Updated: 30 October 2017

[Print version]

CEE 577: Surface Water Quality Modeling

Lecture #18

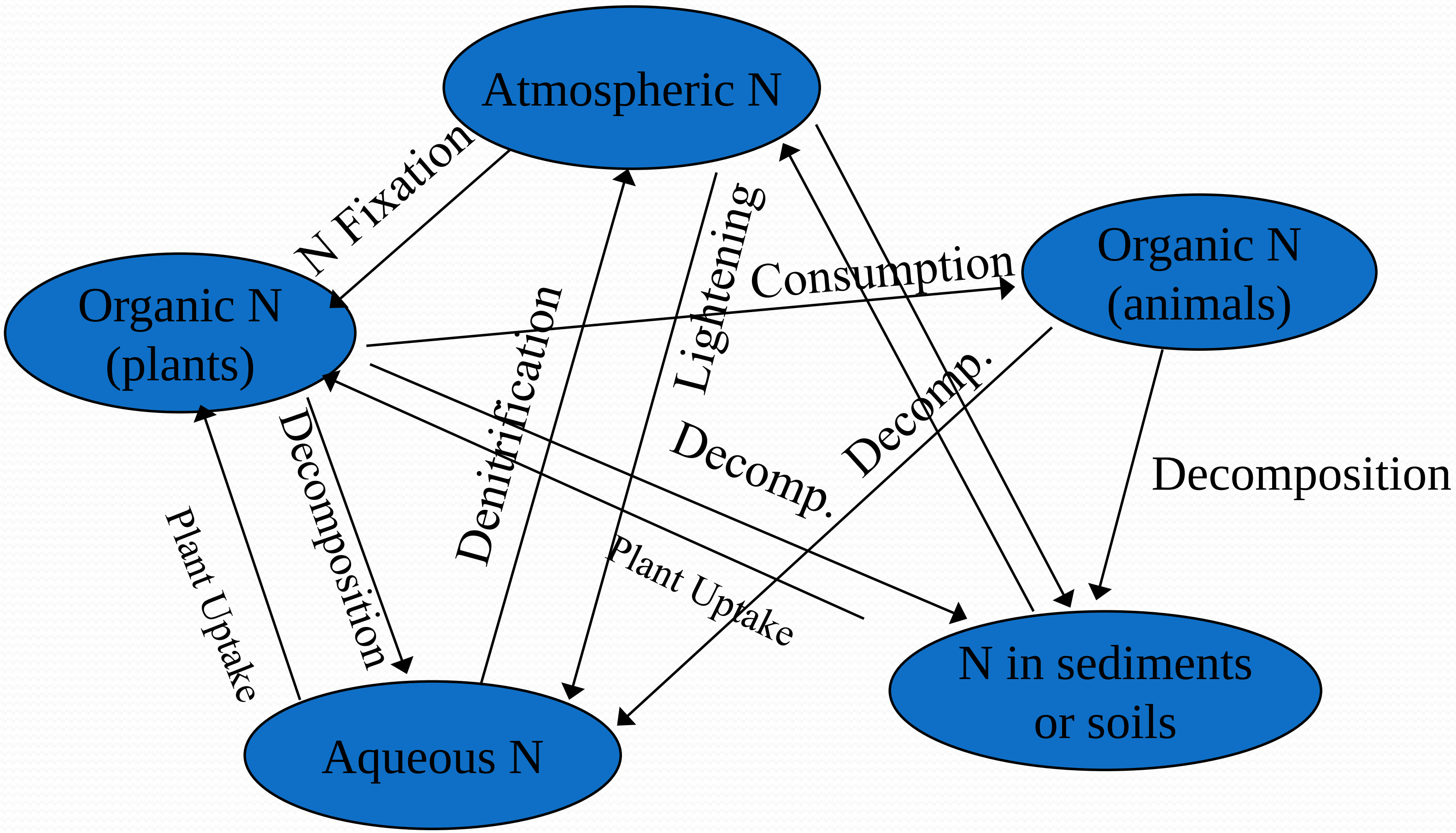
Streeter-Phelps: Distributed Sources & Nitrogen

(Chapra, L22 & L23)

Nitrogen (Chapra L23)

- Nitrification/Denitrification
  - nitrification: oxygen consuming
  - denitrification: anaerobic, form N_2
- Eutrophication
  - stimulates plant growth
- Nitrate pollution
  - from fertilizers and nitrification
- Ammonia toxicity (NH_3 form)

Nitrogen Cycle



Nitrification/Denitrification

Nitrification: will satisfy NBOD and NH_3 toxicity

$$NH_4^+ + \tfrac{3}{2} O_2 \xrightarrow{Nitrosomonas} NO_2^- + H_2O + 2H^+$$

$$NO_2^- + \tfrac{1}{2} O_2 \xrightarrow{Nitrobacter} NO_3^-$$

Can be combined with traditional activated sludge so that NBOD is removed along with CBOD; occurs naturally in surface waters

