT

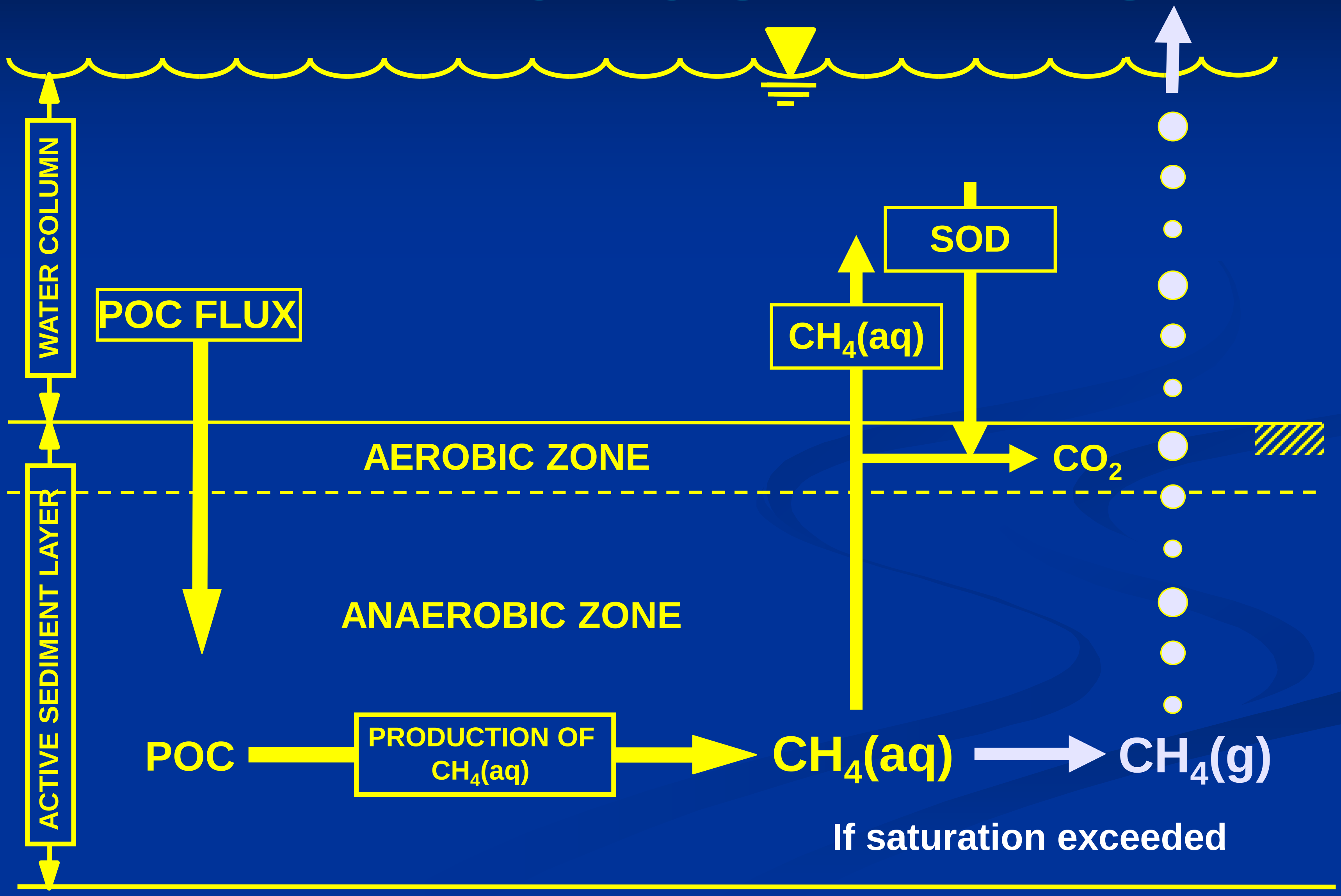


$$\mathrm{SOD} = \alpha\, \mathrm{COD}^{0.5}$$

WHERE DOES NONLINEARITY COME FROM?

- **Loss of carbon as methane gas in anaerobic sediments**
- **Competition between reaction and diffusion in aerobic surface sediment**

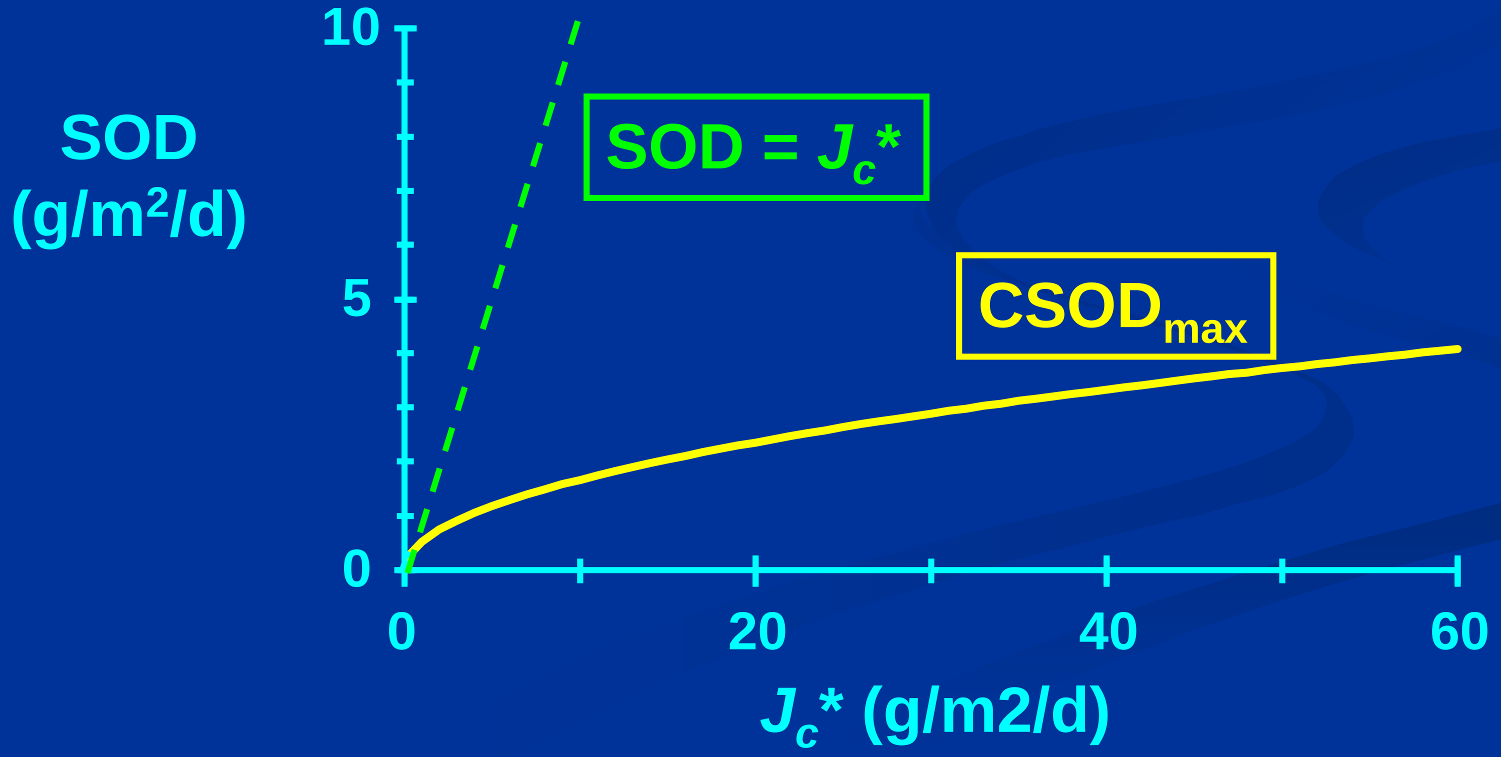
LOSS OF CARBON AS METHANE GAS IN ANAEROBIC SEDIMENTS



SQUARE-ROOT EFFECT DUE TO BUBBLE FORMATION

$$0 = D\frac{d^2c}{dz^2} + S_C$$

$$\mathrm{CSOD}_{\mathrm{max}} = \sqrt{2\kappa_D c_s J_{C*}}$$



COMPETITION BETWEEN REACTION AND DIFFUSION IN AEROBIC SURFACE SEDIMENT

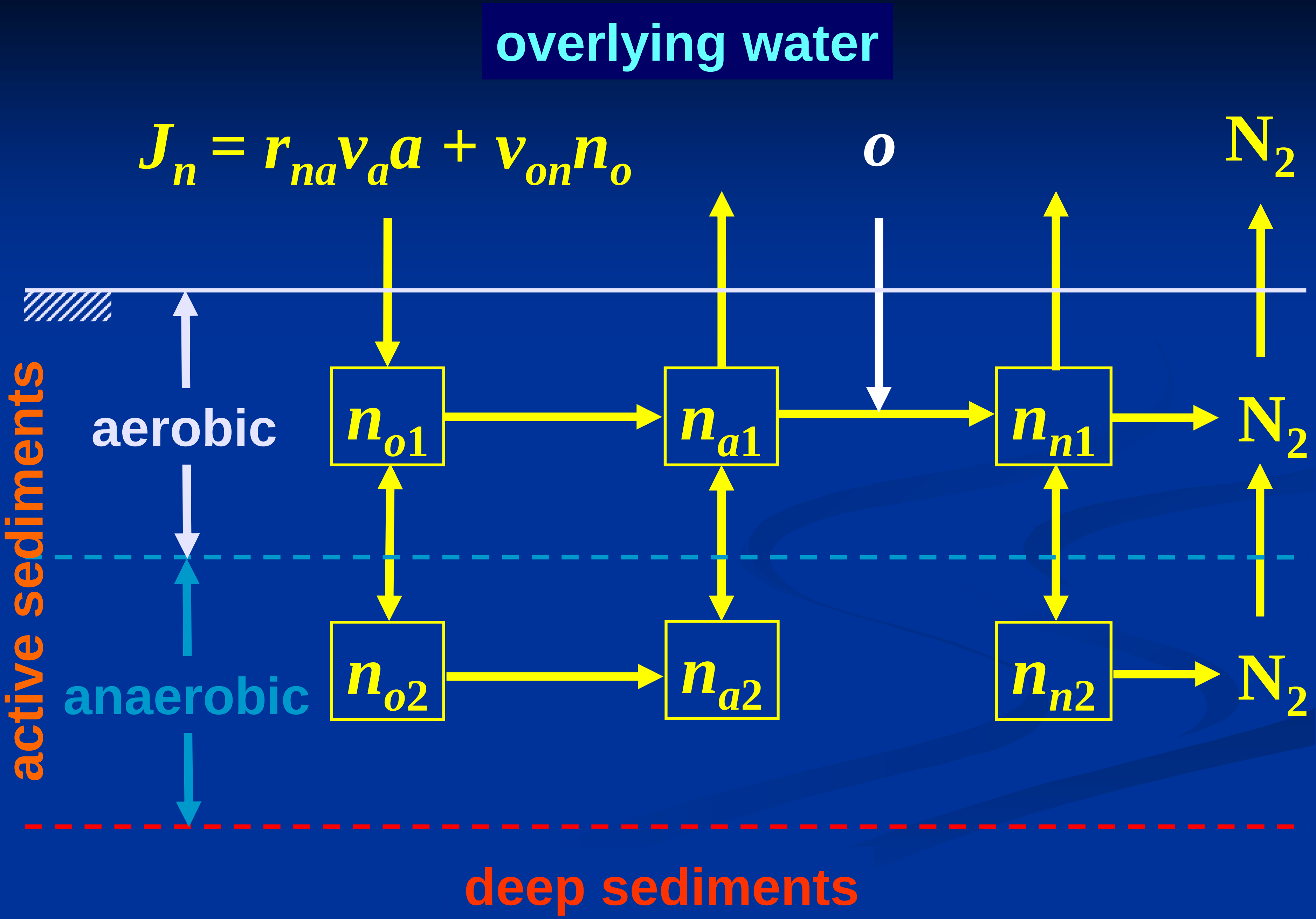
Mass Balance:

$$V_1 \frac{dc_1}{dt} = v_s A c_0 - v_b A c_1 - kV_1 c_1$$

Flux Balance (divide by A):

