Eutrophication in Flowing Waters

April 1, 2020

1. Reflection: What specific sources can contribute to eutrophication in a flowing water system? Can you point to a real-world example?

2. Stream Phytoplankton/Nutrient Interaction
3. Stream Phytoplankton Models
4. Modeling with QUAL2E
5. Fixed Plants in Streams

Flowing Waters

There are two main reasons why special modeling frameworks are necessary for flowing waters (e.g. streams and estuaries).

First: their physics are different (horizontal transport).

Second: shallower flowing water will be dominated by fixed plants (macrophytes, periphyton) rather than free-floating phytoplankton.

Stream Phytoplankton/Nutrient Interactions

Simple Phytoplankton/Nutrient Analysis

Stream eutrophication can be developed through simple analysis. First, determine whether nutrients will be limiting in the immediate vicinity of a sewage outfall.

Simple Phytoplankton/Nutrient Analysis

-Nutrient-limiting at vicinity of outfall (effluent-to-flow ratio ~2%)?

-Nutrient-limiting at outfall (5 times less than k_{sn}, k_{sp})?

Downstream, the nutrients may be limiting, thus Thomann and Mueller developed the following steady-state mass balance for a downstream stretch with constant hydrogeometric properties :

$$U\frac{da}{dx} = \frac{da}{dt^*} = \left[k_g(T, I) - k_d - \frac{v_a}{H}\right]a = k_{net}a$$

where t^* = travel time (d) and k_{net} = net gain of phytoplankton (d^{-1}).

Simple Phytoplankton/Nutrient Analysis

The growth rate does not depend on nutrients as in previous discussions. The following analysis will apply when $n \geq 0.1$ mgN L^{-1} and $p \geq 0.025$ mgP L^{-1}. Assuming constant plant stoichiometry, balances for nitrogen and phosphorus follow:

$$\frac{dn}{dt^*} = -a_{na} k_g(T, I) a$$

$$\frac{dp}{dt^*} = -a_{pa} k_g(T, I) a$$

Simple Phytoplankton/Nutrient Analysis

Using the boundary conditions of $a = a_0$, $n = n_0$, and $p = p_0$ at the mixing point we can solve these equations:

$$a = a_0 e^{k_{net} t^*}$$

$$n = n_0 + \frac{a_{na} k_g a_0}{k_{net}} \left(1 - e^{k_{net} t^*}\right)$$

$$p = p_0 + \frac{a_{pa} k_g a_0}{k_{net}} \left(1 - e^{k_{net} t^*}\right)$$

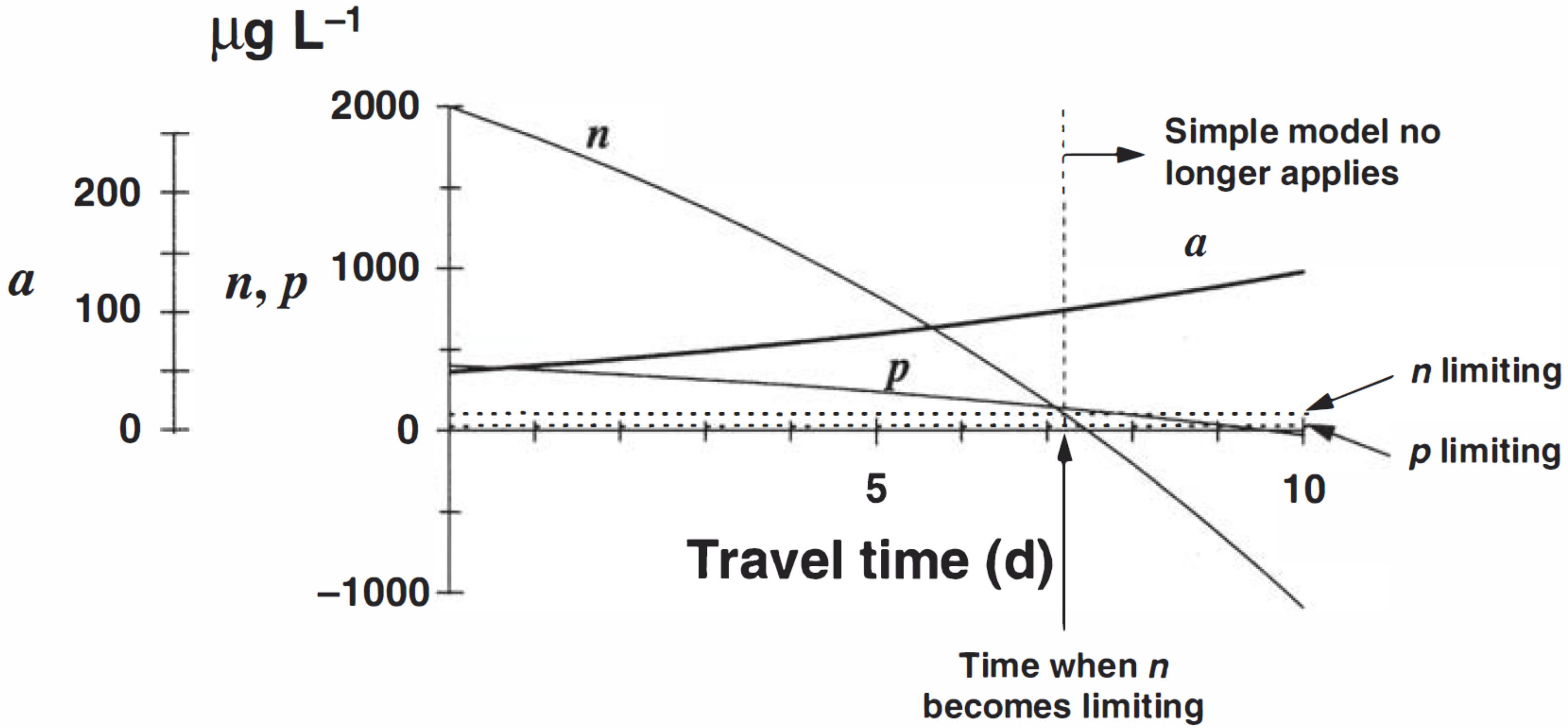


FIGURE 36.1
Plot of nutrient and phytoplankton concentrations downstream from a point source.