Denitrification: will remove nitrate, nutrient control

$$NO_3^- + \text{ organic } \rightarrow N_2 \uparrow + CO_2 + H_2O$$

Requires an **anaerobic** environment

Modeling Nitrification

$$L_N = L_{N_o} e^{-k_n t} + \frac{S_D}{k_n}\left(1 - e^{-k_n t}\right)$$

Point

Distributed

$L_N = 4.57*TKN$

In-class problem I

- A poorly treated municipal wastewater is discharged into Evergreen Brook at milepoint zero. In addition there is a continuous discharge of soluble BOD from a series of hog farms extending from milepoint zero to mile 25.
  - The WWTP discharges sufficient BOD such that there is 12 mg/L BOD at the point of mixing, 30% of which is particulate
  - The hog farms release 5 g-BOD/d for every foot of stream length
  - The stream can be considered to have a uniform depth of 4 ft, a width of 22 ft and a rocky bottom. Velocity is 3 mi/d.
  - Assume a BOD settling rate of 1.2 d^{-1}
- What is the BOD concentration 10 miles downstream and how much originates from each source (WWTP vs hog farm)?

In-class problem II

- First determine distributed loading term

$$S_d = \frac{S_d''}{A_c} = \frac{S_d'}{H} = \frac{5 \, {}^{g}\!/_{ft-d}}{4\,ft(22\,ft)}\left(\frac{1\,ft^3}{28.3L}\right) = 2.0\frac{mg}{L-d}$$

- Next estimate deoxygenation rate

$$k_d = C\left(\frac{H}{8}\right)^{-0.434} = 0.3\left(\frac{4}{8}\right)^{-0.434} = 0.405d^{-1}$$

- Then formulate BOD model

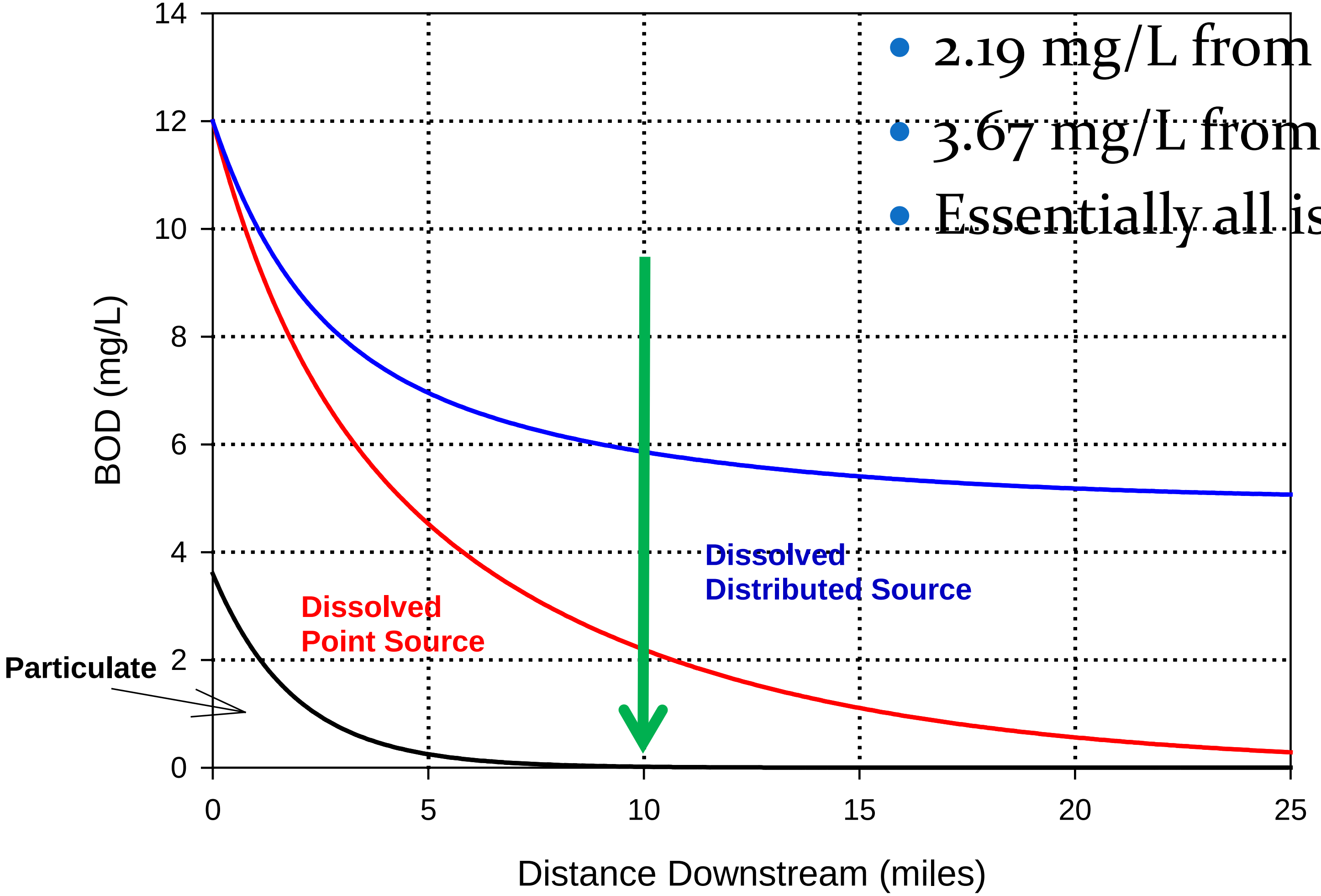
$$L = L_o e^{-k_r t} + \frac{S_D}{k_r}\left(1 - e^{-k_r t}\right)$$