$$H_1 \frac{dc_1}{dt} = v_s c_0 - v_b c_1 - kH_1 c_1$$

Flux
Mass Balance



overlying water

$$J_n = r_{na} v_a a + v_{on} n_o$$

o

N_2

aerobic

n_{o1}

n_{a1}

n_{n1}

N_2

anaerobic

n_{o2}

n_{a2}

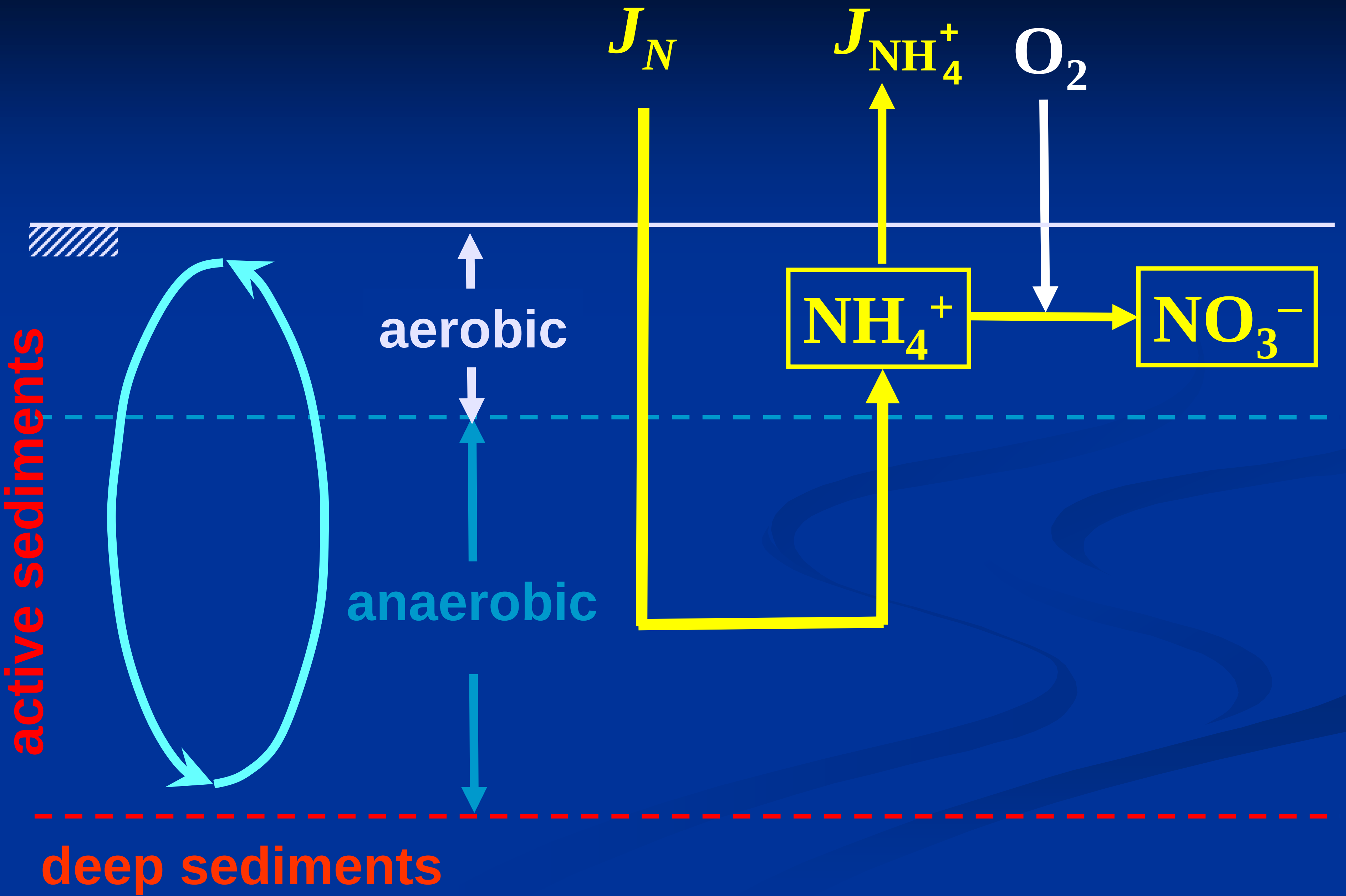
n_{n2}

N_2

active sediments

deep sediments

overlying water



J_N

$J_{NH_4^+}$

O_2

aerobic

NH_4^+

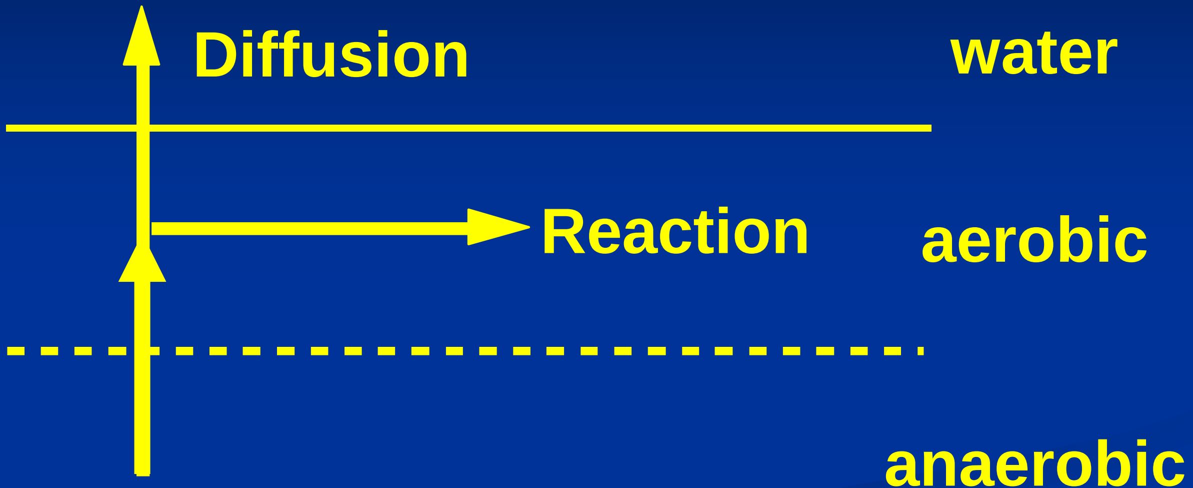
NO_3^-

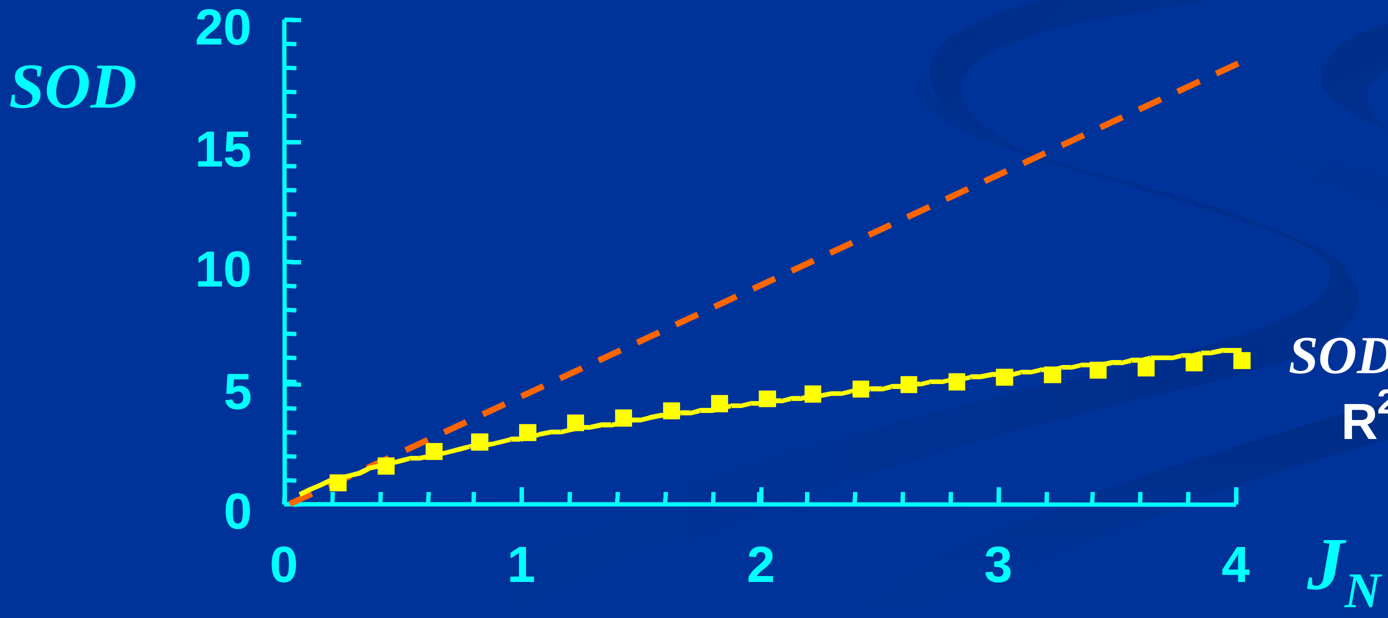
anaerobic

active sediments

deep sediments

DIFFUSION/REACTION COMPETITION IN THE AEROBIC LAYER





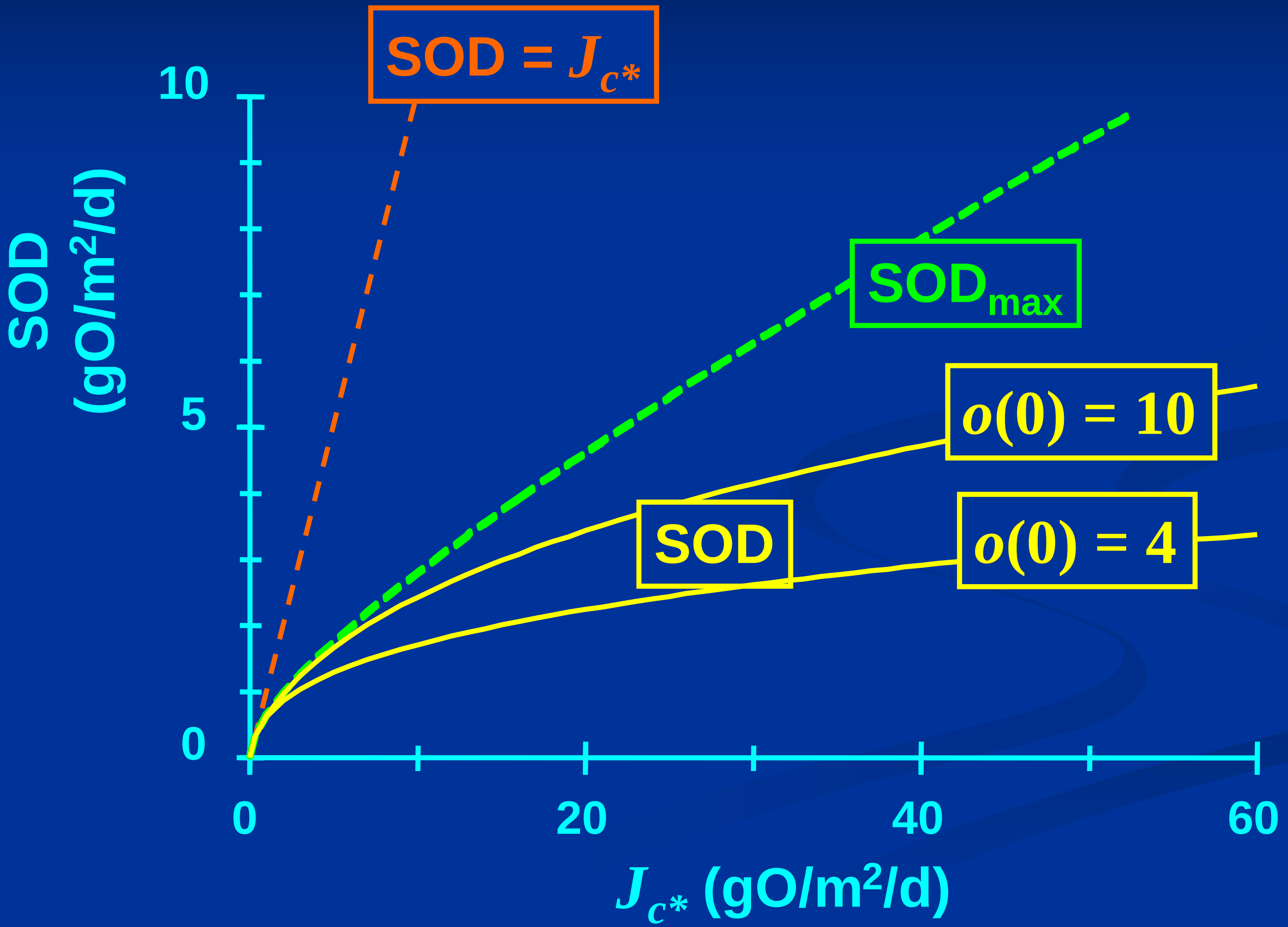
$SOD = 2.77\ J_n^{0.6}$

$R^2 = 0.9827$

TOTAL SOD = CSOD + NSOD

$$\mathrm{SOD} = \underbrace{\sqrt{2\kappa_D c_s J_{C*}}\,\frac{1}{1+\dfrac{D_c \mathrm{SOD}^2}{D_o^2 o_w^2 k_{c1}}}}_{\text{CSOD}} + \underbrace{r'_{on} a_{no} J_{C*}\,\frac{1}{1+\dfrac{D_n \mathrm{SOD}^2}{D_o^2 o_w^2 k_{n1}}}}_{\text{NSOD}}$$