Simple Phytoplankton/Nutrient Analysis

Thomann and Mueller have shown that the previous equations can be used to determine the critical travel times exactly,

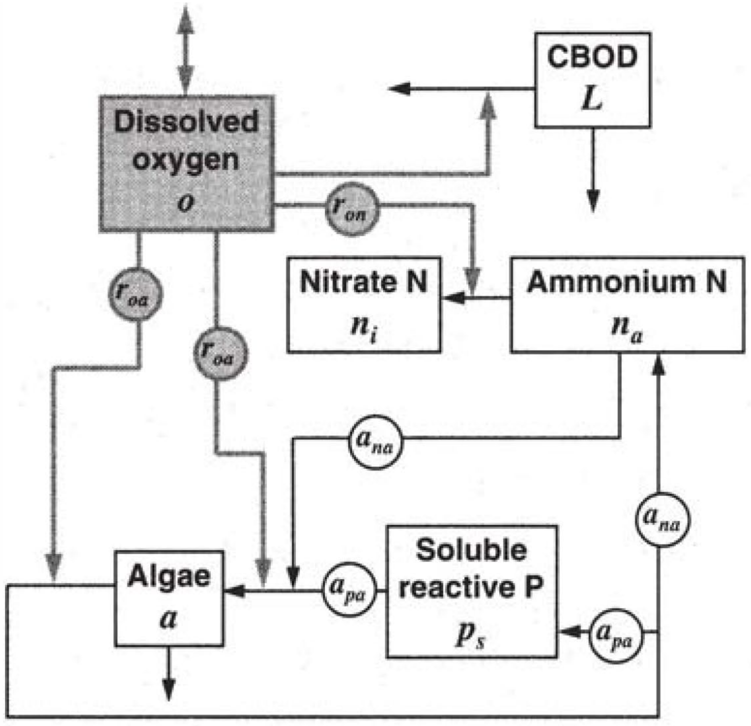
$$t_n^* = \frac{1}{k_{net}} \ln\left(\frac{n_0' + n_0 - 100}{n_0'}\right) \quad where\ n_0' = \frac{a_{na} k_g a_0}{k_{net}}$$

$$t_p^* = \frac{1}{k_{net}} \ln\left(\frac{p_0' + p_0 - 25}{p_0'}\right) \quad where\ p_0' = \frac{a_{pa} k_g a_0}{k_{net}}$$

where t_n* and t_p* = travel times (d) for nitrogen and phosphorus limitation, respectively.

Stream and Estuary Phytoplankton Models

Phytoplankton kinetics can be integrated into a general model for a one-dimensional stream or estuary:



$$\frac{\partial a}{\partial t} = E\frac{\partial^2 a}{\partial x^2} - U\frac{\partial a}{\partial x} + (k_g - k_{ra})a - \frac{v_a}{H}a$$

FIGURE 36.2
A simple oxygen balance for a stream including phytoplankton growth.

Stream and Estuary Phytoplankton Models

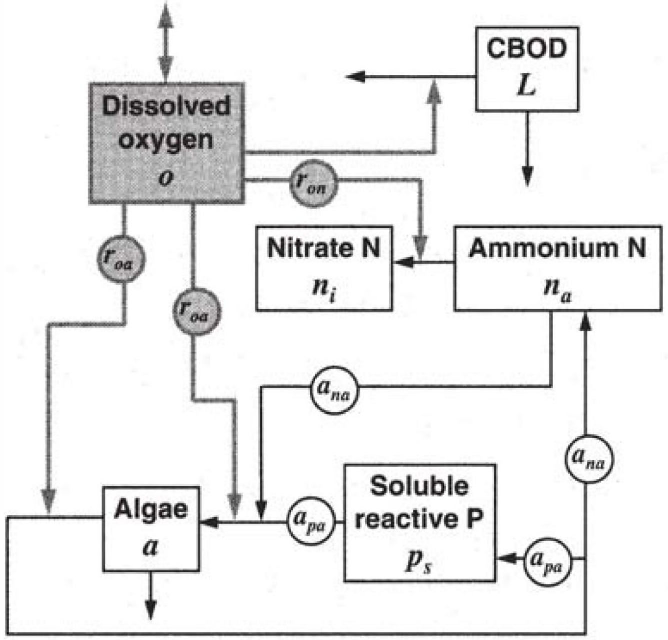


FIGURE 36.2
A simple oxygen balance for a stream including phytoplankton growth.

$$\frac{\partial L}{\partial t} = E\frac{\partial^2 L}{\partial x^2} - U\frac{\partial L}{\partial x} - k_d L - \frac{v_s}{H}L$$

$$\frac{\partial p}{\partial t} = E\frac{\partial^2 p}{\partial x^2} - U\frac{\partial p}{\partial x} - a_{pa}(k_g - k_{ra})a$$

$$\frac{\partial n_a}{\partial t} = E\frac{\partial^2 n_a}{\partial x^2} - U\frac{\partial n_a}{\partial x} - a_{na}(k_g - k_{ra})a - k_n n_a$$

$$\frac{\partial n_i}{\partial t} = E\frac{\partial^2 n_i}{\partial x^2} - U\frac{\partial n_i}{\partial x} + k_n n_a$$

$$\frac{\partial o}{\partial t} = E\frac{\partial^2 o}{\partial x^2} - U\frac{\partial o}{\partial x} - k_d L - r_{on}k_n n_a + r_{oa}(k_g - k_{ra})a + k_a(o_s - o)$$

EXAMPLE 36.1. NUMERICAL STREAM PHYTOPLANKTON SIMULATION. Duplicate the calculations in Fig. 36.1, but use nutrient limitation explicitly.

