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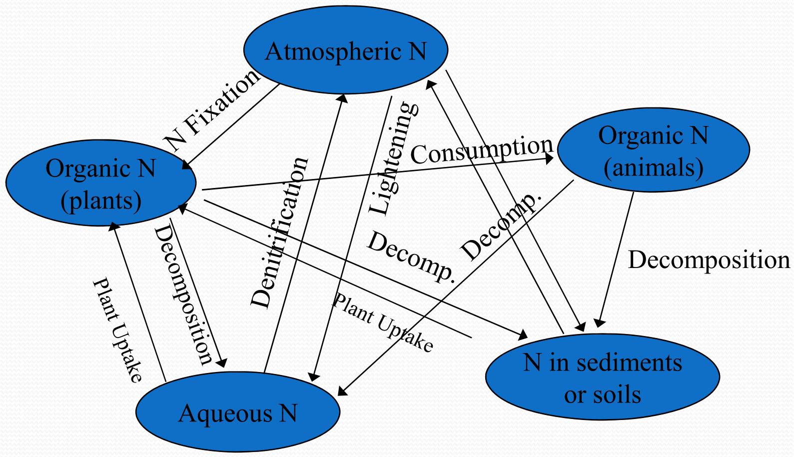
CEE 577: Surface Water Quality Modeling

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

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

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

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

- 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

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

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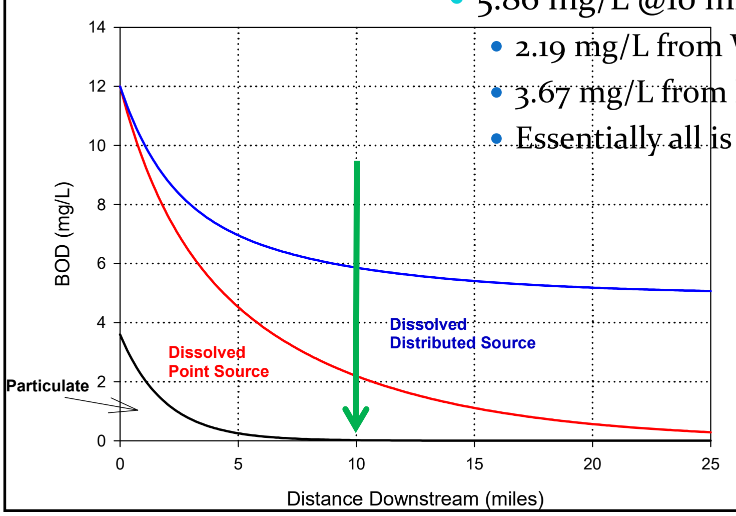
In-class problem II

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



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Full Equation

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

$$+ \boxed{\frac{k_n L_{No}}{k_a - k_n}\left(e^{-k_n t} - e^{-k_a t}\right)} \rightarrow \textbf{Point NBOD}$$

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

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

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

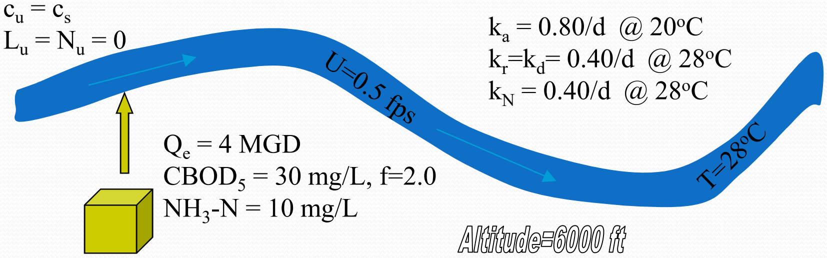
Distributed NBOD

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.

Q_u = 20 cfs
$c_u = c_s$
$L_u = N_u = 0$

k_a = 0.80/d @ 20°C
$k_r = k_d$ = 0.40/d @ 28°C
k_N = 0.40/d @ 28°C



Q_e = 4 MGD
$CBOD_5$ = 30 mg/L, f=2.0
NH_3-N = 10 mg/L

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.

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

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

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

Problem (cont.)

- Adjust Reaction rates to ambient temp.

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

- Determine t_{crit}

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

Problem (cont.)

- Then get x_{crit}
- And c_s is:
  - accounting for temp. & altitude
- Finally the c_{min} is:

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

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

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

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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

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

$$L_{o(allowable)} = \frac{D_{crit(allowable)} L_o}{D_{crit}} = \frac{1.19(105.7)}{5.55}$$
$$= 23\,\tfrac{mg}{L}$$

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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

      ft/s ft

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

      mi²/d ft

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

    - from dye studies
  - calculate dimensionless estuary # $n = \dfrac{k_d E}{U^2}$
  - use Chapra's criteria
    - n<0.1, advection predominates
    - n>10, diffusion predominates
  - or calculate reaeration/deoxygenation ratio & use O'Connor figure $\phi = \dfrac{k_a}{k_d}$

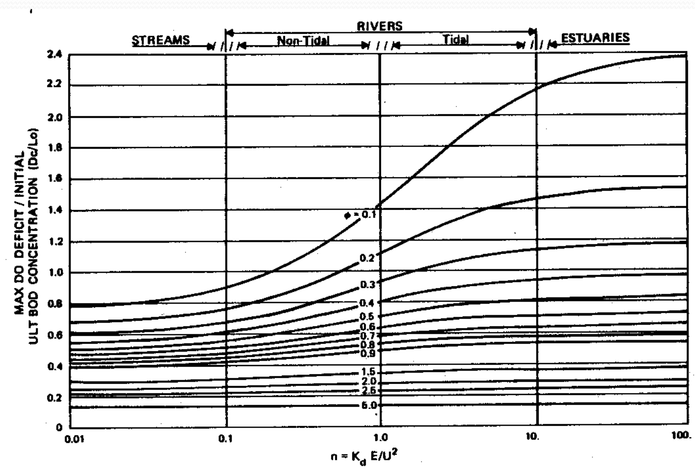


Figure 3-0. Dissolved oxygen response as a function of K_d E/U².