TOTAL SOD = CSOD + NSOD



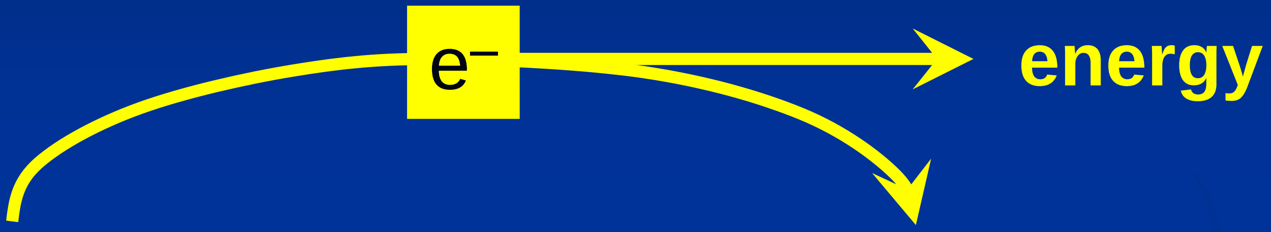
OXIDATION-REDUCTION

“REDOX”

- **Oxidation:**
  - **Loss of electrons (energy)**
- **Reduction:**
  - **Gain of electrons (energy)**
  - **Charge is “reduced”**

“Aerobic respiration”

$$[CH_2O] + O_2 \rightarrow CO_2 + H_2O$$



$[CH_2O]$	O_2
Oxidized	Reduced
Reductant	Oxidant
Electron donor	Electron acceptor

REDOX SEQUENCE

$CH_2O + O_2 \longrightarrow \boxed{CO_2}$ Aerobic respiration

$+ NO_3^- \longrightarrow N_2 + \boxed{CO_2}$ Denitrification

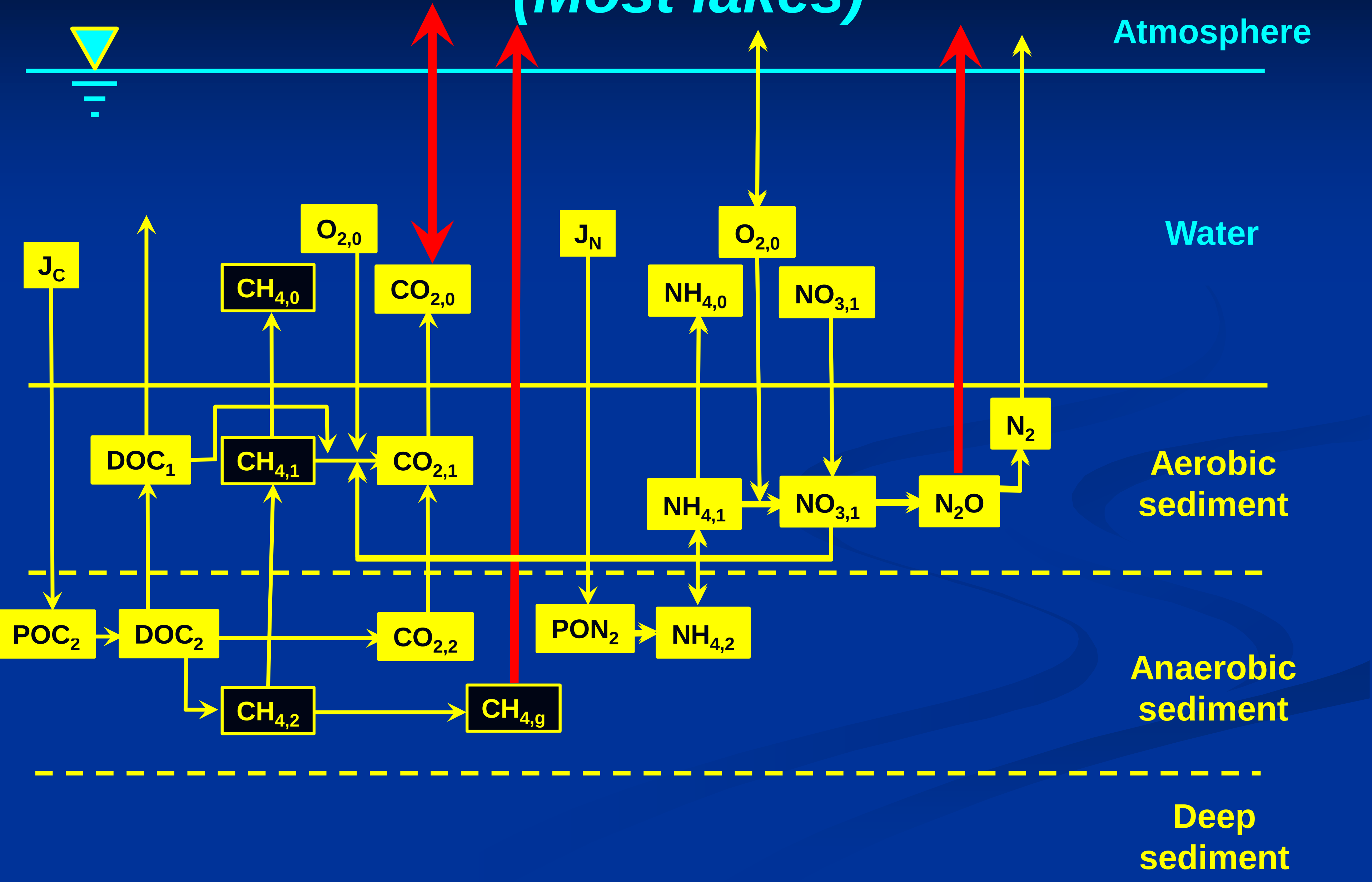
$+ MnO_2(s) \longrightarrow Mn^{2+} + \boxed{CO_2}$ Manganese reduction

$+ FeOOH(s) \longrightarrow Fe^{2+} + \boxed{CO_2}$ Iron reduction

$\boxed{+ SO_4^{2-} \longrightarrow HS^- + \boxed{CO_2} \quad \text{Sulfate reduction}}$

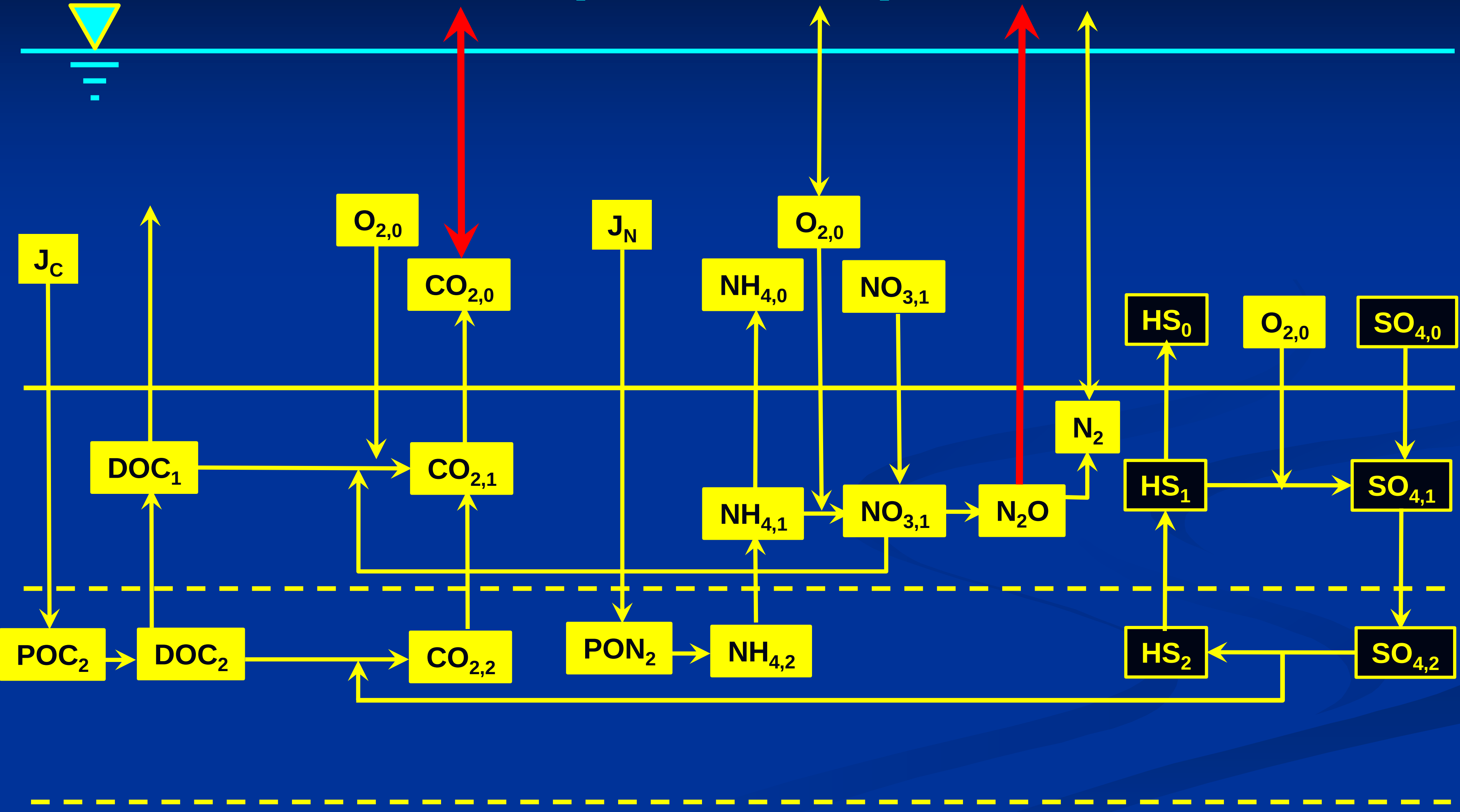
$+ CH_2O \longrightarrow \boxed{CH_4} + \boxed{CO_2}$ Methane formation “methanogenesis”

LOW SULFATE SYSTEMS
(Most lakes)



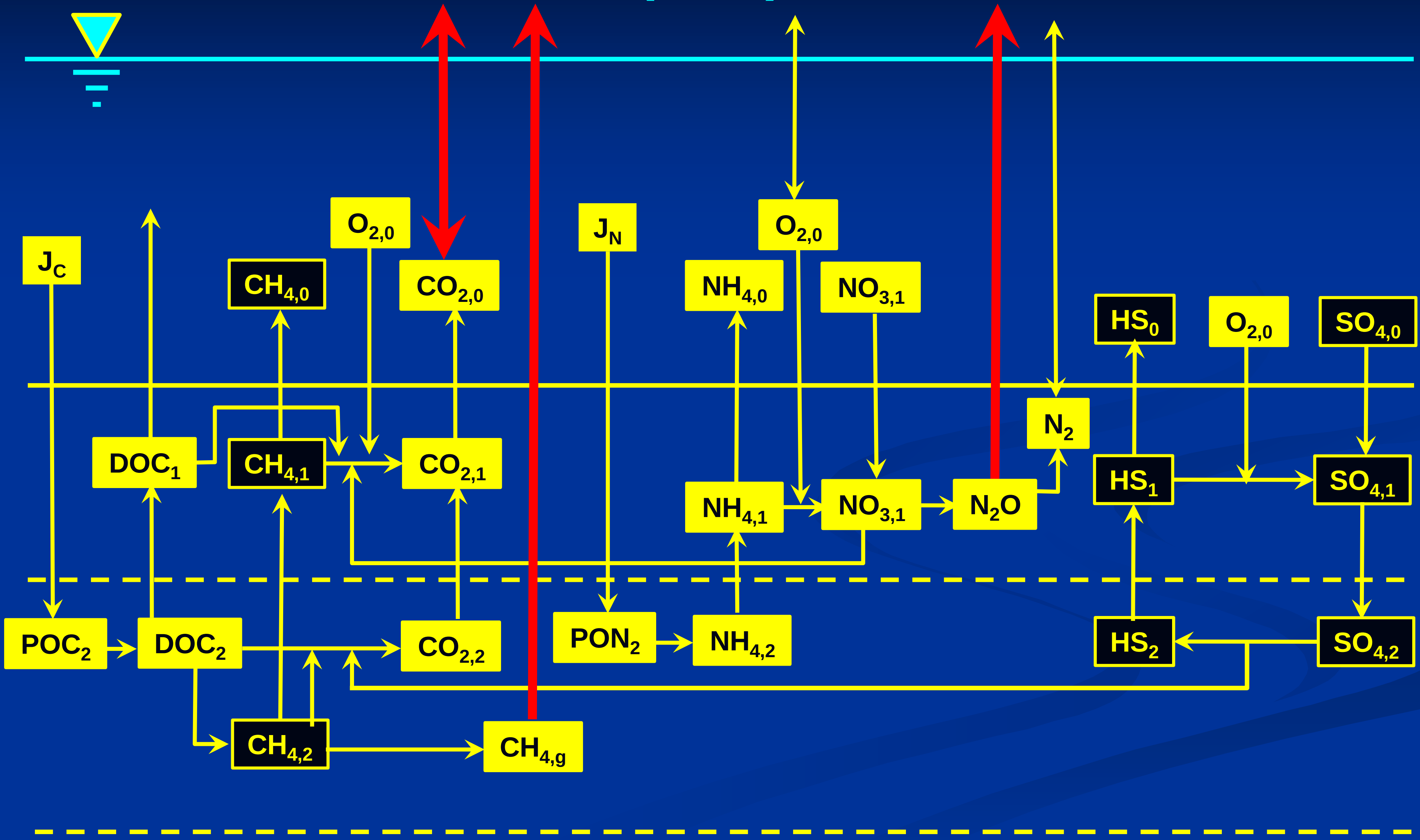
HIGH SULFATE SYSTEMS

(Estuaries)