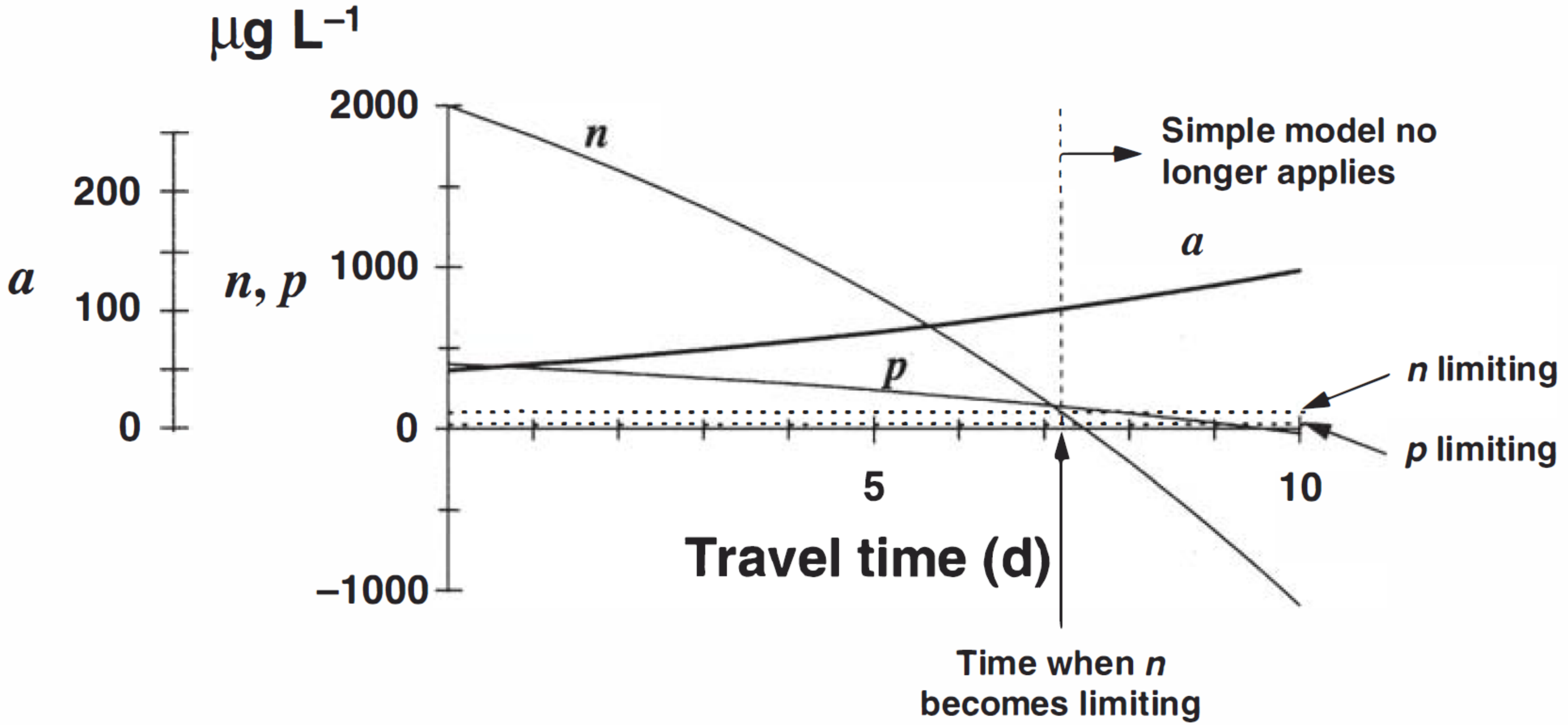


FIGURE 36.1
Plot of nutrient and phytoplankton concentrations downstream from a point source.

Modeling Eutrophication With QUAL2E

This section shows how EPA's QUAL2E model can be used to simulate temperature and nutrient/algae dynamics in flowing water.

Temperature and QUAL2E

The general mass transport equation for QUAL2E is:

$$\frac{\partial c}{\partial t} = \frac{\partial\left(A_x E \frac{\partial c}{\partial x}\right)}{A_x \partial x} dx - \frac{\partial (A_x U c)}{A_x \partial x} dx + \frac{dc}{dt} + \frac{s}{V}$$

Similarly the heat balance is:

$$\frac{\partial T}{\partial t} = \frac{\partial\left(A_x E \frac{\partial T}{\partial x}\right)}{A_x \partial x} dx - \frac{\partial (A_x U T)}{A_x \partial x} dx + \frac{s}{\rho C V}$$

we have omitted the source term dT/dt, meaning that internal heat generation or loss is negligible.

Temperature and QUAL2E

The external sources and sinks of heat are usually purely dependent on transfer across the air-water interface:

$$s = H_{sn} + H_{an} - (H_{br} + H_c + H_e)$$

where H_{sn} = net solar shortwave radiation

H_{an} = net atmospheric longwave radiation

H_{br} = longwave back radiation from water

H_c = conduction

H_e = evaporation

This equation can be substitute into the previous to yield the final heat balance. QUAL2E with several additional modification then can calculate the budget.

