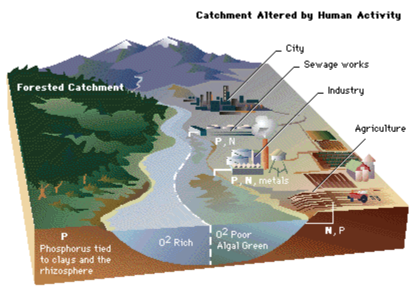
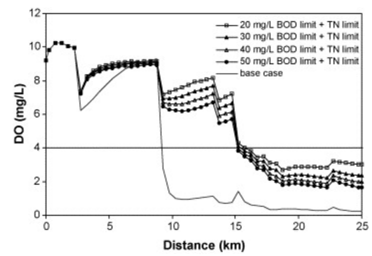
Introduction to Modeling Eutrophication Using QUAL2Kw





Nicholas von Stackelberg, P.E.

December 4, 2012

UTAH DEPARTMENT OF ENVIRONMENTAL QUALITY

QUAL2Kw Background

- Developed specifically to simulate dissolved oxygen dynamics in riverine systems
- Widely applied to eutrophication TMDLs and WLAs in the US and internationally
- Developers
  - Dr. Steven Chapra, Tufts University
  - Greg Pelletier, Washington Dept of Ecology
  - Maintained and distributed by Washington Dept of Ecology
- Related Models
  - QUAL2E – Brown and Barnwell 1987
  - QUAL2K – distributed by EPA

QUAL2Kw Fundamentals

- **Receiving water model** – simulates flow and kinetics of advective systems
- **One dimensional** - channel is uniformly mixed vertically and laterally
- **Steady state flow** - non-uniform, steady flow is simulated
- **Diel meteorology & water quality** – Meteorology and water quality constituents can be varied over 24-hours
- **Flow and water quality inputs** - Point and non-point loads and abstractions can be simulated
- **Water quality kinetics** – temperature, pH, sediment, pathogens, nutrients, organic matter, algal growth and dissolved oxygen

Slide 3

QUAL2Kw Limitations

Does <u>not</u> simulate:

- **Watershed processes**
- **Non-uniform mixing –** 2D or 3D transport
- **Unsteady flow**
  Beta version with non-steady, non-uniform flow using kinematic wave flow routing now available
- **Scour and deposition**
- **Adsorption/desorption to sediment**
- **Organisms –** zooplankton, macroinvertebrates, fish
- **Reservoirs**

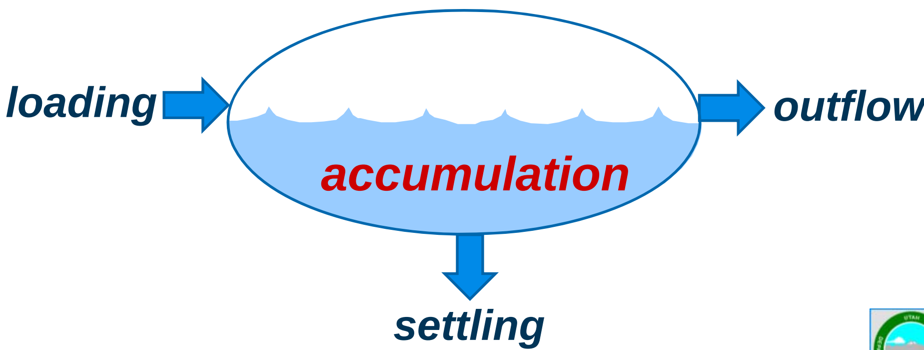
Slide 4

Mechanistic Model

Conservation of Mass

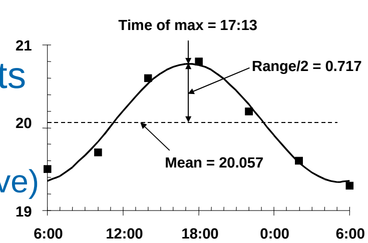
For a finite volume over a unit time period:

Accumulation = Loading – Outflow +/- Reaction - Settling

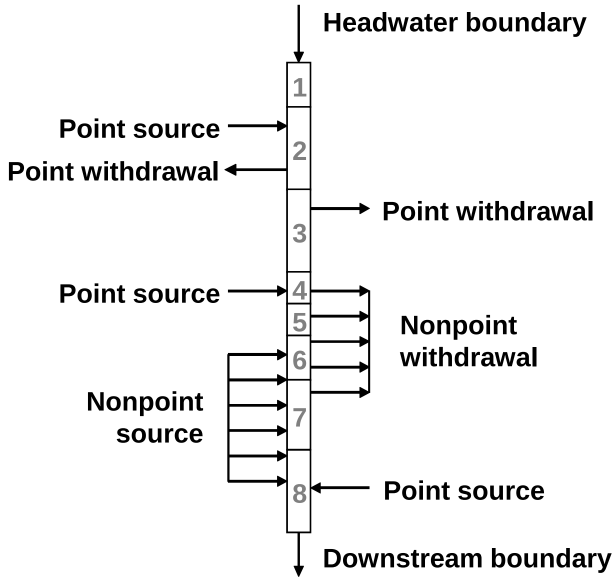


Model Inputs

- Dry weather – no precipitation
- Headwaters (hourly)
- Point Sources (sine wave)
  - Tributaries
  - Wastewater treatment plants
  - Industrial discharges
- Point Abstractions (sine wave)
  - Canals/diversions
- Diffuse Sources (sine wave)
  - Groundwater



Model Segmentation



Hydraulics

Flow (*Q*) → depth (*H*) and velocity (*U*)