SOME “SIGNIFICANT” LAKES

(Iseo)



$O_{2,0}$ J_N $O_{2,0}$

J_C $CH_{4,0}$ $CO_{2,0}$ $NH_{4,0}$ $NO_{3,1}$ HS_0 $O_{2,0}$ $SO_{4,0}$

N_2

DOC_1 $CH_{4,1}$ $CO_{2,1}$ HS_1 $SO_{4,1}$

$NH_{4,1}$ $NO_{3,1}$ N_2O

POC_2 DOC_2 $CO_{2,2}$ PON_2 $NH_{4,2}$ HS_2 $SO_{4,2}$

$CH_{4,2}$ $CH_{4,g}$

LAKE ISEO EXAMPLE

Hypo O_2 = 10 mg/L
J_C^* = 10 $gO_2\,m^{-2}\,d^{-1}$
Temp = 6.3 °C
Depth = 150 m

High (Present) Sulfate
SO_4 = 48.4 $mgSO_4\,L^{-1}$

SOD = 7.6285 $gO_2\,m^{-2}\,d^{-1}$

NSOD = 0.4670 $gO_2\,m^{-2}\,d^{-1}$
CSOD = 0.0023 $gO_2\,m^{-2}\,d^{-1}$
SSOD = 7.1591 $gO_2\,m^{-2}\,d^{-1}$

No Sulfate
SO_4 = 0 $mgSO_4\,L^{-1}$

SOD = 1.2069 $gO_2\,m^{-2}\,d^{-1}$

NSOD = 1.1144 $gO_2\,m^{-2}\,d^{-1}$
CSOD = 0.0926 $gO_2\,m^{-2}\,d^{-1}$
SSOD = 0 $gO_2\,m^{-2}\,d^{-1}$

Presence of SO_4

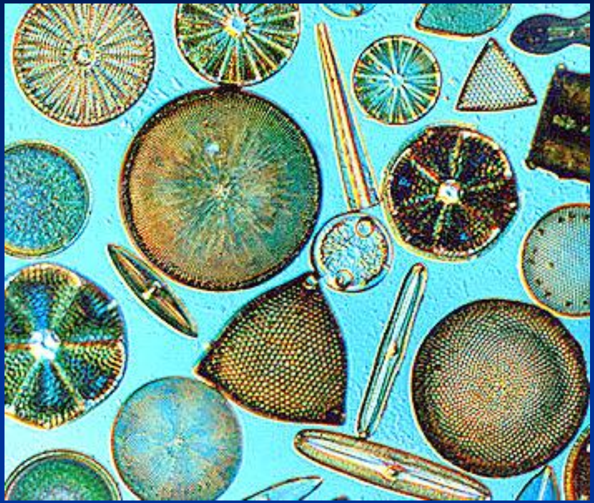
- Bad for lake
  - *Increases SOD*
- Good for climate
  - *Decreases loss of methane to atmosphere*

Further Research

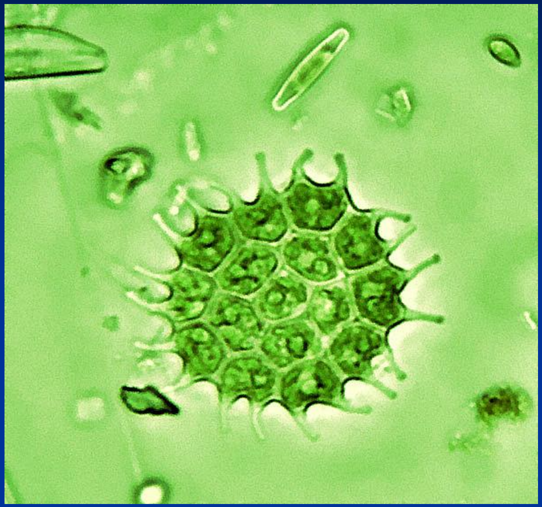
- ***Effect of meromixis on sediment mixing***
- ***Effect of water motion on sediment-water exchange***
- ***Incorporation of full chemistry into sediment models***

Harmful Algal Blooms (HABs)

Functional Groups



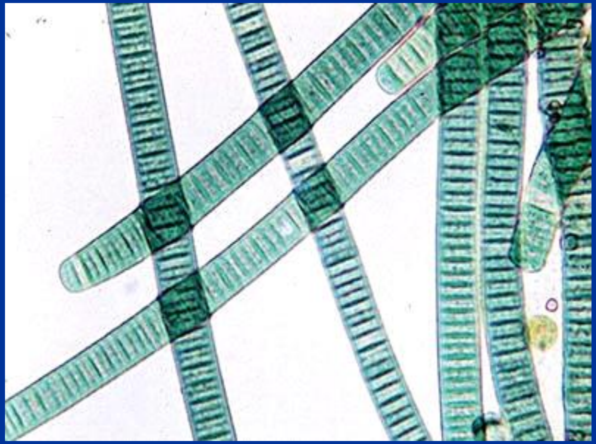
(a) Diatoms



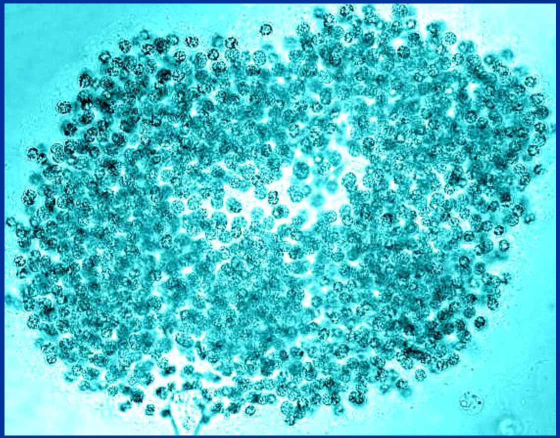
(b) Greens

"Good Algae"

(i.e., nontoxic,
edible phytoplankton)



(c) N-fixing Bluegreens
"Oscillatoria"



(d) non-N-fixing Bluegreens
"Microcystis"

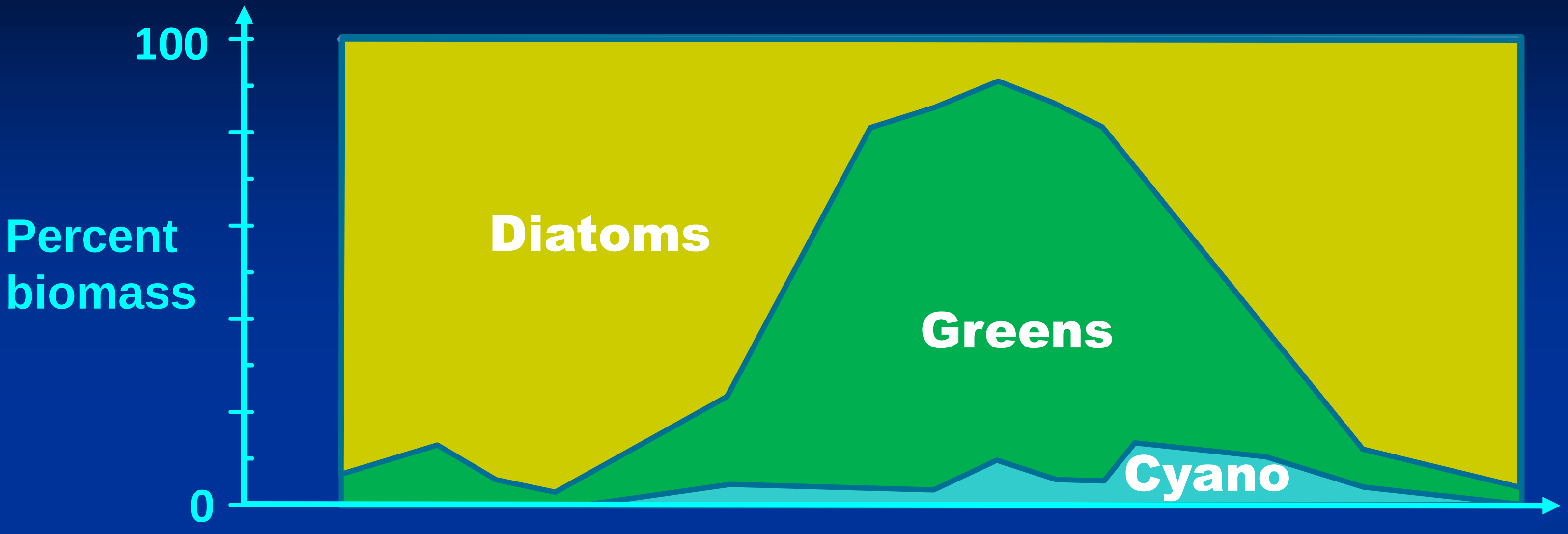
Cyanobacteria
(HABs)

(AKA Blue Green Algae)

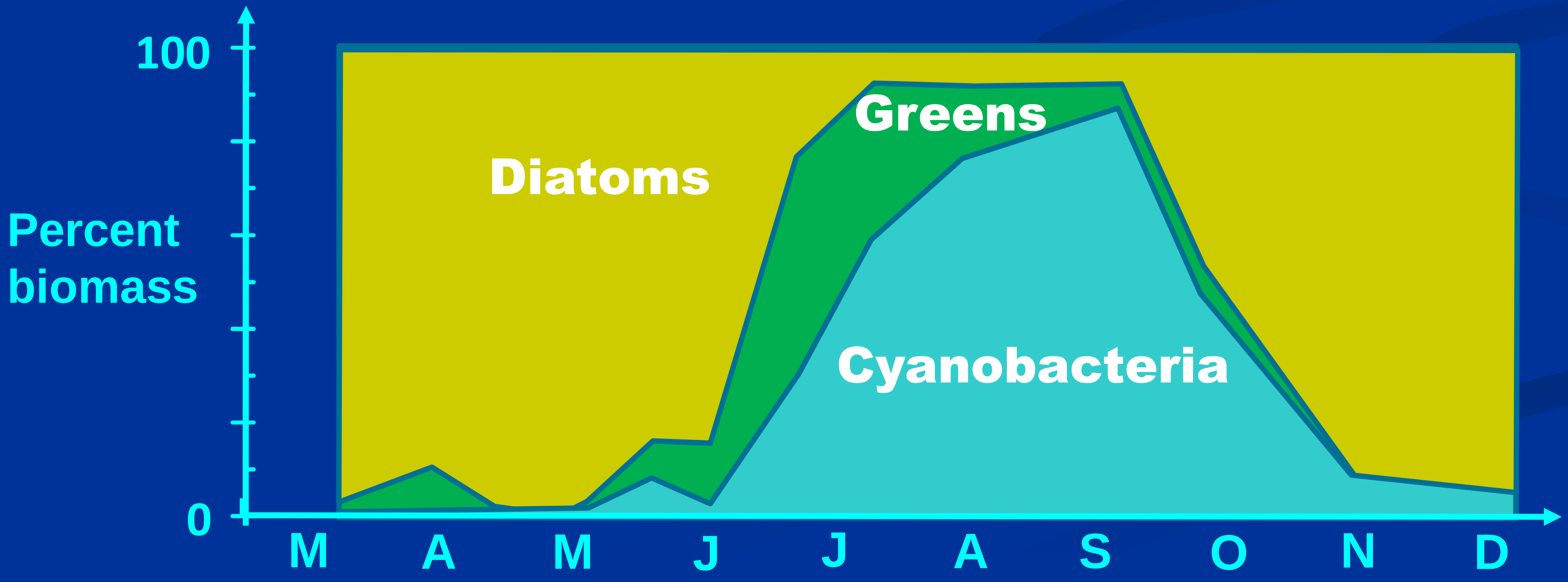
"The cockroaches of the water"