Temperature and QUAL2E

Temperature simulation shows a stead rise due to meteorology. A drop along the distance is induced due to tributary flow.

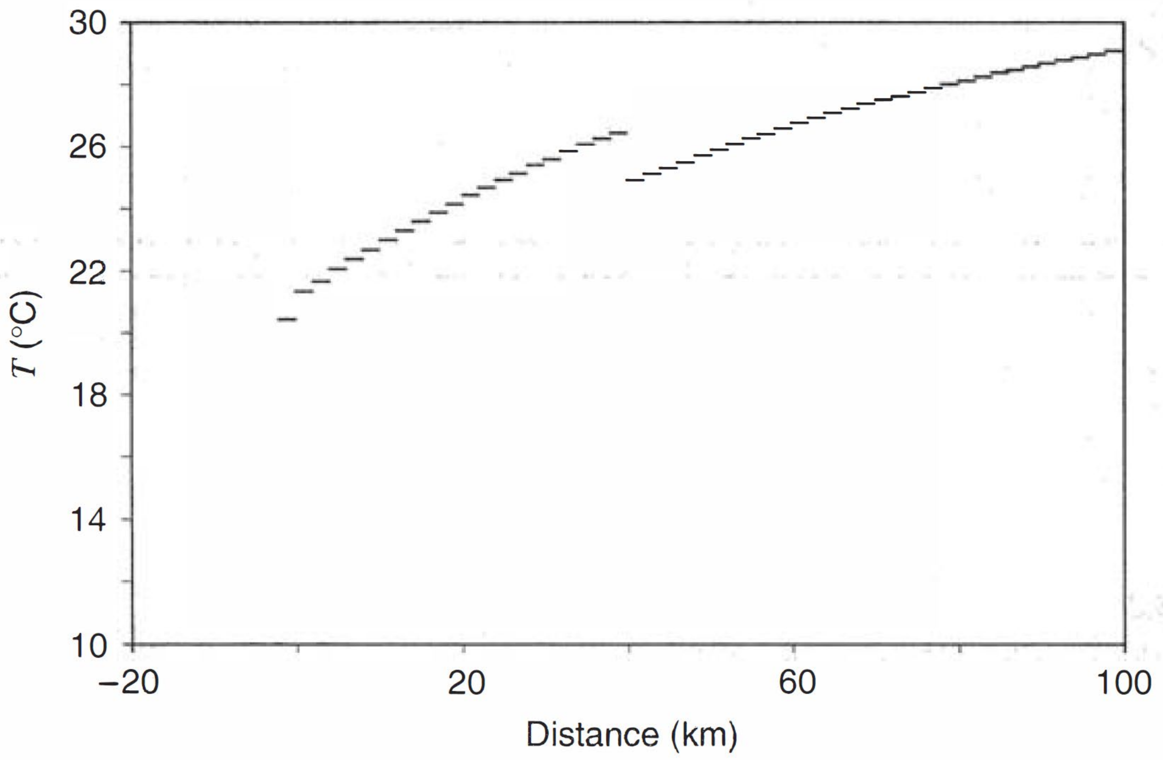


FIGURE 36.4
QUAL2E output for temperature.

Temperature and QUAL2E

For the plot of oxygen we see that the temperature rise causes the oxygen saturation to decrease in the downstream direction.