Figure prepared by O'Connor

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

Full Equation

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

$$\boxed{+\frac{k_n L_{No}}{k_a - k_n}\left(e^{-k_n t} - e^{-k_a t}\right)} \rightarrow \text{Point NBOD}$$

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

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

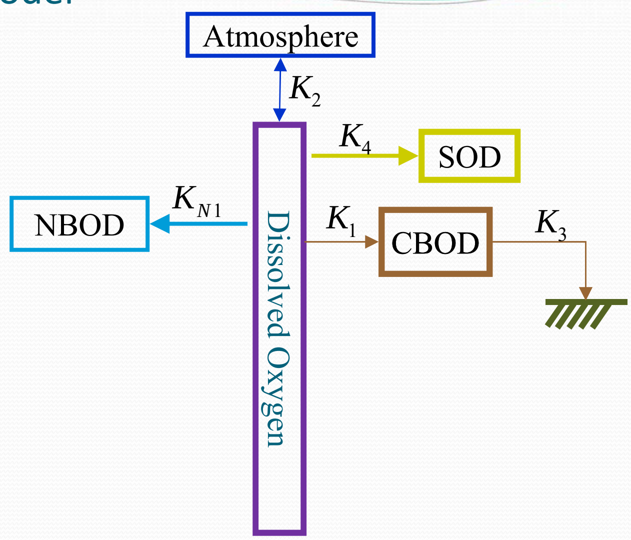
$$\boxed{+\frac{k_n S_{Nd}}{k_n k_a}\left(1 - e^{-k_a t}\right) - \frac{k_n S_{Nd}}{k_n\left(k_a - k_n\right)}\left(e^{-k_n t} - e^{-k_a t}\right)}$$

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



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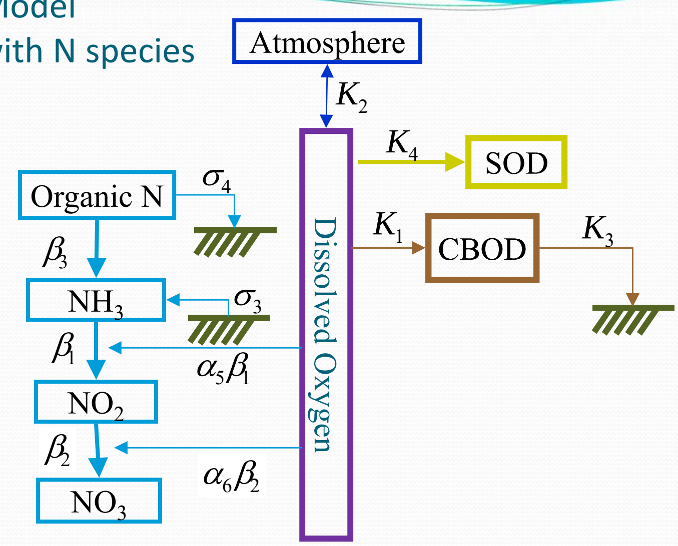
General Model Kinetics with N species



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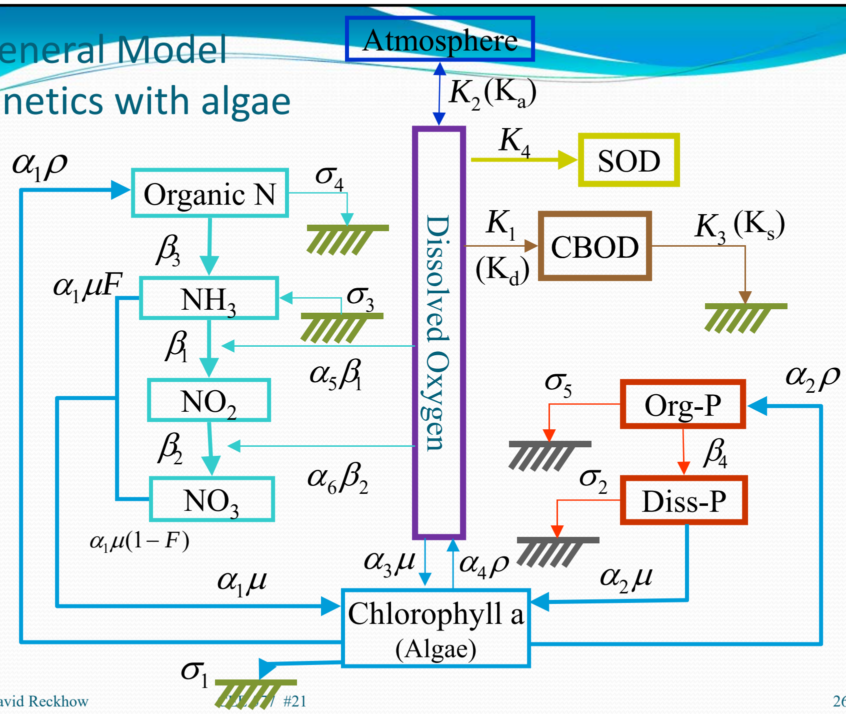
Additional notes on WLA (cont.)

- 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