deoxygenation only, no settling

$$= 12(0.3)e^{-1.605 x/U} + 12(0.7)e^{-0.405 x/U} + \frac{2}{0.405}\left(1 - e^{-0.405 x/U}\right)$$

In-class problem II

- 5.86 mg/L @10 mi
  - 2.19 mg/L from WWTP
  - 3.67 mg/L from hog farms
  - Essentially all is dissolved



Full Equation

$$D = D_o e^{-k_a t} + \frac{k_d L_o}{k_a - k_r}\left(e^{-k_r t} - e^{-k_a t}\right)$$

$$+ \frac{k_n L_{No}}{k_a - k_n}\left(e^{-k_n t} - e^{-k_a t}\right)$$

Point NBOD

$$+ \frac{-P + R + \left(\frac{S_B^{'}}{H}\right)}{k_a}\left(1 - e^{-k_a t}\right)$$

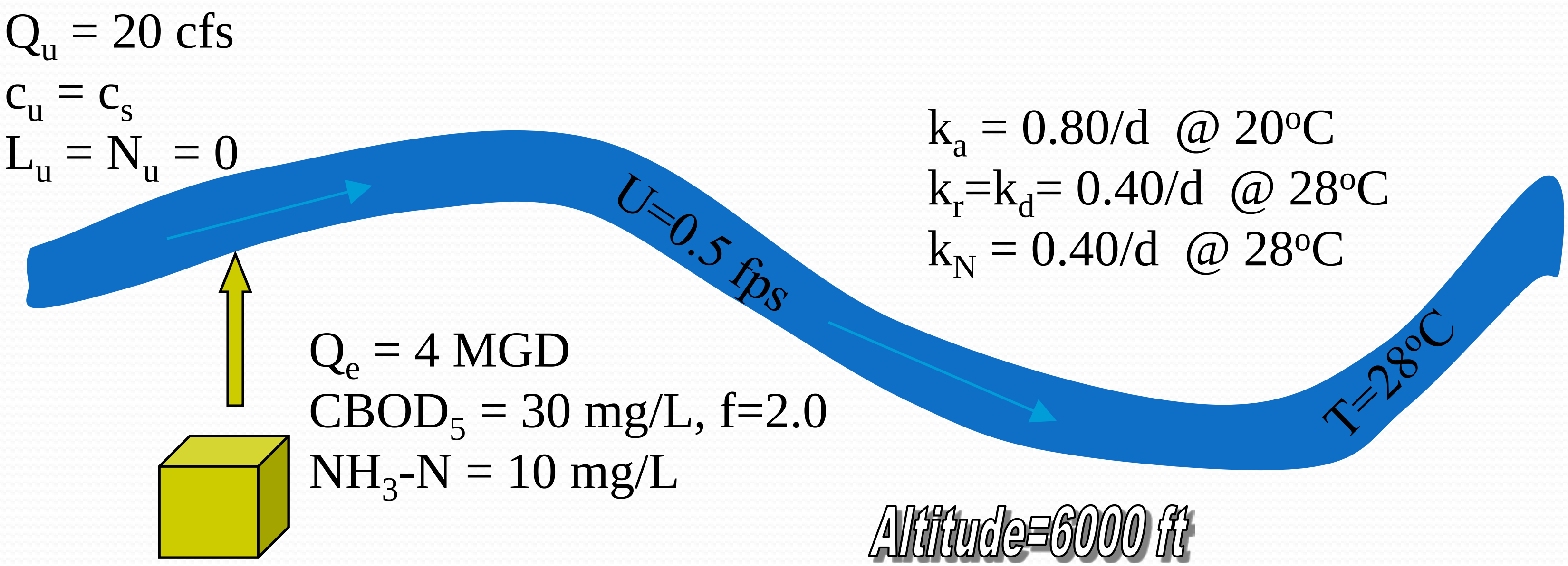
$$+ \frac{k_d S_d}{k_r k_a}\left(1 - e^{-k_a t}\right) - \frac{k_d S_d}{k_r\left(k_a - k_r\right)}\left(e^{-k_r t} - e^{-k_a t}\right)$$

$$+ \frac{k_n S_{Nd}}{k_n k_a}\left(1 - e^{-k_a t}\right) - \frac{k_n S_{Nd}}{k_n\left(k_a - k_n\right)}\left(e^{-k_n t} - e^{-k_a t}\right)$$