Seasonal Succession of Phytoplankton in Lakes

(*a*) Oligotrophic



(*b*) Hypereutrophic

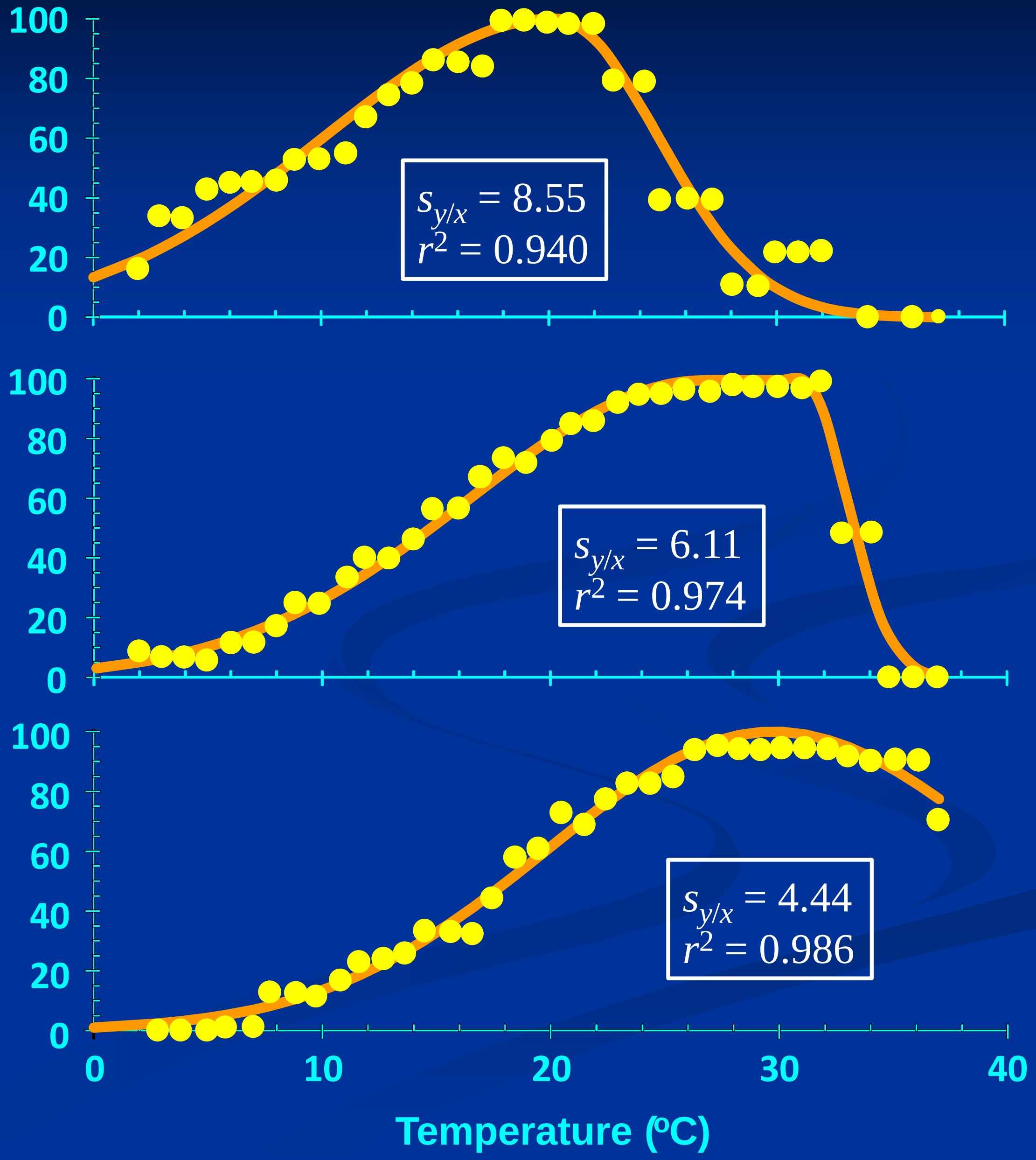


Principal Components Governing Seasonal Succession Patterns

Why do cyanobacteria win?

- ***Temperature***
- ***Nutrient limitation***
- ***Grazing***
- ***Settling/buoyancy***

Paerl & Otten 2012

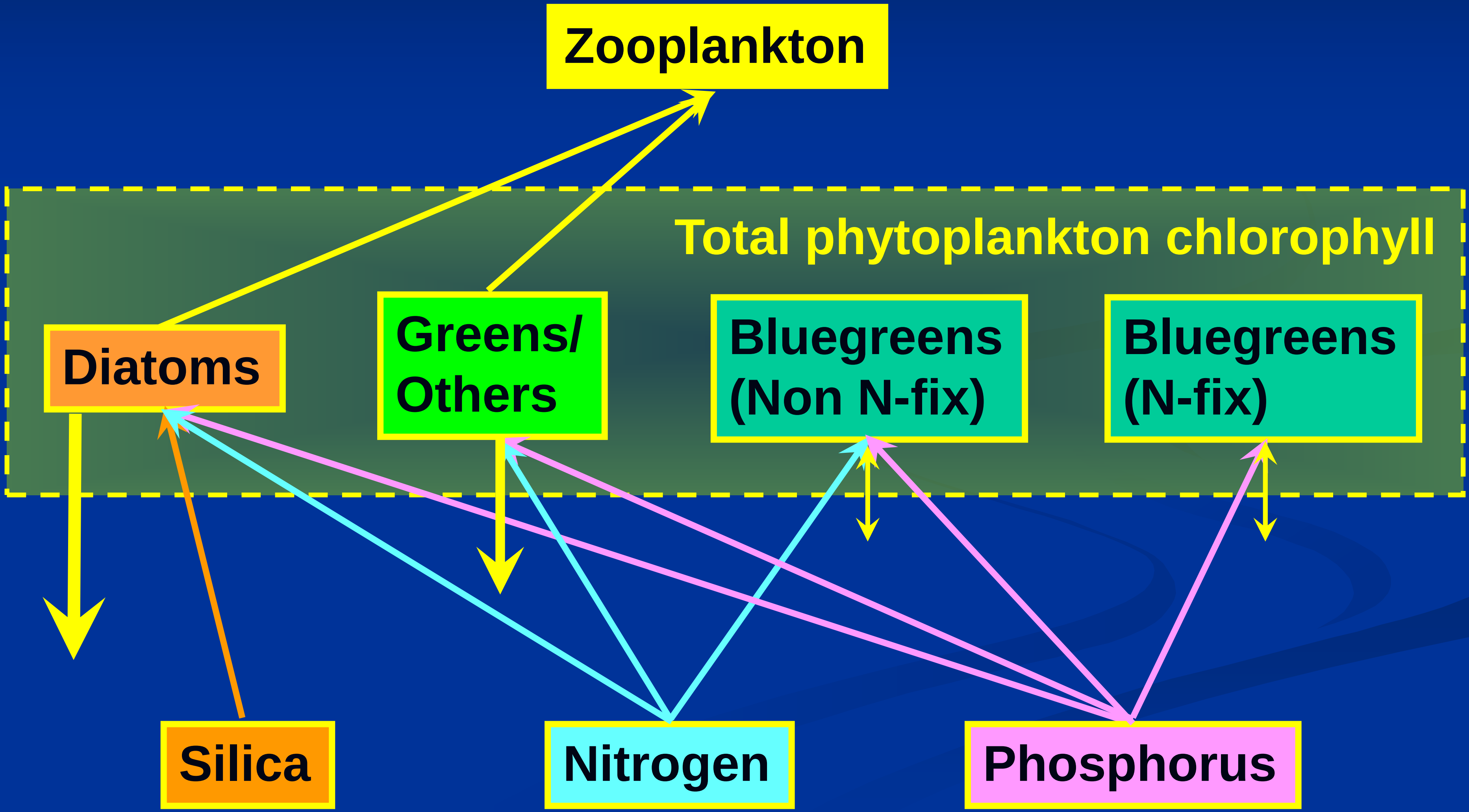


$s_{y/x} = 8.55$
$r^2 = 0.940$

$s_{y/x} = 6.11$
$r^2 = 0.974$

$s_{y/x} = 4.44$
$r^2 = 0.986$

NUTRIENT LIMITATION, SETTLING & GRAZING



Zooplankton

Total phytoplankton chlorophyll

Diatoms

Greens/ Others

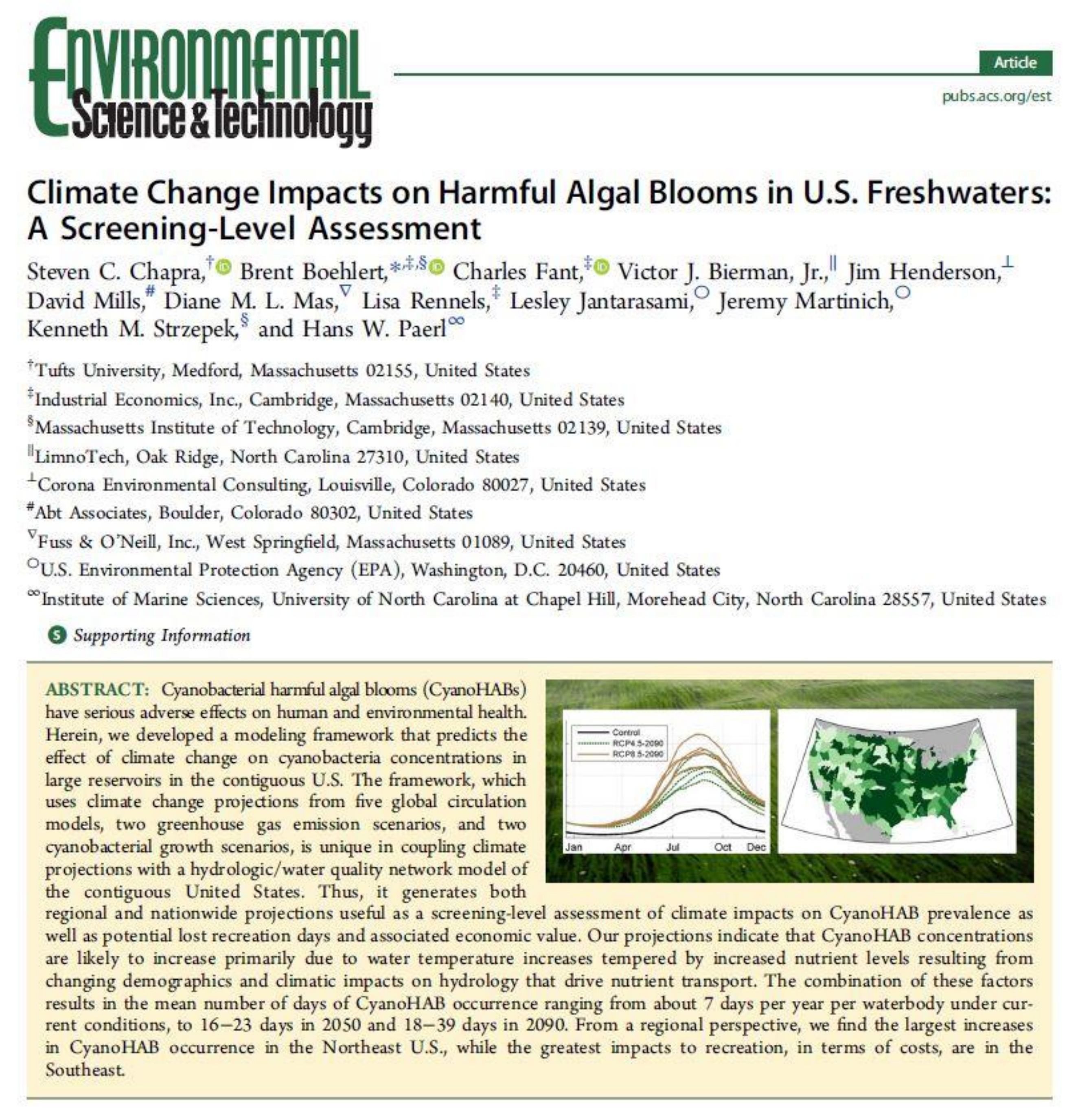
Bluegreens (Non N-fix)