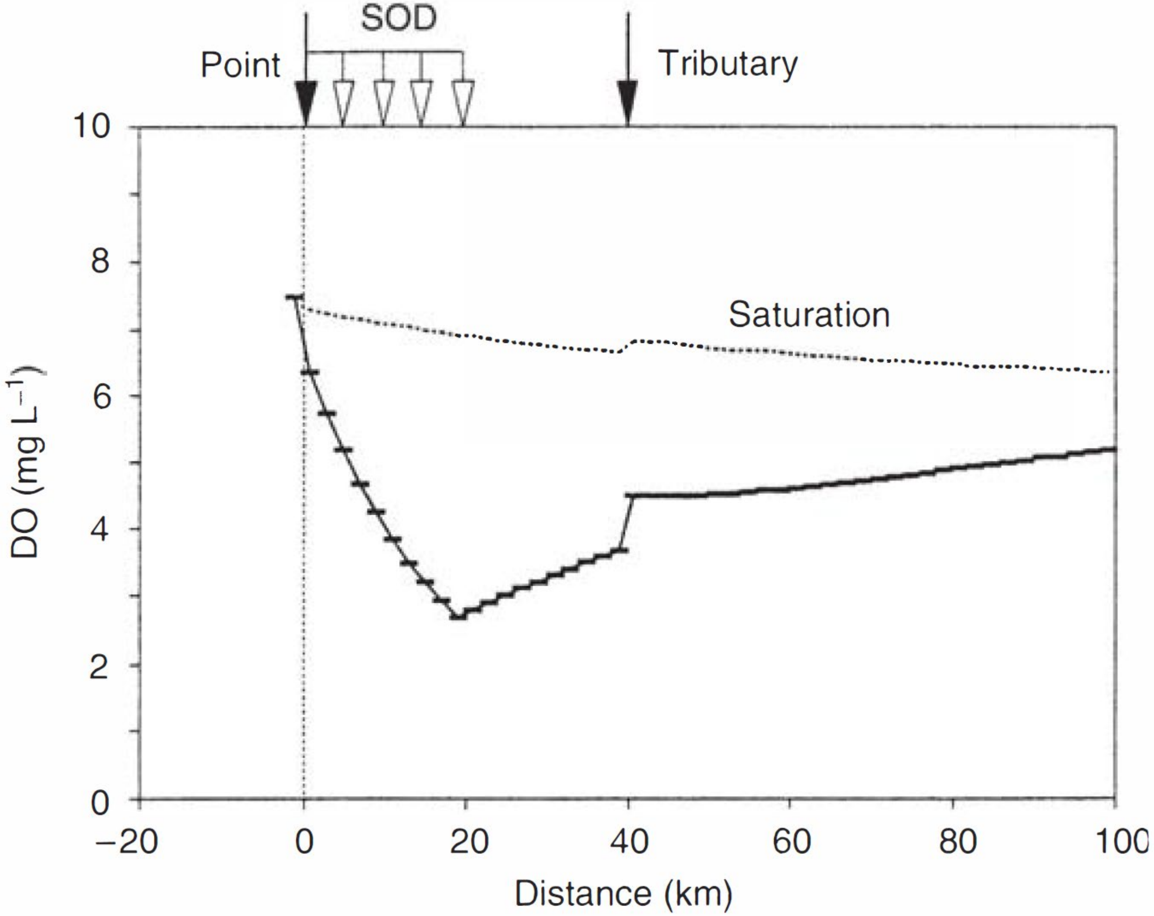


FIGURE 36.5
QUAL2E output for oxygen with variable temperature.

Starting from initial experimental conditions, how many tributaries would you incorporate into a project on flowing waters for parameter development?

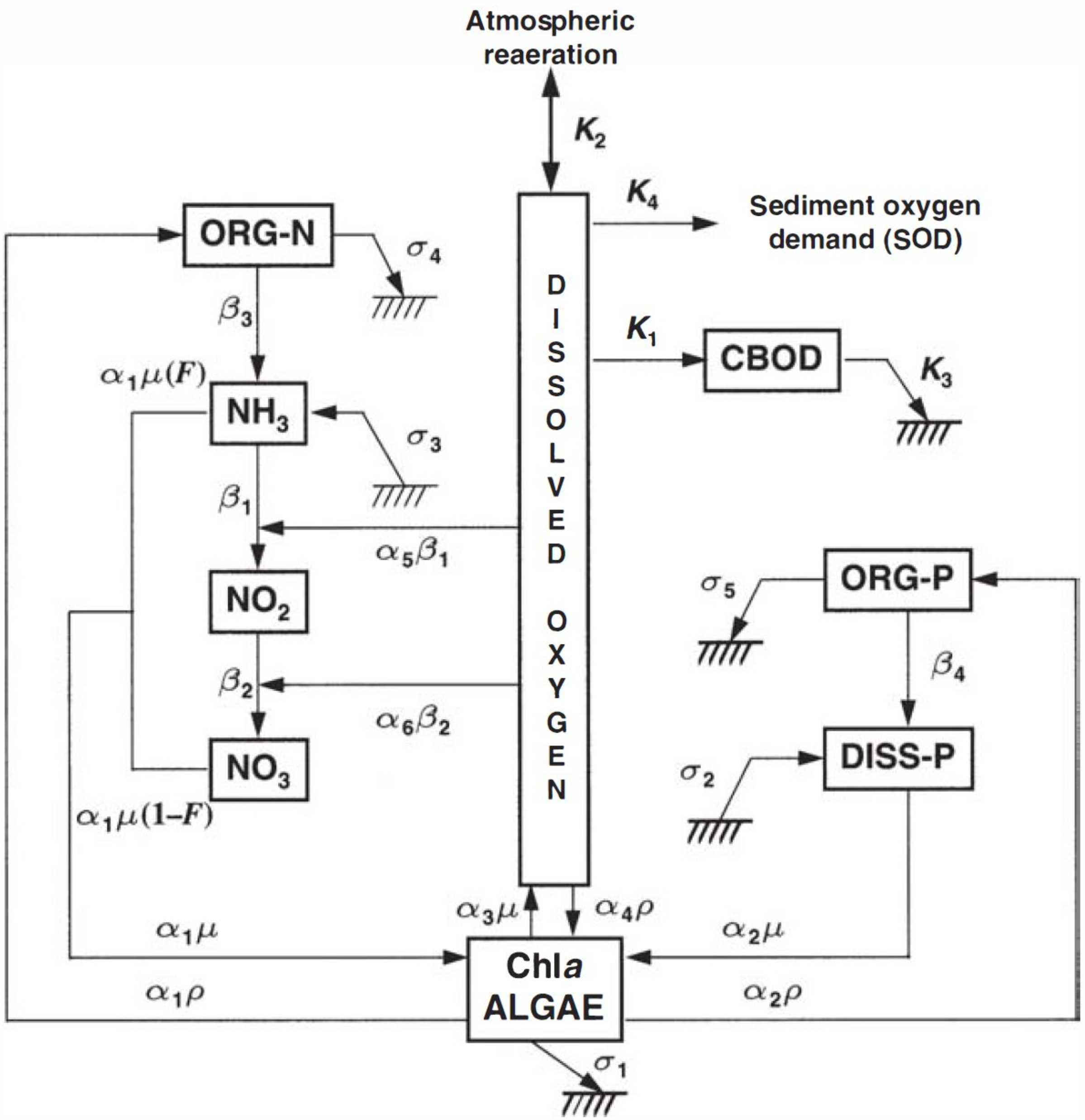


FIGURE 36.6
QUAL2E kinetics showing nutrient/plant interactions.

Nutrients and Algae in QUAL2E

Now we turn to nutrients and plants. The diagrams shows the simulation of the nutrients (nitrogen and phosphorus) and calculates impact on plant biomass.

These have an impact on oxygen, first via nitrification process, second through production of plant growth (photosynthesis/respiration).