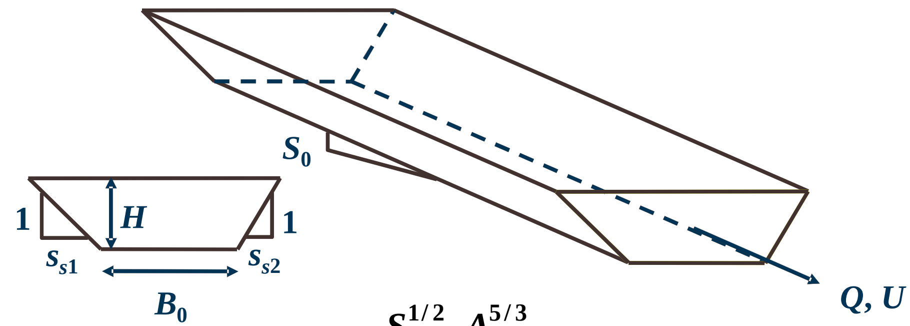
Given Q: solve for H and U

- Rating Curve
- Mannings Equation for Trapezoidal Channel
- Weir Equation

Reach worksheet

Mannings Equation

Trapezoidal Channel

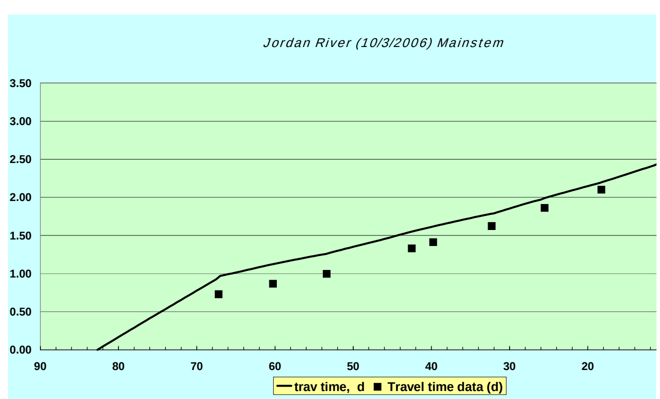


$$Q = \frac{S_0^{1/2}}{n} \frac{A_c^{5/3}}{P^{2/3}}$$

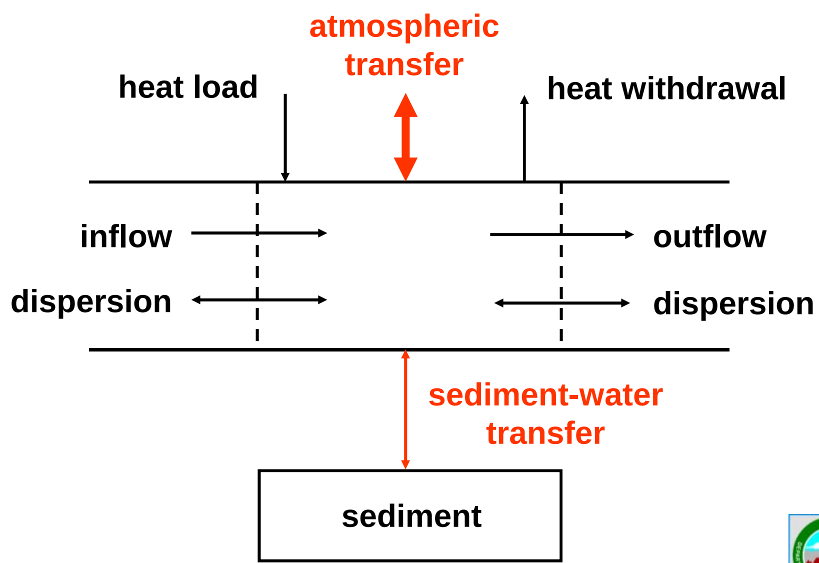
Solves for H and U, given Q, S_0, B_0, s_s

Travel Time

$$\tau_k = \frac{U_k}{Q_k} \qquad t_{t,i} = \sum_{k=1}^{i} \tau_k$$

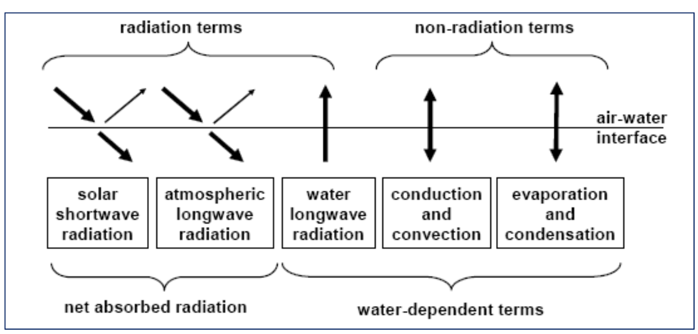


Heat Balance



Slide 11

Water Surface Heat Balance



Slide 12

Meteorological Data

Air Temperature

Dew Point Temperature

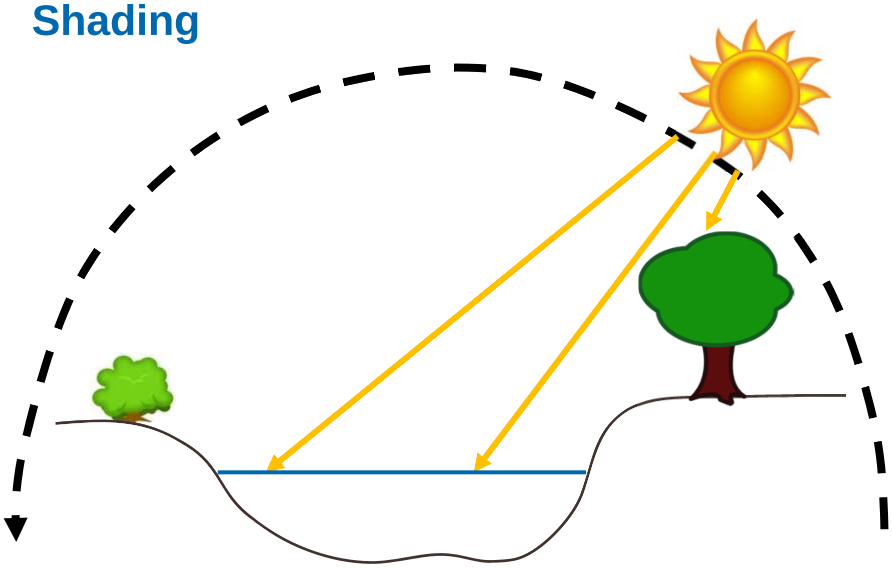
$$J = J_{sn} + \sigma (T_{air} + 273.15)^4 \left(A + 0.031\sqrt{e_{air}}\right)(1 - R_L) - \varepsilon\sigma (T_s + 273.15)^4 - c_1 f(U_w)(T_s - T_{air}) - f(U_w)(e_s - e_{air})$$

Solar Radiation (Cloud Cover)