Bluegreens (N-fix)

Silica

Nitrogen

Phosphorus



Environmental Science & Technology

Article

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Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwaters: A Screening-Level Assessment

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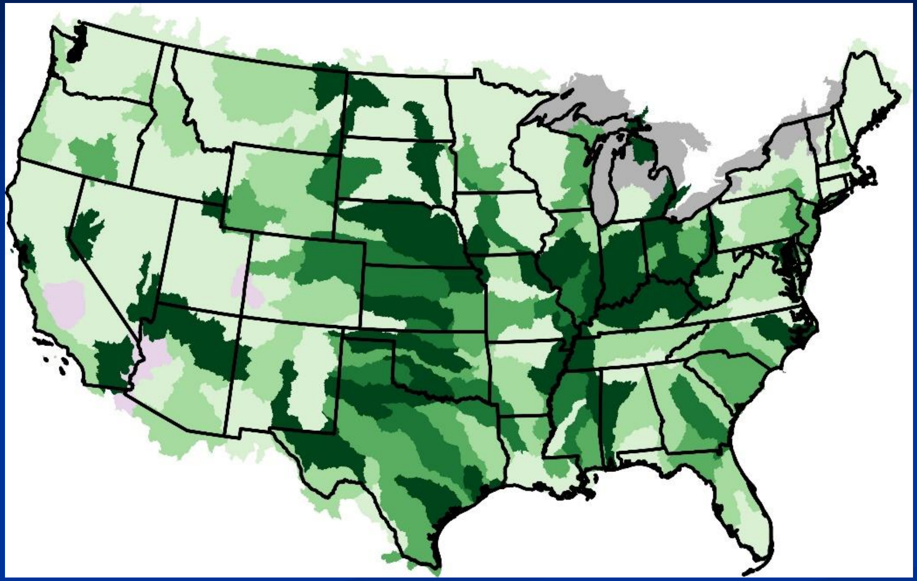
Supporting Information

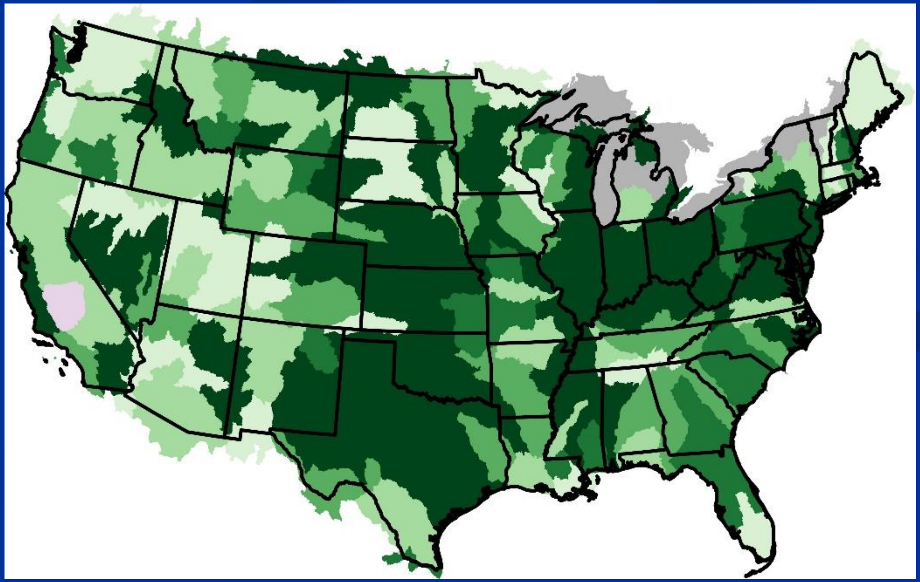
ABSTRACT: Cyanobacterial harmful algal blooms (CyanoHABs) have serious adverse effects on human and environmental health. Herein, we developed a modeling framework that predicts the effect of climate change on cyanobacteria concentrations in large reservoirs in the contiguous U.S. The framework, which uses climate change projections from five global circulation models, two greenhouse gas emission scenarios, and two cyanobacterial growth scenarios, is unique in coupling climate projections with a hydrologic/water quality network model of the contiguous United States. Thus, it generates both regional and nationwide projections useful as a screening-level assessment of climate impacts on CyanoHAB prevalence as well as potential lost recreation days and associated economic value. Our projections indicate that CyanoHAB concentrations are likely to increase primarily due to water temperature increases tempered by increased nutrient levels resulting from changing demographics and climatic impacts on hydrology that drive nutrient transport. The combination of these factors results in the mean number of days of CyanoHAB occurrence ranging from about 7 days per year per waterbody under current conditions, to 16–23 days in 2050 and 18–39 days in 2090. From a regional perspective, we find the largest increases in CyanoHAB occurrence in the Northeast U.S., while the greatest impacts to recreation, in terms of costs, are in the Southeast.