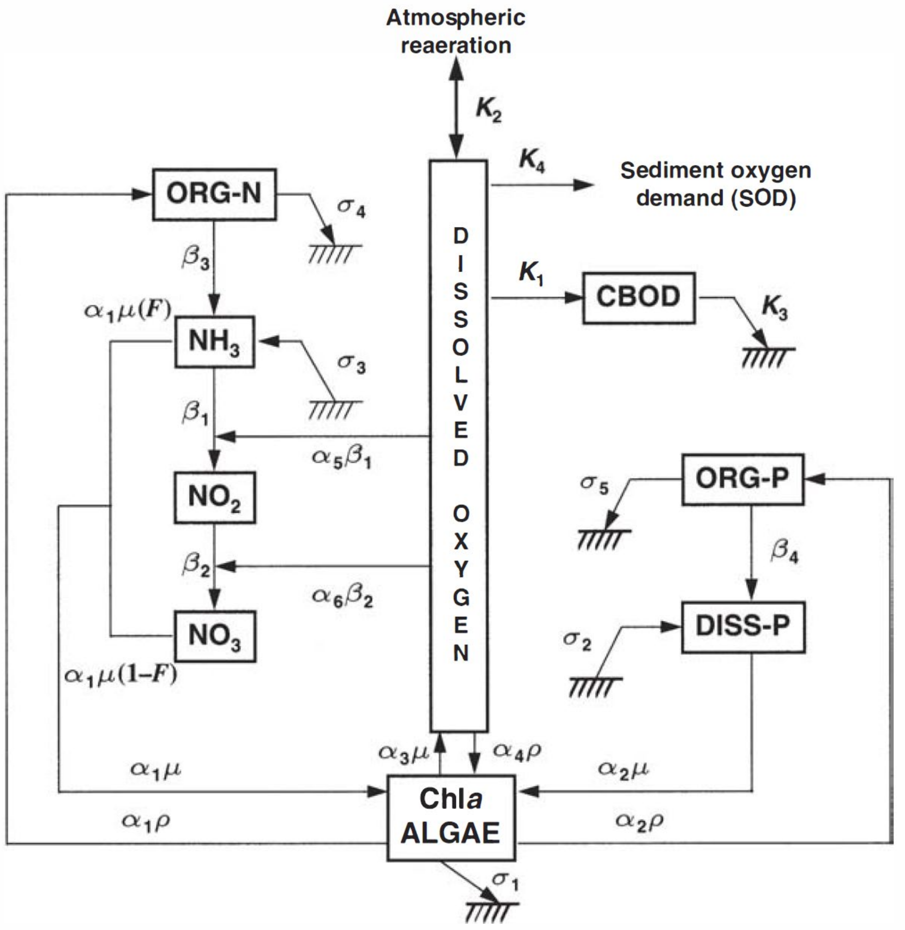


FIGURE 36.6
QUAL2E kinetics showing nutrient/plant interactions.

Nutrients and Algae in QUAL2E

QUAL2E kinetics are:

Algae (A):

$$\frac{dA}{dt} = \mu A - \rho A - \frac{\sigma_1}{H} A$$

Accumulation Growth Respiration Settling

Organic nitrogen (*N₄*):

$$\frac{dN_4}{dt} = \alpha_1 \rho A - \beta_3 N_4 - \sigma_4 N_4$$

Accumulation Respiration Hydrolysis Settling

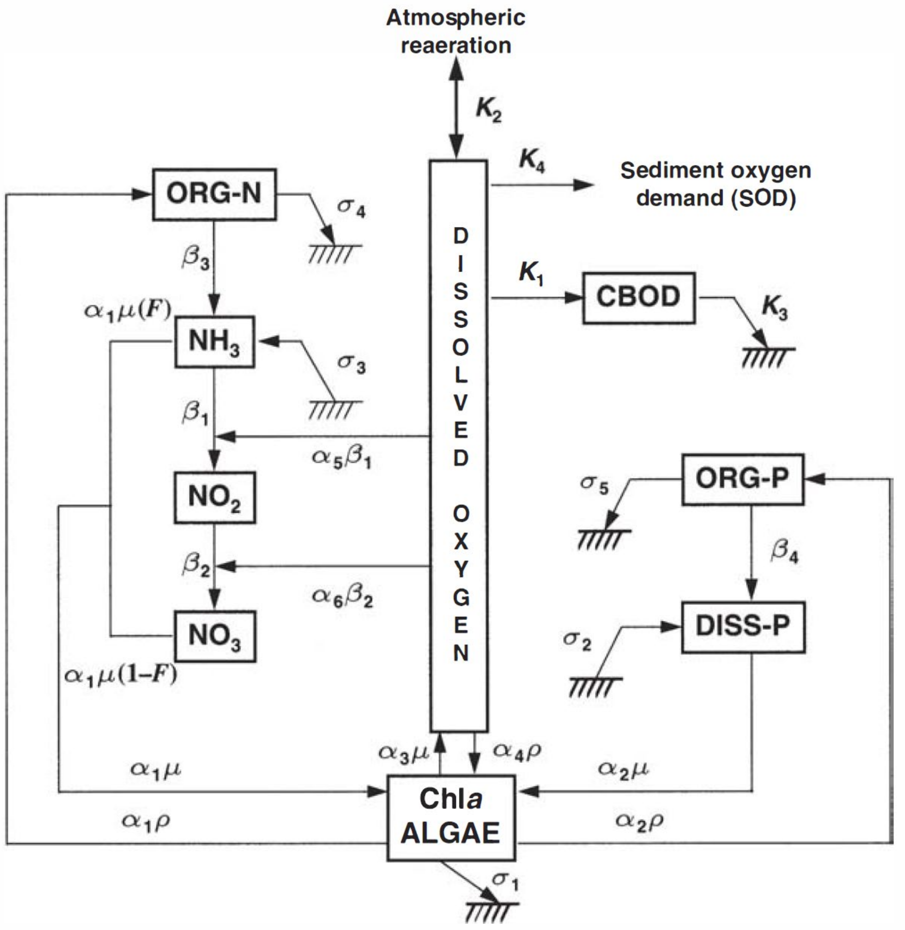


FIGURE 36.6
QUAL2E kinetics showing nutrient/plant interactions.