Distributed NBOD

Sample Problem (T&M, pg.309)

- Problem
  - Determine the maximum allowable ultimate oxygen demand (UOD) in the effluent entering the stream if the DO concentration is to equal or exceed 5 mg/L. Assume the effluent DO is equal to the stream's DO saturation concentration.



Problem (cont.)

- Analysis of existing conditions
  - Loading
    - BOD and NBOD may be treated as one UOD load since the decay rates are the same in the stream. Assume only the ammonia is significant in the NBOD.

$$UOD(mg/L) = fxCBOD_5 + 4.57x(NH_3 - N)$$
$$= 2.0x30 + 4.57x10 = 105.7 mg/L$$

$$W(UOD) = 4MGDx105.7 \tfrac{mg}{L} x8.34 = 3530 lb/d$$

$$L_o = \frac{W(UOD)}{Q_u + Q_e} = \frac{3530 lb/d}{(20cfs + 4(1.548)cfs)5.4}$$
$$= 25.0 \tfrac{mg}{L}$$

Problem (cont.)

- Adjust Reaction rates to ambient temp.

$$k_a = k_a(20^o C) x \theta^{T-20}$$
$$= 0.8(1.024)^{(28-20)} = 0.97 d^{-1} @ 28^o C$$

- Determine t_{crit}

$$t_{crit} = \frac{1}{k_a - k_r} \ln\left[\frac{k_a}{k_r}\left(1 - \frac{D_o(k_a - k_r)}{k_d L_o}\right)\right]$$
$$= \frac{1}{0.97 - 0.40} \ln\left[\frac{0.97}{0.40}\left(1 - \frac{0(0.97 - 0.40)}{0.40(25.0)}\right)\right]$$
$$= 1.55 d$$

Problem (cont.)

- Then get x_{crit}

$$x = Ut = 0.5\,fps\left(\frac{16.4\,mpd}{fps}\right)1.55d = 12.7mi$$

- And c_s is:
  - accounting for temp. & altitude

$$c_s = 6.19\,\frac{mg}{L}$$

- Finally the c_{min} is:

$$\begin{aligned} c_{\min} &= c_s - L_o \frac{k_d}{k_a} e^{-k_r t_{crit}} \\ &= 6.19 - 25.0\frac{0.40}{0.97} e^{-0.40(1.55)} \\ &= 0.64\,\frac{mg}{L} \end{aligned}$$

Problem (end)

- Determine allowable load, if WQC require 5.0 mg/L minimum D.O.
  - Recognize that the loading:deficit relationship is linear

$$D_{crit} \equiv c_s - c_{min} = L_o \frac{k_d}{k_a} e^{-k_r t_{crit}}$$

Also, t_{crit} is independent of L when D_o=0

  - so determine allowable L

$$\frac{D_{crit}}{L_o} = \frac{D_{crit(allowable)}}{L_{o(allowable)}}$$

$$L_{o(allowable)} = \frac{D_{crit(allowable)} L_o}{D_{crit}} = \frac{1.19(105.7)}{5.55}$$

$$= 23 \tfrac{mg}{L}$$

Additional notes on WLA

Not from Chapra

- Selecting a model
  - number of dimensions
    - usually 1, major gradients are longitudinal, very minor gradients in lateral and vertical directions
    - sometimes 2, deep rivers or river-run impoundments; use should be justified
    - never 3, except research and a few extraordinary cases

Additional notes on WLA (cont.)

- Loads, sources & sinks
  - Categorize
    - category I - major sources controlling water quality
      - thorough data collection - temporal variation
    - category II - background sources
      - small to moderate data collection
  - necessary data
    - long-term BOD,with nitrification inhibition
    - analysis of all forms of nitrogen
      - org-N, NH_3, NO_2, NO_3

Additional notes on WLA (cont.)

- Time scale
  - steady state
  - quasi-steady state
    - const. loads, constant Q, diurnal DO variations due to photosynthesis
    - const. loads, variable Q
    - variable loads, constant Q
    - others
  - Fully time-variable analysis

Additional notes on WLA (cont.)

- Design Conditions
  - 7Q10 - summer
    - generally endorsed by USEPA
  - Spring Floods - large event
    - storm intensity, sequences, recessional hydrograph
  - Ice cover - winter
- Spatial Extent
  - well into the zone of recovery

Additional notes on WLA (cont.)