Critical HABs blooms in USA

2050



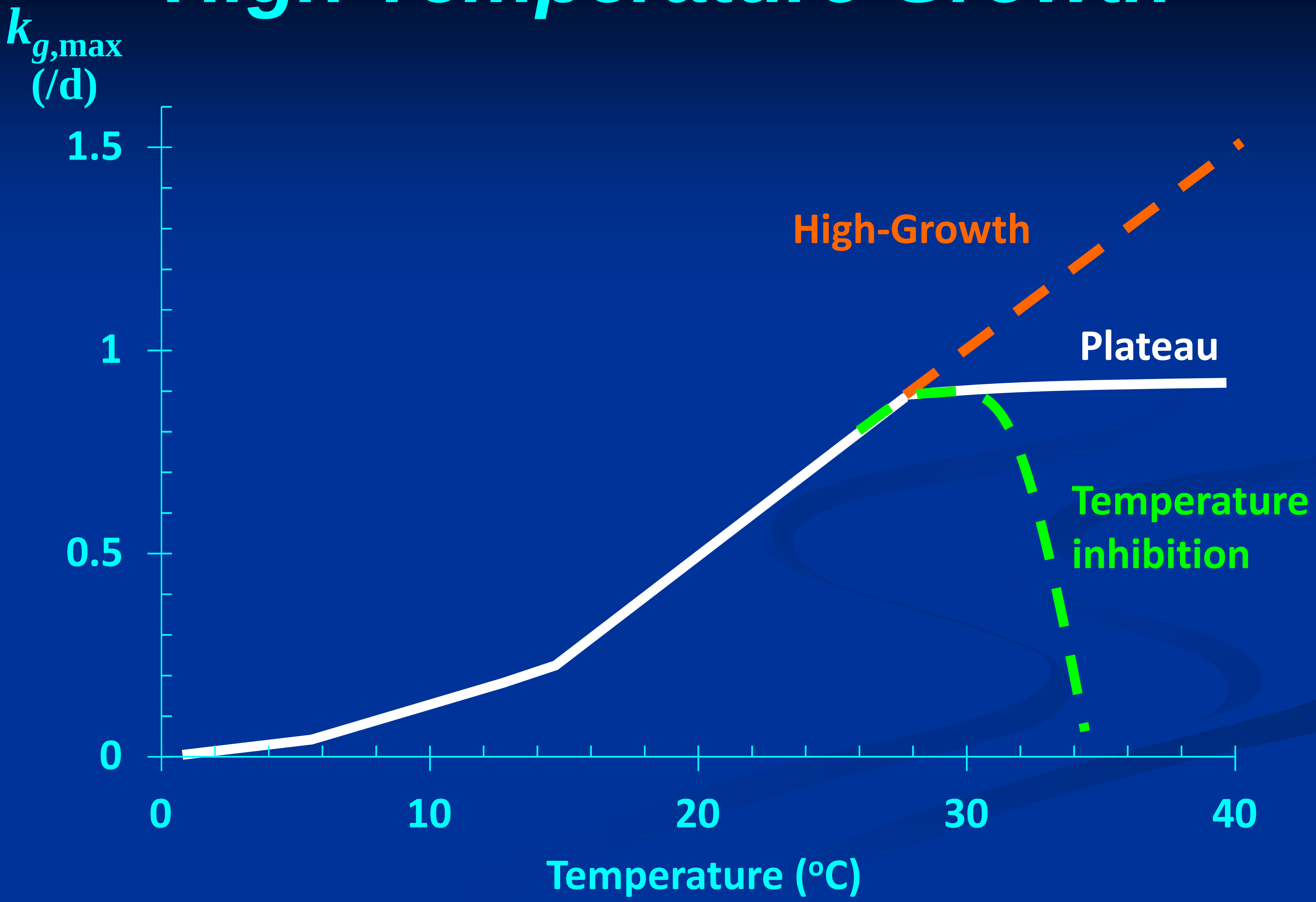
2090



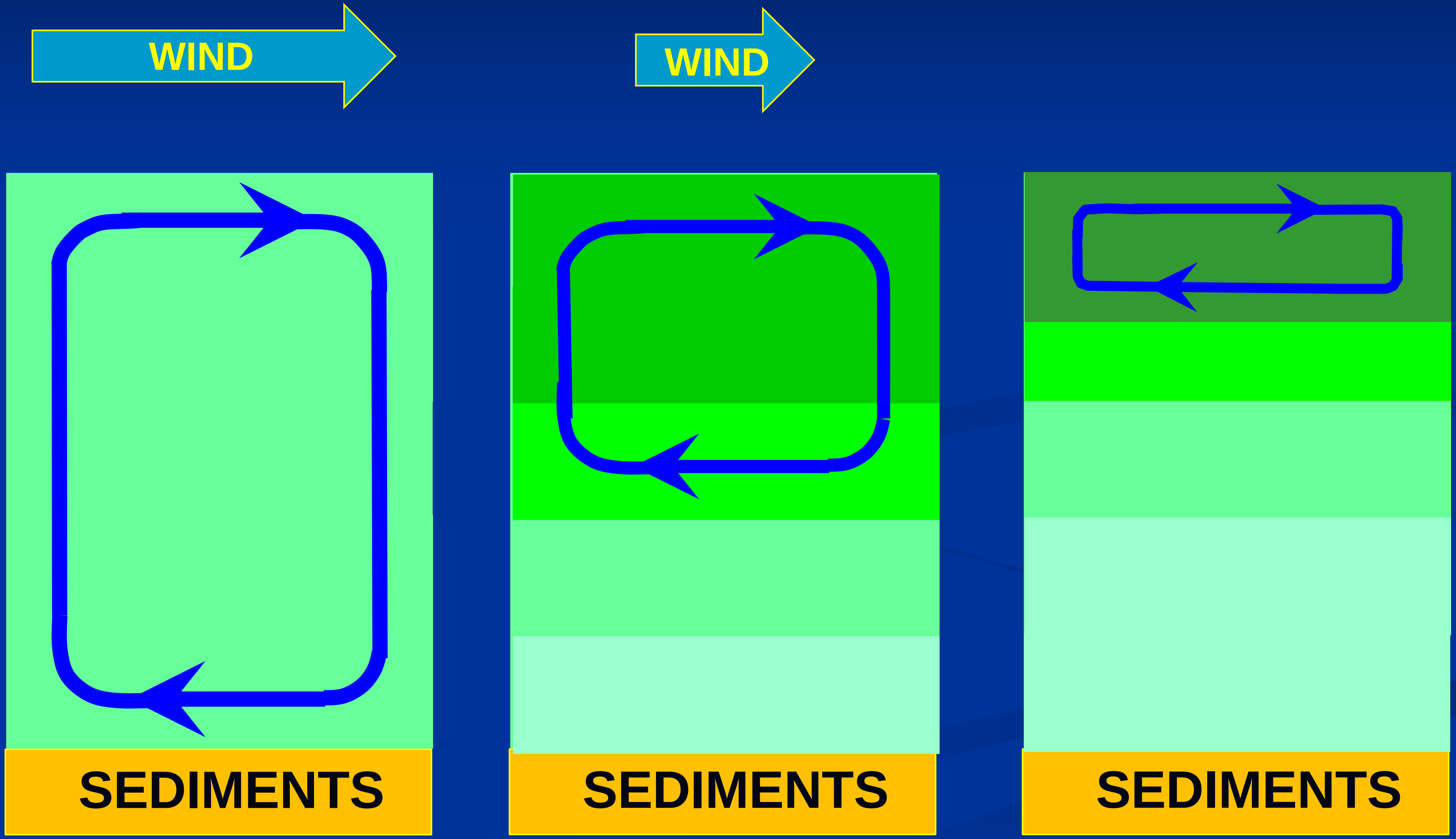
Research Issues

- ***High temperature kinetics***
- ***Scum formation***

High Temperature Growth

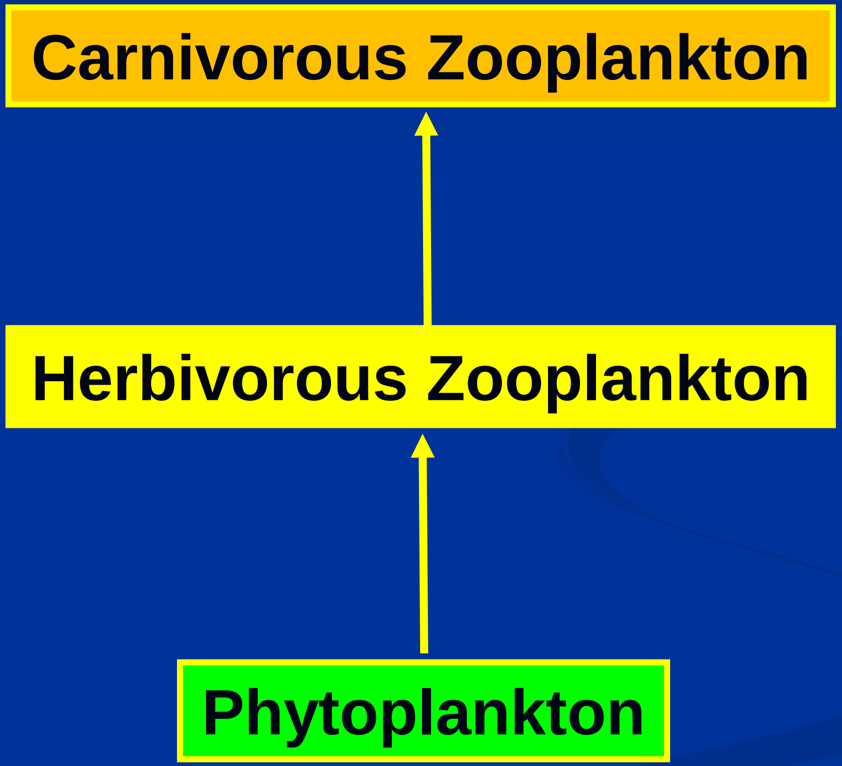


SCUM FORMATION



Upper Food Chain

FIRST FOOD CHAIN

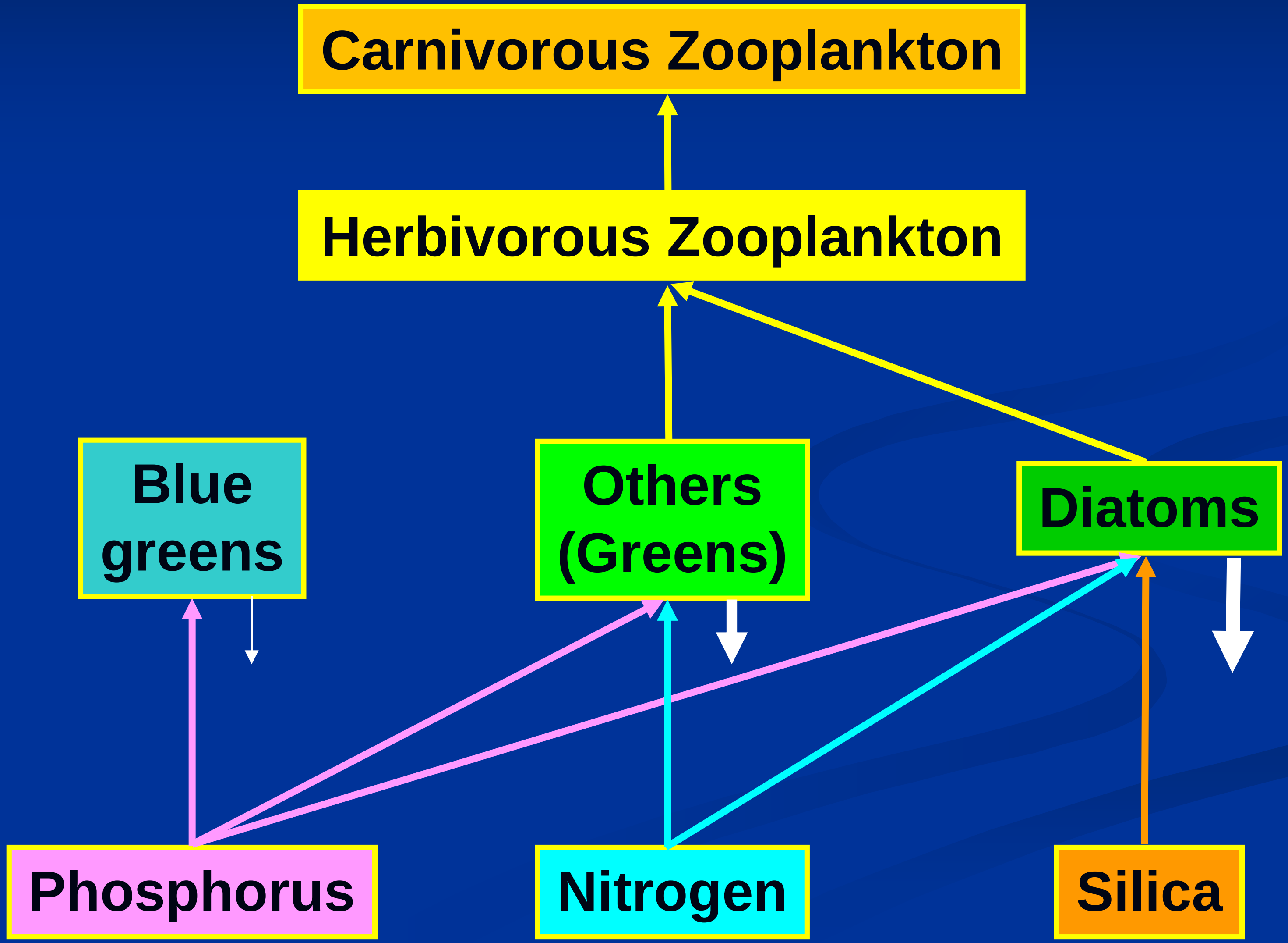


Carnivorous Zooplankton

Herbivorous Zooplankton

Phytoplankton

SIMPLE HABs MODEL



Carnivorous Zooplankton

Herbivorous Zooplankton

Blue greens

Others (Greens)

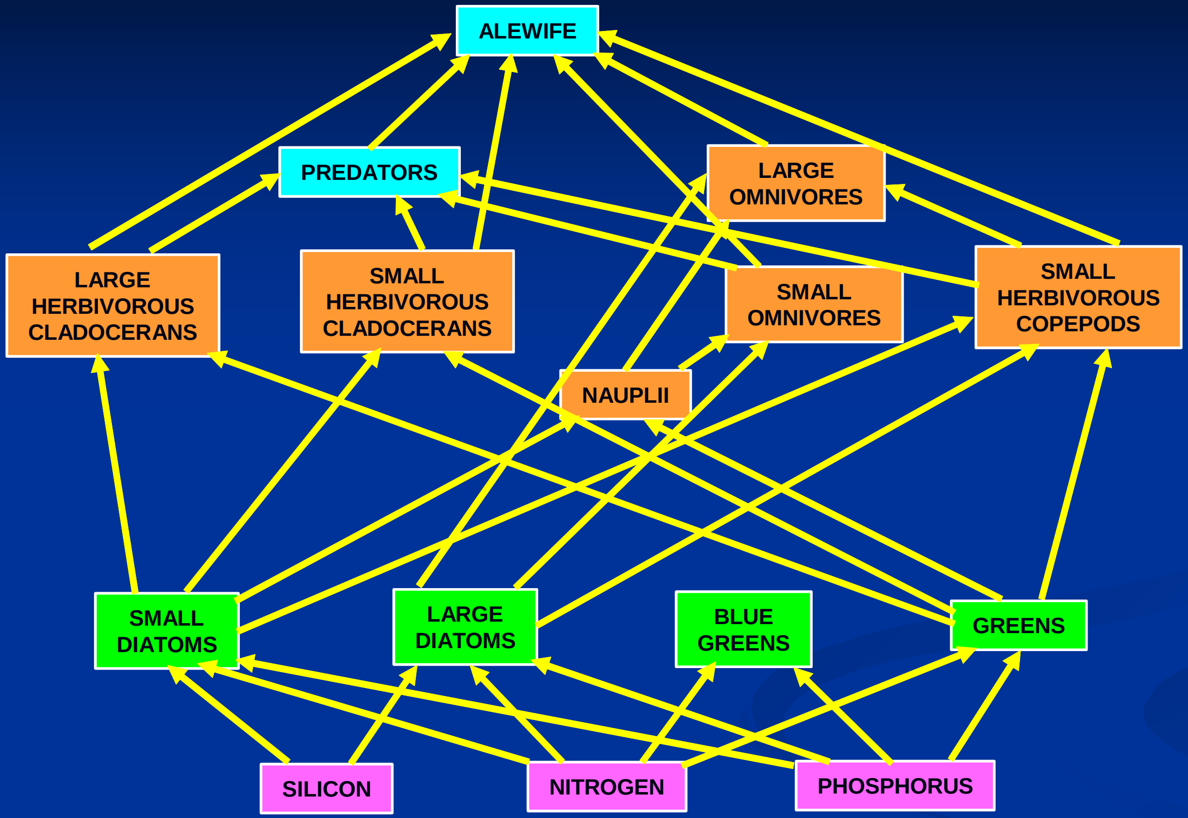
Diatoms

Phosphorus

Nitrogen

Silica

UPPER TROPHIC LEVEL



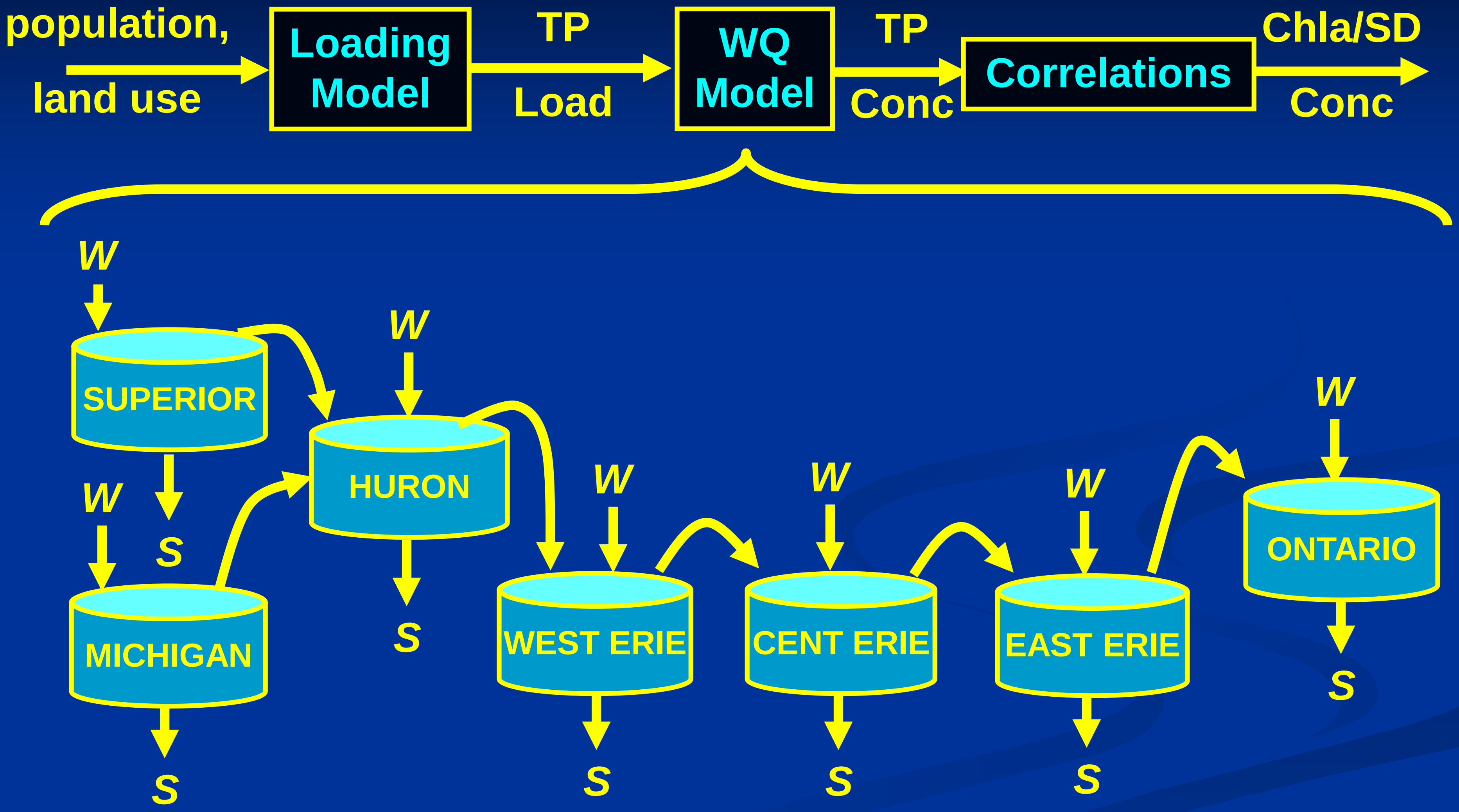
- ***WQ modeling's dirty little secret***
  - ***Where did the zooplankton go?***
- ***Bottom-up versus top-down***
- ***Invasive species***