Nutrients and Algae in QUAL2E

Ammonia nitrogen (N_1):

$$\frac{dN_1}{dt} = \beta_3 N_4 - \beta_1 N_1 - \frac{\sigma_3}{H} - F_1 \alpha_1 \mu A$$

Accum Hydrolysis Nitrifictn Sediment Growth

Nitrite nitrogen (*N_2*):

$$\frac{dN_2}{dt} = \beta_1 N_1 - \beta_2 N_2$$

Accumulation Nitrification Nitrification

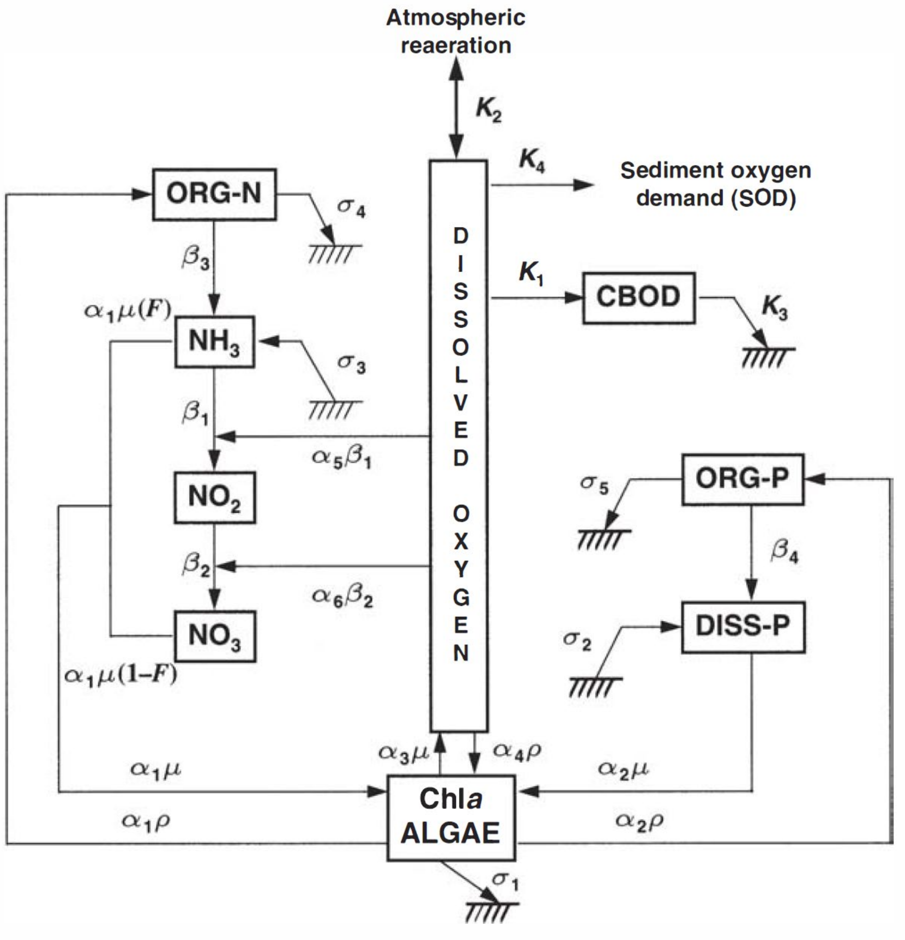


FIGURE 36.6
QUAL2E kinetics showing nutrient/plant interactions.

Nutrients and Algae in QUAL2E

Nitrate nitrogen (N_3):

$$\frac{dN_3}{dt} = \beta_2 N_2 - (1-F)\alpha_1 \mu A$$

Accum Nitrification Growth

Organic phosphorus (P_1):

$$\frac{dP_1}{dt} = \alpha_2 \rho A - \beta_4 P_1 - \sigma_5 P_1$$

Accumulation Respiration Decay Settling

Inorganic phosphorus (P_2):