- Dispersion (is it significant?)
  - calculate E
    - from slope
    - from dye studies
  - calculate dimensionless estuary #
  - use Chapra's criteria
    - n<0.1, advection predominates
    - n>10, diffusion predominates
  - or calculate reaeration/deoxygenation ratio & use O'Connor figure

$$E = 3.4x10^{-5}\frac{UB^2}{HU^*}$$

E: mi²/d; U: ft/s; B: ft; H: ft

$$U^* = \sqrt{gHS}$$

$$n = \frac{k_d E}{U^2}$$

$$\phi = \frac{k_a}{k_d}$$

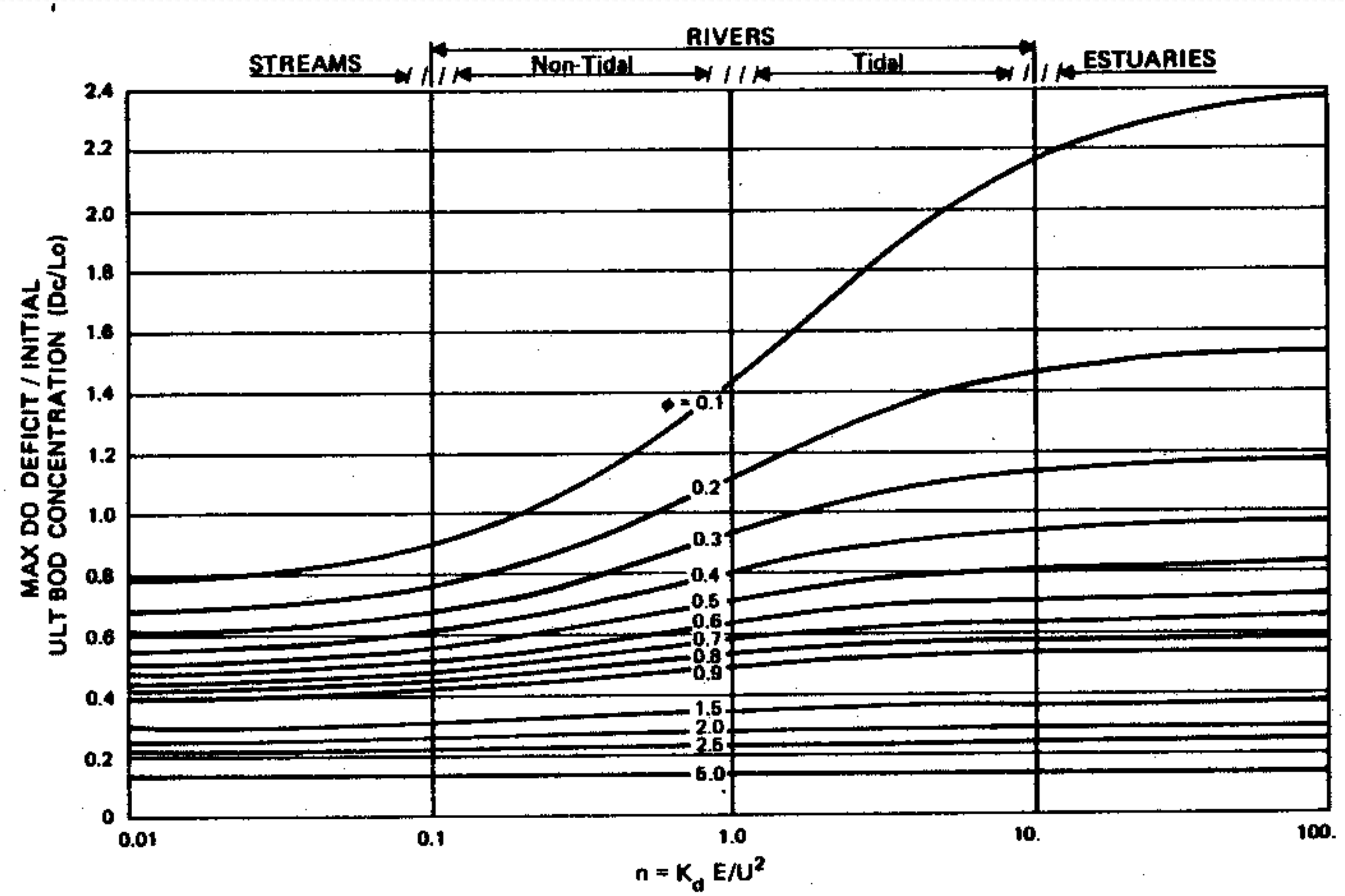


Figure 3-0. Dissolved oxygen response as a function of K_d E/U^2.