Wind Speed

Slide 13

Shading



Slide 14

Shading Estimation Tools

TTools for ArcGIS

- Oregon DEQ
  - http://www.deq.state.or.us/WQ/TMDLs/tools.htm

Shade.xls Excel Spreadsheet

- Washington DOE
  - http://www.ecy.wa.gov/programs/eap/models.html

Water Quality Constituents

Table 5 Model state variables

Variable	Symbol	Units*
Conductivity	s	μmhos
Inorganic suspended solids	m_i	mgD/L
Dissolved oxygen	o	mgO_2/L
Slowly reacting CBOD	c_s	mgO_2/L
Fast reacting CBOD	c_f	mgO_2/L
Organic nitrogen	n_o	μgN/L
Ammonia nitrogen	n_a	μgN/L
Nitrate nitrogen	n_n	μgN/L
Organic phosphorus	p_o	μgP/L
Inorganic phosphorus	p_i	μgP/L
Phytoplankton	a_p	μgA/L
Detritus	m_o	mgD/L
Pathogen	X	cfu/100 mL
Alkalinity	Alk	$mgCaCO_3/L$
Total inorganic carbon	c_T	mole/L
Bottom algae biomass	a_b	mgA/m^2
Bottom algae nitrogen	IN_b	mgN/m^2
Bottom algae phosphorus	IP_b	mgP/m^2

* mg/L ≡ g/m^3

Inorganic Suspended Solids

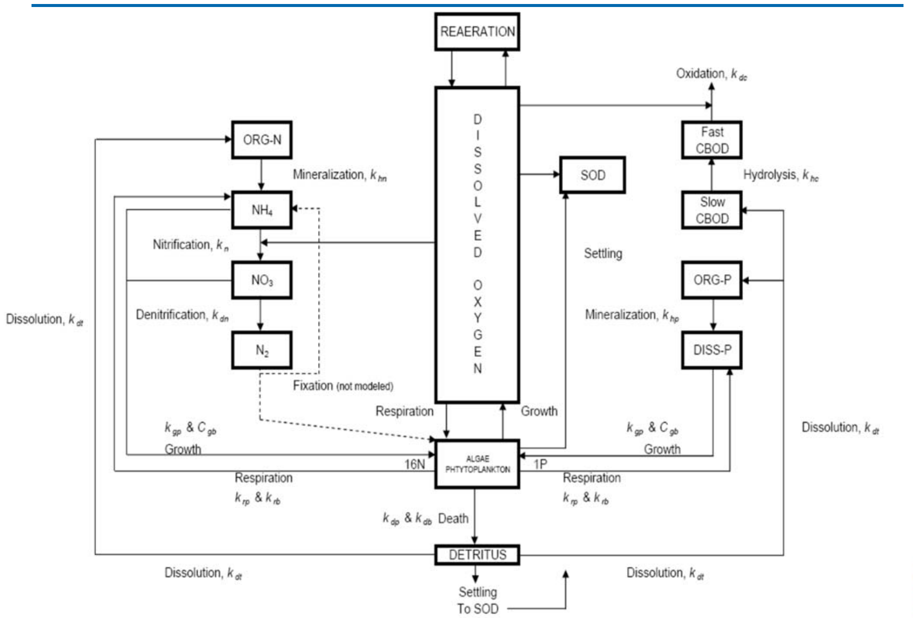
$$\text{ISS Settling} = \frac{v_i}{H} * \text{ISS}$$

v_i: ISS settling velocity

H: water depth

Slide 17

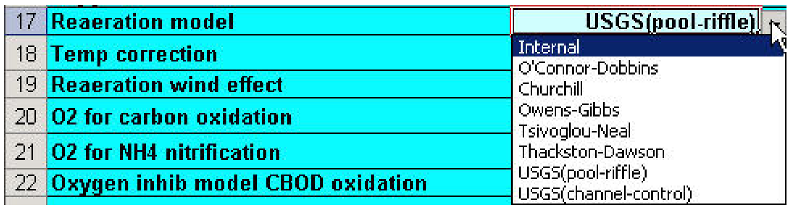
Dissolved Oxygen



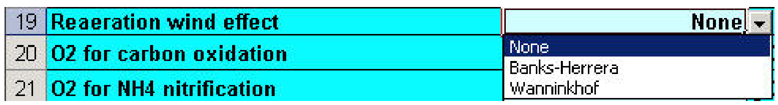
Slide 18

Reaeration

Effect of Water Velocity (8 formulas)