GENERAL, ISSUES, QUESTIONS AND CHALLENGES

(Please indulge me)

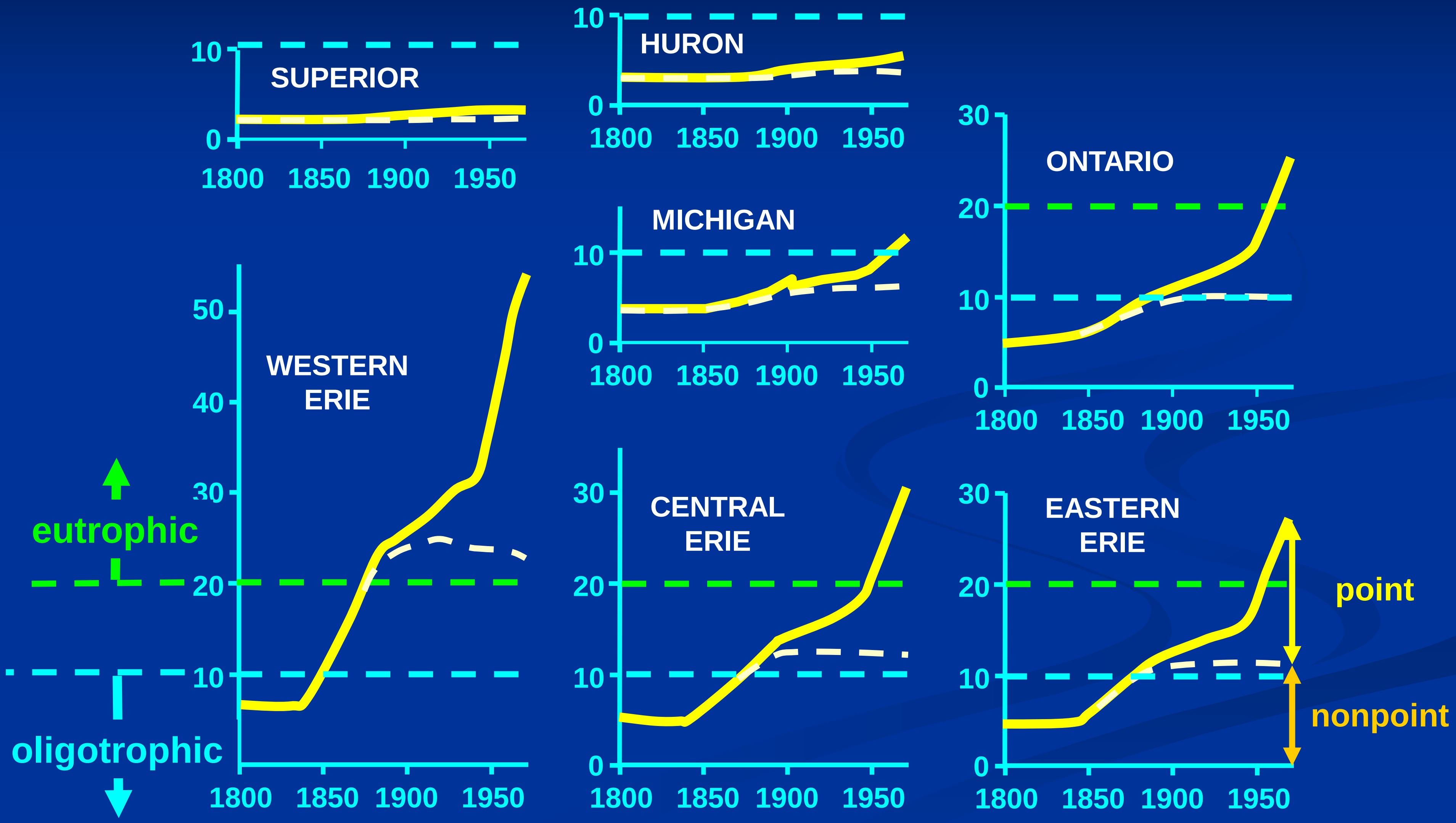
- Data stewardship
- Watershed modeling
- Interdisciplinary cooperation
- Systems approach

GREAT LAKES TP MODEL

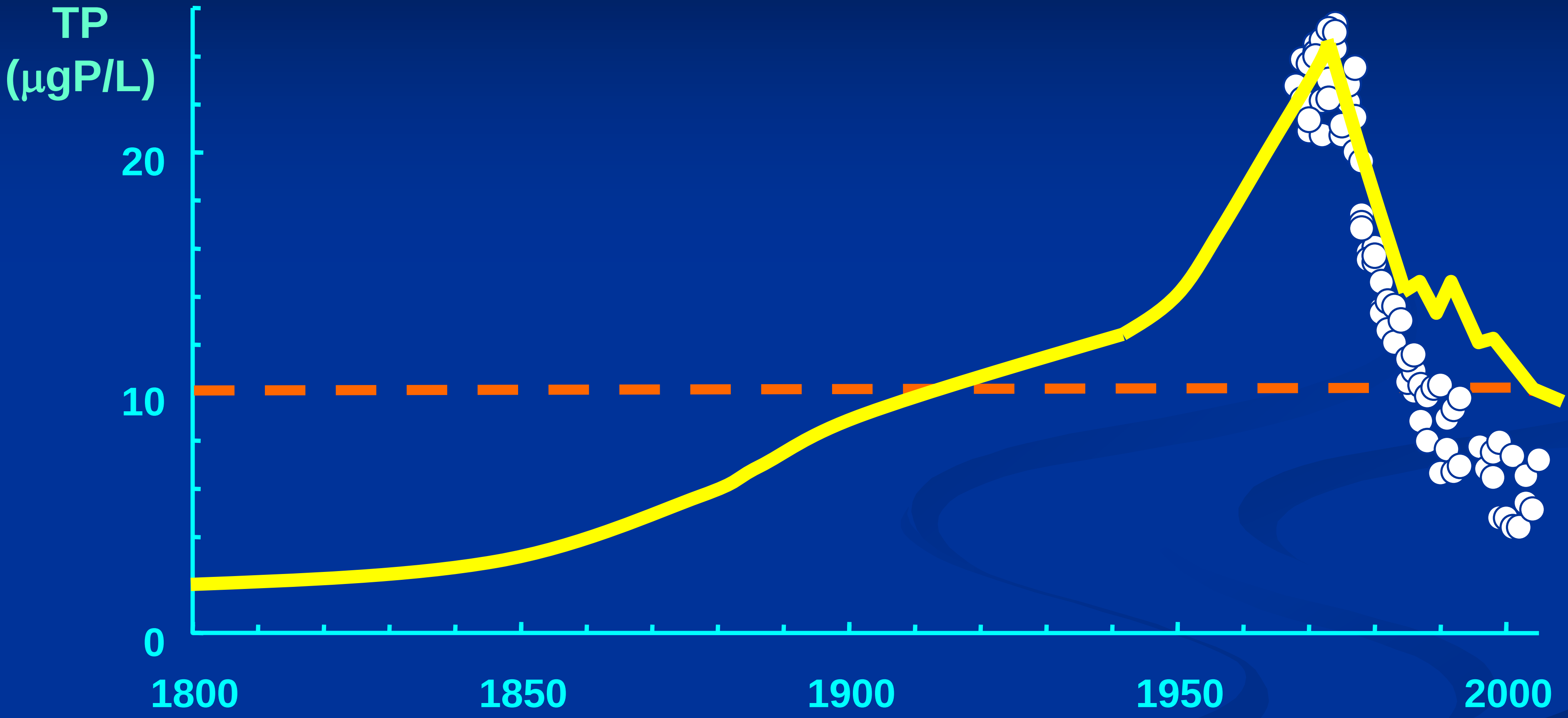


DECISION-SUPPORT MODEL

TP CONCENTRATIONS



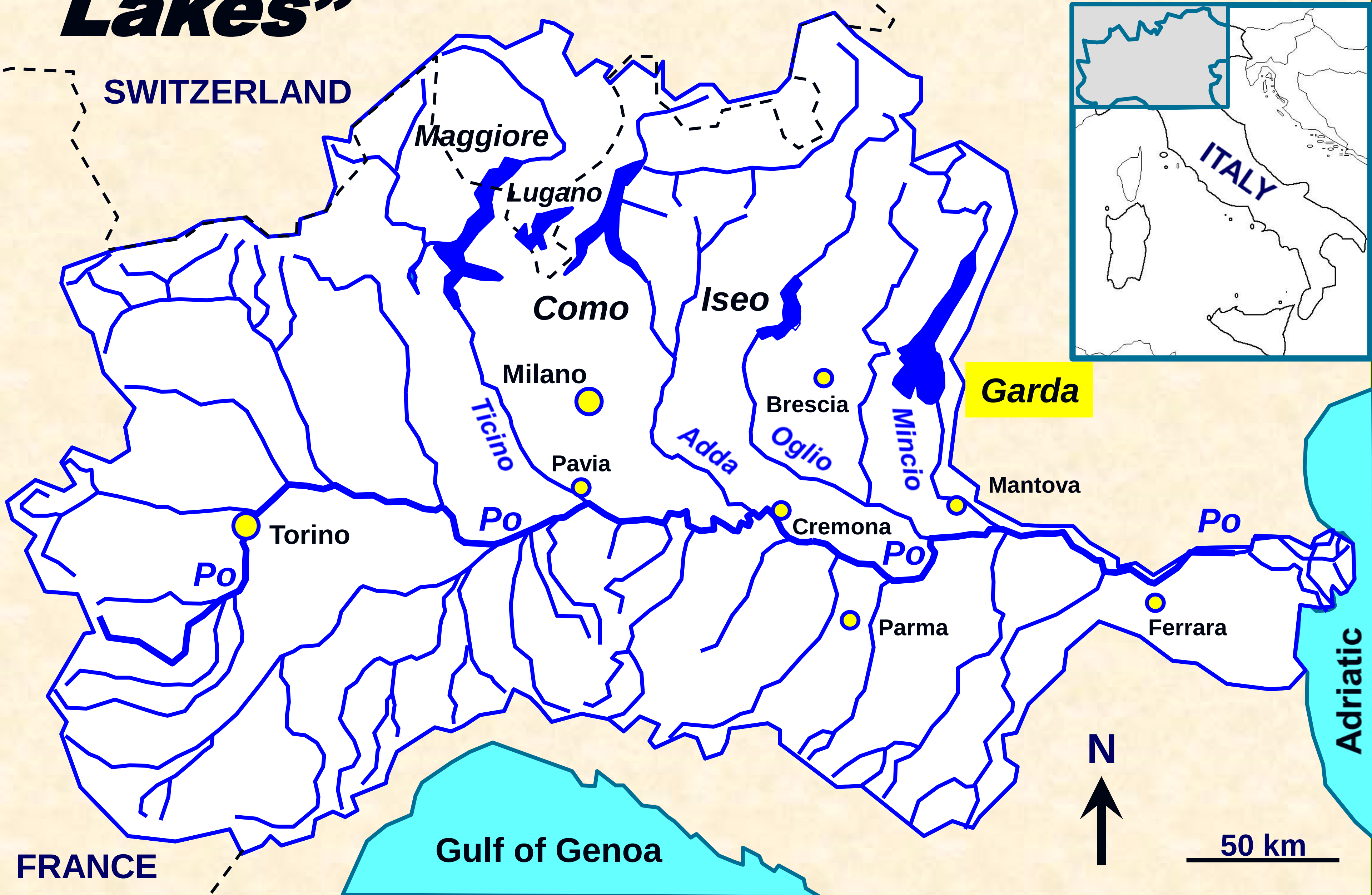
LAKE ONTARIO



Much better than expected!

(and maybe too much)

The Pre Alpine Italian "Great Lakes"




THE END