Figure prepared by O'Connor

From: Technical Guidance Manual for Performing Waste Load Allocations: Book II, Chapter 1

Full Equation

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$$+ \frac{k_n L_{No}}{k_a - k_n}\left(e^{-k_n t} - e^{-k_a t}\right)$$

Point NBOD

$$+ \frac{-P + R + \left(S_B^{'} / H\right)}{k_a}\left(1 - e^{-k_a t}\right)$$

$$+ \frac{k_d S_d}{k_r k_a}\left(1 - e^{-k_a t}\right) - \frac{k_d S_d}{k_r\left(k_a - k_r\right)}\left(e^{-k_r t} - e^{-k_a t}\right)$$

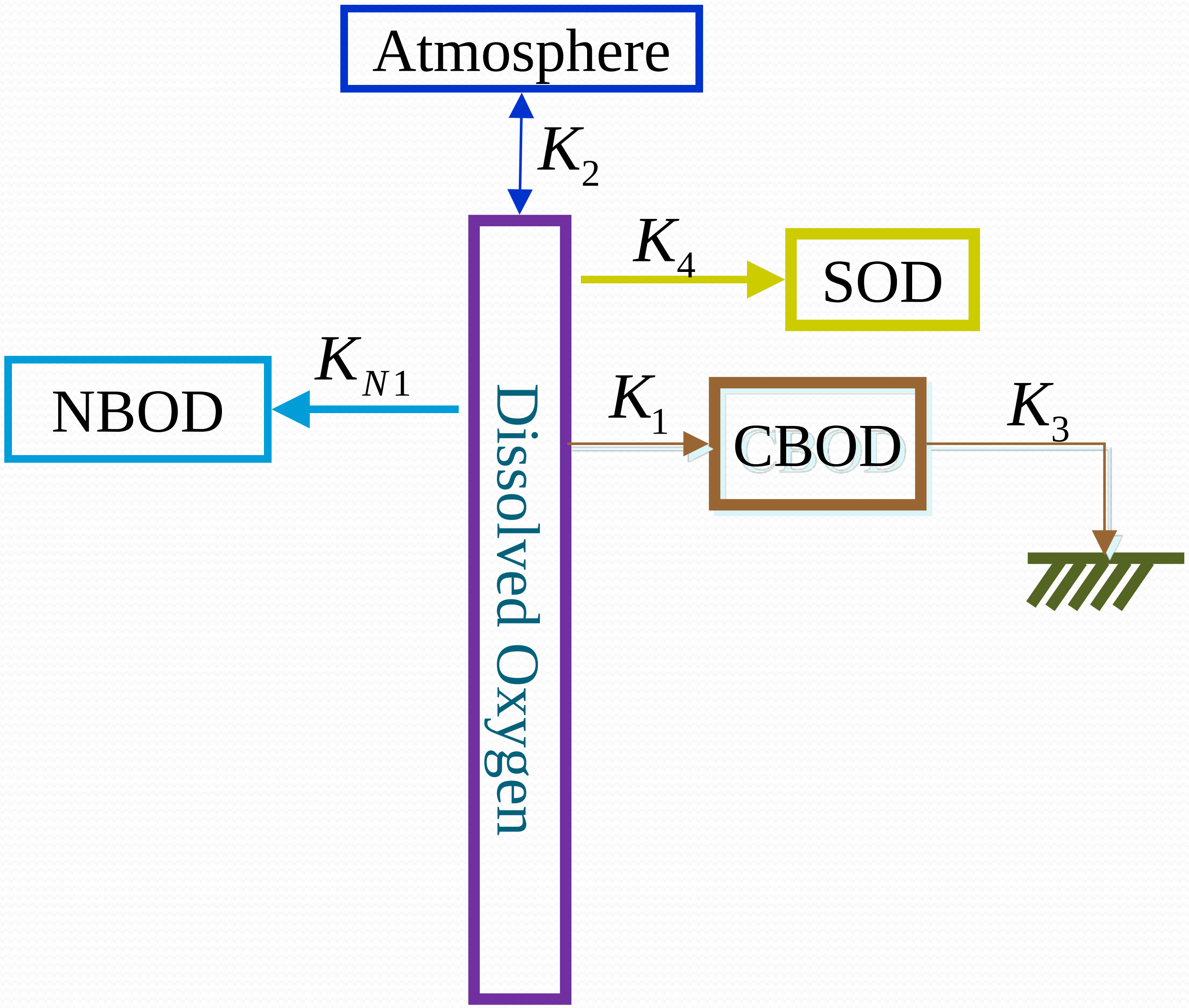
$$+ \frac{k_n S_{Nd}}{k_n k_a}\left(1 - e^{-k_a t}\right) - \frac{k_n S_{Nd}}{k_n\left(k_a - k_n\right)}\left(e^{-k_n t} - e^{-k_a t}\right)$$