Effect of Wind (2 formulas)



Slide 19

Soluble Carbonaceous BOD

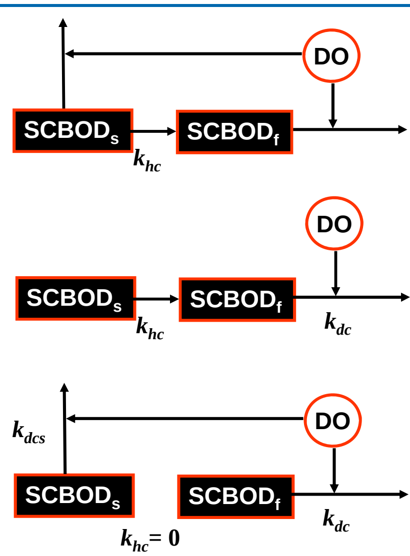
2 Types of SCBOD:

$SCBOD_s$: slow reacting

$SCBOD_f$: fast reacting

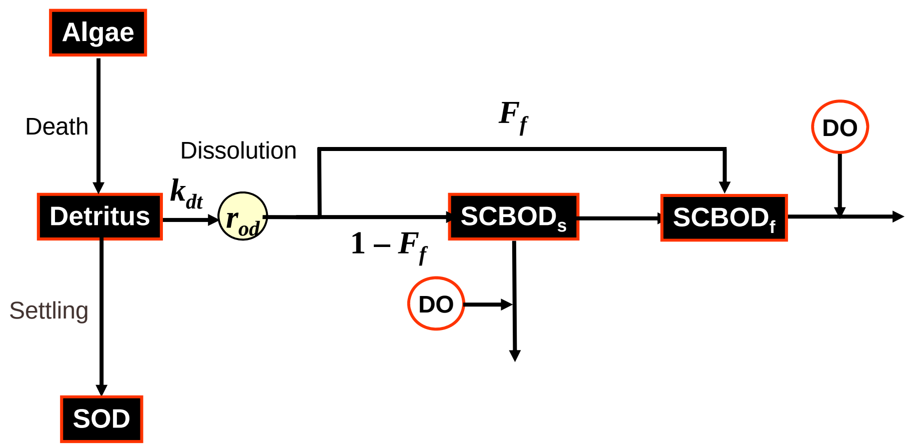
Series:
$k_{dcs} = 0$

Parallel:
$k_{hc} = 0$

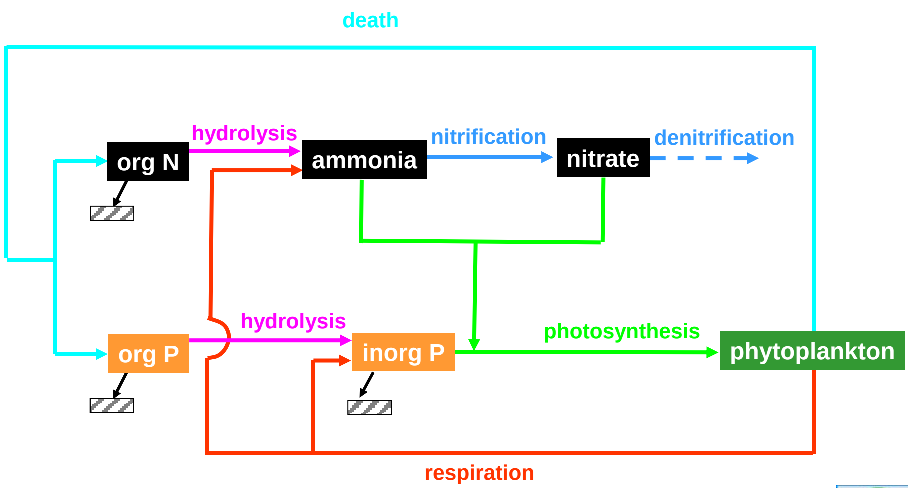


Slide 20

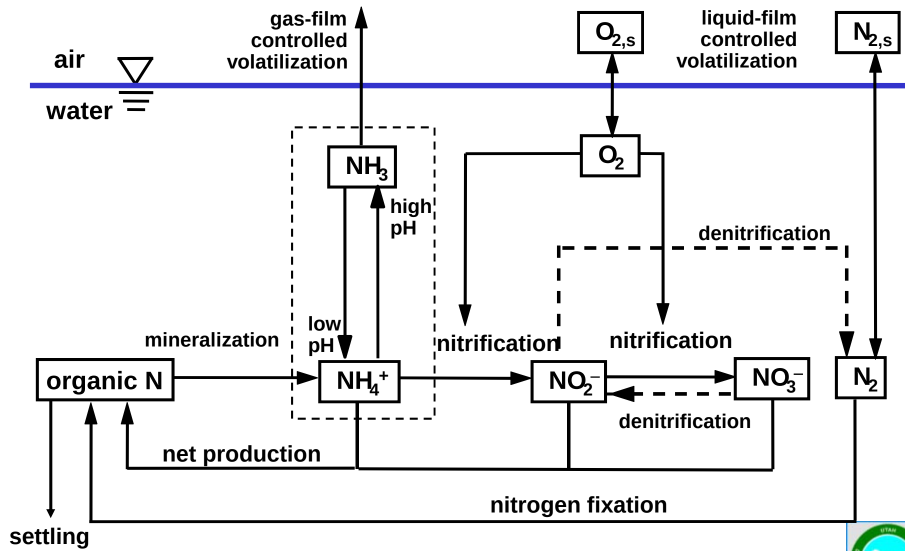
Detritus (Particulate Organic Matter)



Nutrient Cycle

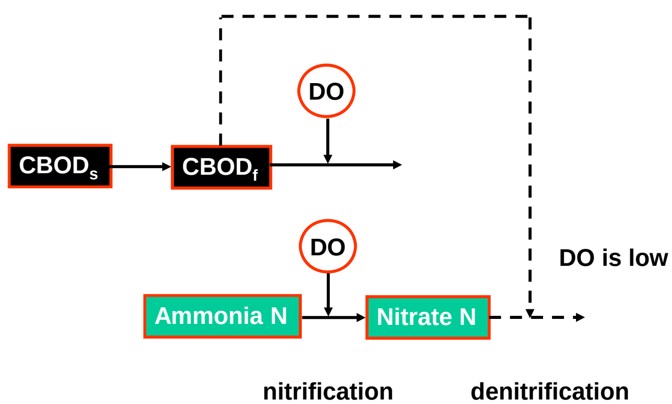


Nitrogen



Slide 23

Nitrification (NBOD)



$$NH_4^+ + 2O_2 \rightarrow 2H^+ + H_2O + NO_3^-$$

$$5CH_2O + 4NO_3^- + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O$$

Slide 24

Algal Growth

- Phytoplankton
  - Free floating algae
- Bottom Algae
  - Fixed to stream substrate
  - Periphyton or benthic algae
  - Filamentous algae
  - Macrophytes

Slide 25

Floating vs. Bottom Plants

	Floating	Bottom
Transport	Yes	No
Types	Diatoms Greens Blue Greens	Periphyton Filamentous Algae Rooted Macrophytes
Units	mgA/m^3	gA/m^2
Light	Ave. Water Column	Bottom Light
Predation	Zooplankton	Insect Larvae, Snails
Substrate	None	Rock vs. Mud

Slide 26

Phytoplankton Kinetics

inorganic nutrients ↑ respiration

detritus organic nutrients ↑ death

$$\frac{da}{dt} = \text{transport} + k_g(T, N, I)\, a - k_r(T)\, a - k_d(T)\, a - (v_s/H)\, a$$