Distributed NBOD

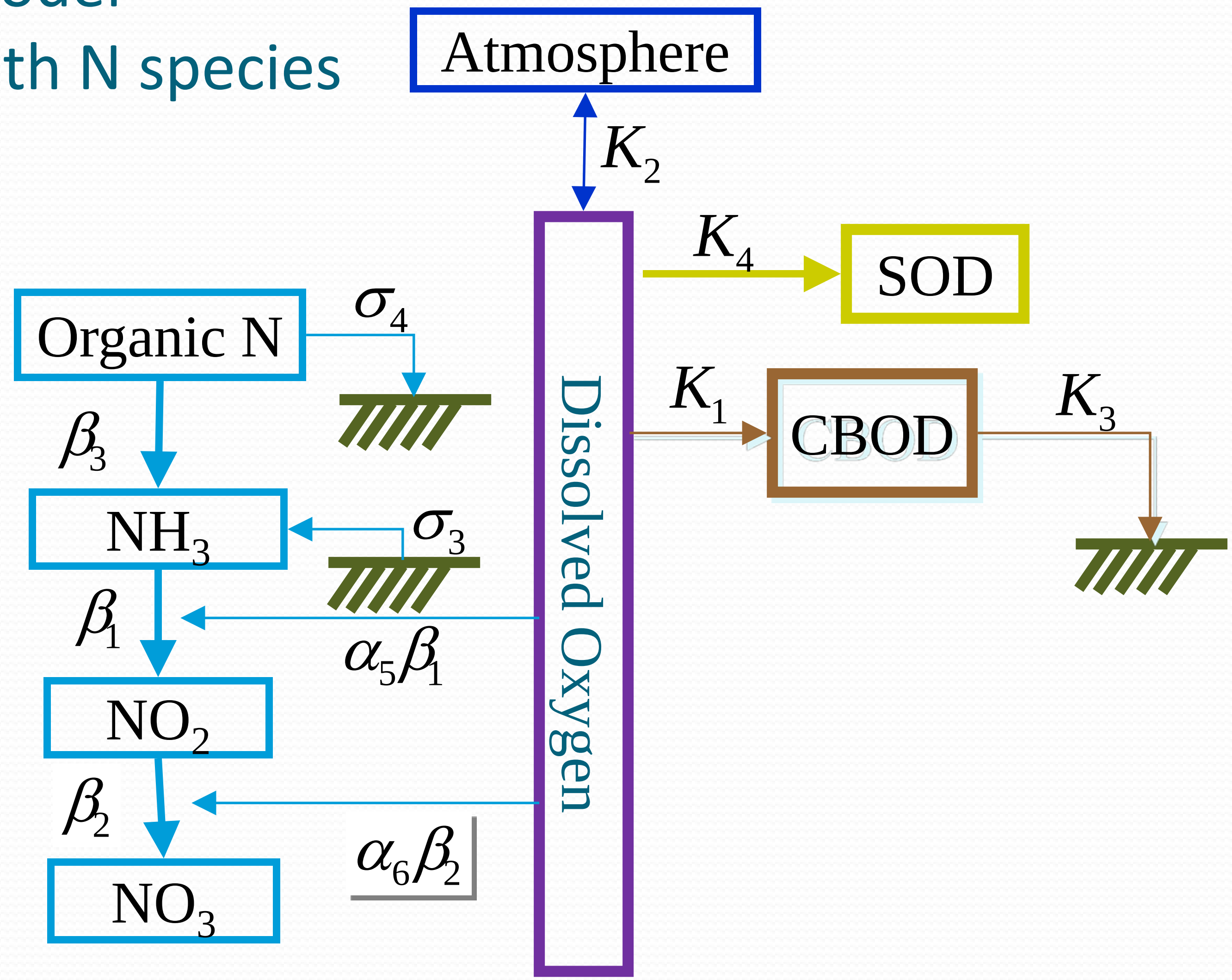
Additional notes on WLA (cont.)

- Nitrogen modeling
  - NBOD
    - measure and model TKN only
  - all 4 major species
    - org-N, NH_3, NO_2, and NO_3
    - requires separate analysis of loadings, rate coefficients, etc.

General Model Kinetics



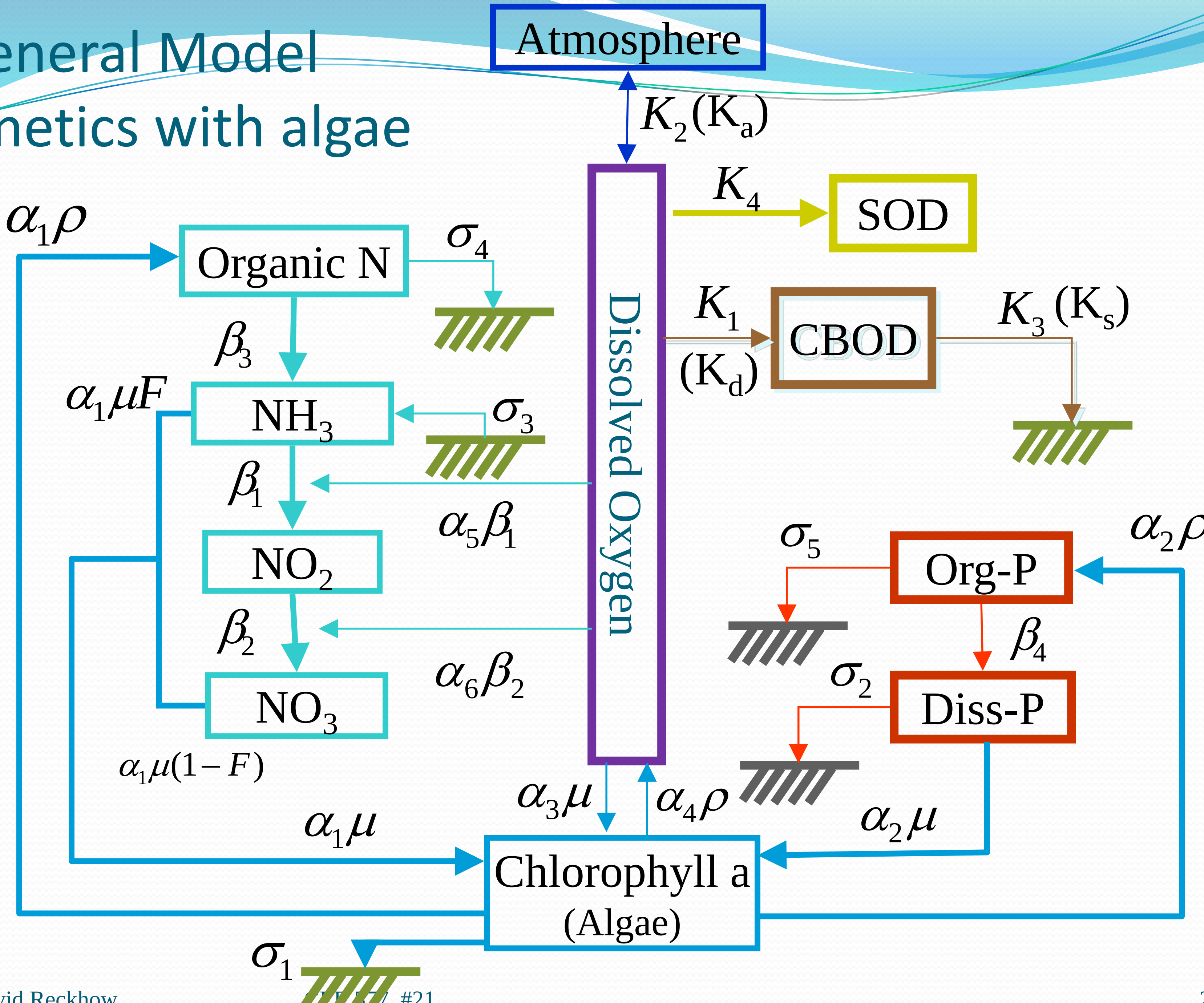
General Model
Kinetics with N species



Additional notes on WLA (cont.)

- Algal modeling
  - Level I
    - measure P-R: diurnal swings in D.O.
  - Level II
    - measure chlorophyll a, light, light extinction, nutrients "in-situ"
    - calculate P-R
  - Level III
    - assess nutrient loadings, light extinction
    - model nutrient conc., chlorophyll a, P-R

General Model
Kinetics with algae



- To next lecture

- Ohio River

Fayette
Union
Preble
Montgomery
Greene
Fayette
Franklin
Butler
Warren
Clinton
INDIANA
OHIO
KENTUCKY
WEST VIRGINIA
Ripley
Dearborn
Hamilton
NEWPORT
Highland
Clermont
Jackson
Ohio
BOONE
KENTON
CAMPBELL
Brown
Gallia
Adams
Scioto
MARKLAND L&D
MELDAHL L&D
SOUTH SHORE
GALLATIN
PENDLETON
BRACKEN
MAYSVILLE
CARROLL
GRANT
GREENUP
Lawrence
MASON
VANCEBURG
RUSSELL
TRIMBLE
OWEN
ROBERTSON
LEWIS
HENRY
HARRISON
ASHLAND
Cabell
BOYD
FLEMING
NICHOLAS
CARTER
SCOTT
SHELBY
FRANKLIN
BOURBON
ROWAN
Wayne
BATH
ELLIOTT
LAWRENCE
WOODFORD
FAYETTE
MONTGOMERY
ANDERSON
CLARK
MENIFEE
MORGAN
JOHNSON
Ohio River Advisory Area
Miles
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