growth

$$k_g(T, N, I) = k_{g,T}\, \phi_N\, \phi_L$$

temperature nutrients light

settling ↓ sediments

Slide 27

Phytoplankton Stoichiometry

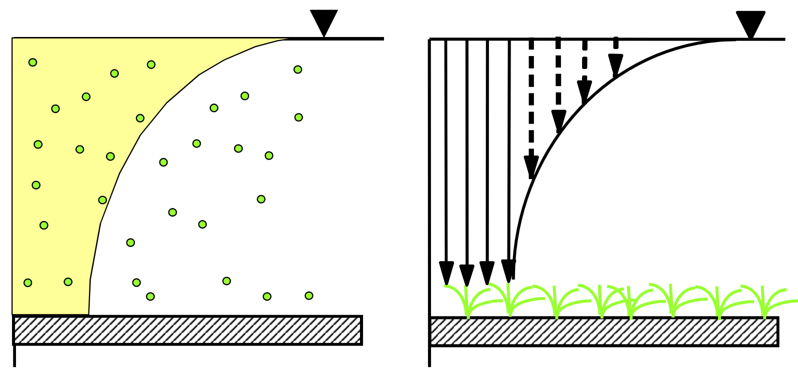
The "Redfield Ratio"

D	C	N	P	A
100%	40%	7.2%	1%	0.5-2.0%

	A	B	C	D
1	***QUAL2K***			
2	***Stream Water Quality Model***			
3	***Streeter River (8/15/2002)***			
4	***Water Column Rates***			
5				
6				
7	*Parameter*	*Value*	*Units*	*Symbol*
8	*Stoichiometry:*			
9	Carbon	40	mgC	
10	Nitrogen	7.2	mgN	
11	Phosphorus	1	mgP	
12	Dry weight	100	mgD	
13	Chlorophyll	1	mgA	

Slide 28

Light Estimation



(*a*) floating plants

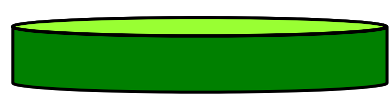
(*b*) bottom algae

Periphyton Growth Rates

Zero-order:

$$\frac{da_b}{dt} = C_{gb}(T)\phi_{Nb}\phi_{Lb}$$

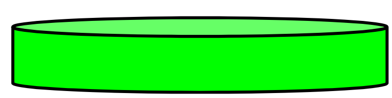
$C_{gb}(T)$ = mgA/m²/d



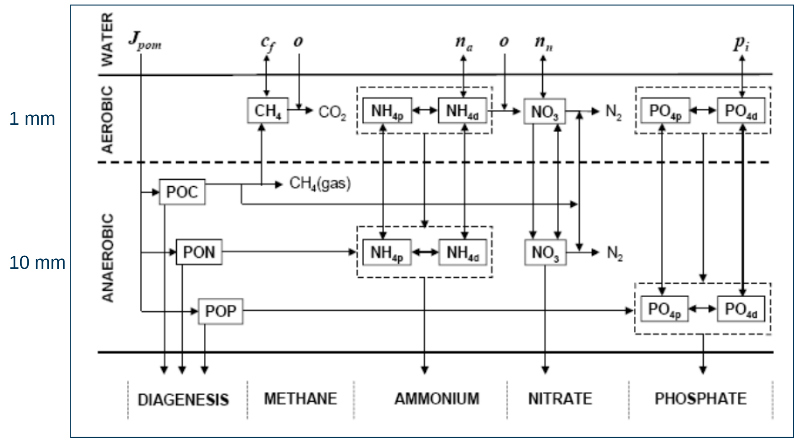
First-order:

$$\frac{da_b}{dt} = k_{gb}(T)\phi_{Nb}\phi_{Lb}\, a_b$$

$k_{gb}(T)a_b$ = mgA/m²/d



Sediment Oxygen Demand



References

QUAL2K2w User Manual (Version 5.1), Greg Pelletier and Steve Chapra, 2008.

QUAL2K2w Theory and Documentation (Version 5.1), Greg Pelletier and Steve Chapra, 2008.

Hydrodynamics and Water Quality: Modeling Rivers, Lakes and Estuaries, Zheng-Gang Ji, John Wiley and Sons, 2008.

Surface Water Quality Modeling, Steven Chapra, WCB McGraw Hill, 1997.

Principles of Surface Water Quality Modeling and Control, R.V. Thomann and J.A. Mueller, Harper and Row, 1987.

Sediment Flux Modeling, Dominic DiToro, John Wiley and Sons, 2001.

The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and Users Manual, L.C. Brown and T.O. Barnwell, EPA/600/3-87-007, 1987.