$$\frac{dP_2}{dt} = \beta_4 P_1 + \frac{\sigma_2}{H} - \alpha_2 \mu A$$

Accumulation Decay Sediment Growth

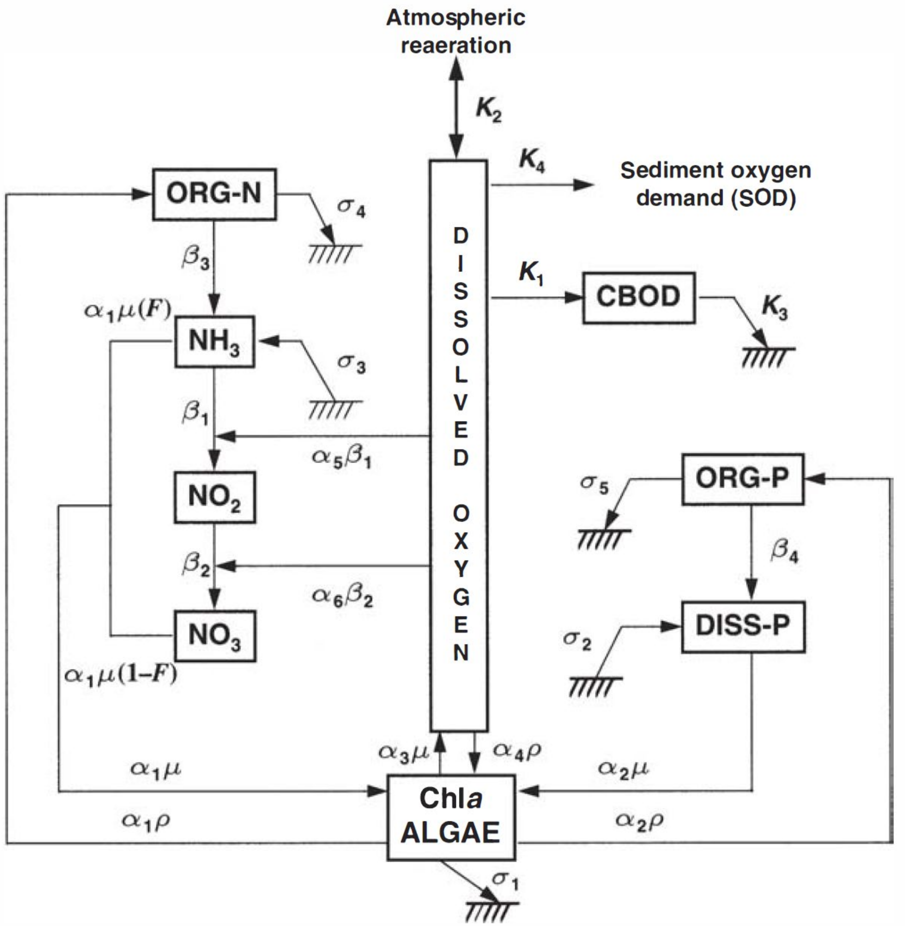


FIGURE 36.6
QUAL2E kinetics showing nutrient/plant interactions.

Nutrients and Algae in QUAL2E

On the oxygen end, when nitrification and plant growth are included, computations are:

Carbonaceous BOD (L):

$$\frac{dL}{dt} = -K_1 L - K_3 L$$

Accum Decay Settling

Dissolved Oxygen (*O*):

$$\frac{dO}{dt} = K_2(O_s - O) - K_1 L - \frac{K_4}{H}$$

Accumulation Reaeration Decomposition SOD

$$+(\alpha_3\mu - \alpha_4\rho)A - \alpha_5\beta_1 N_1 - \alpha_6\beta_2 N_2$$

Growth-Respiration Nitrification

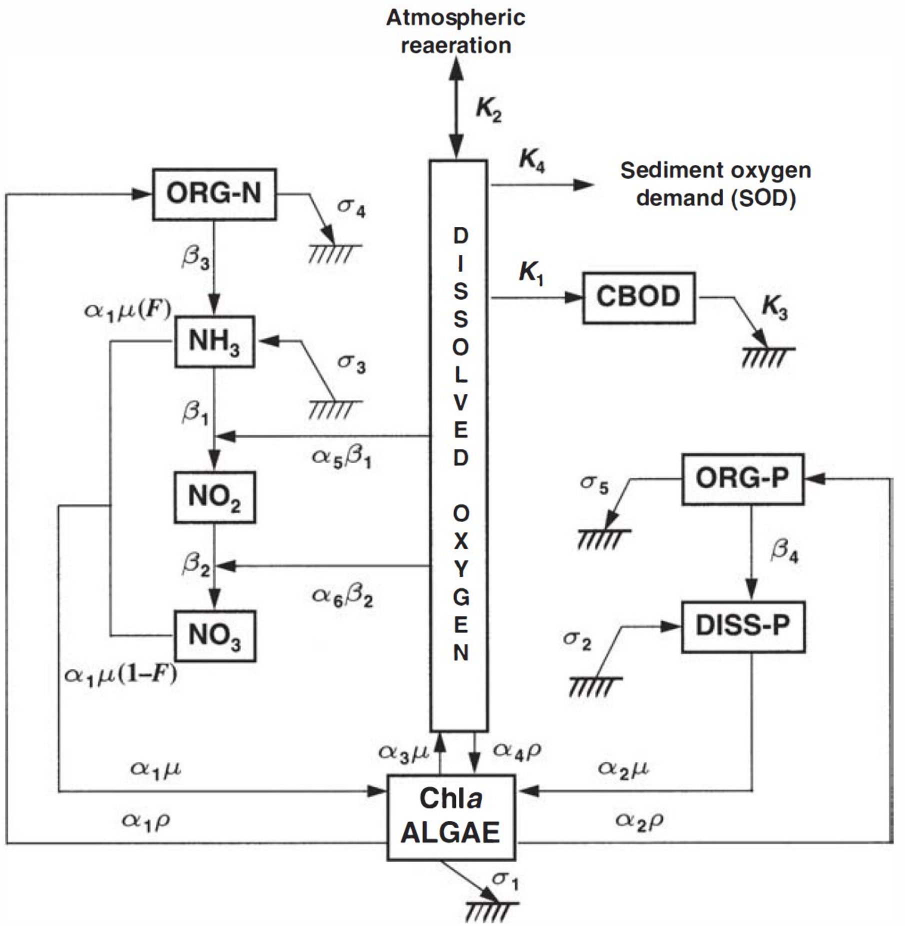


FIGURE 36.6
QUAL2E kinetics showing nutrient/plant interactions.

A plot of the QUAL2E output for the algae/nutrient run is shown here. The oxygen levels are less than previous runs because of the effect of nitrification.

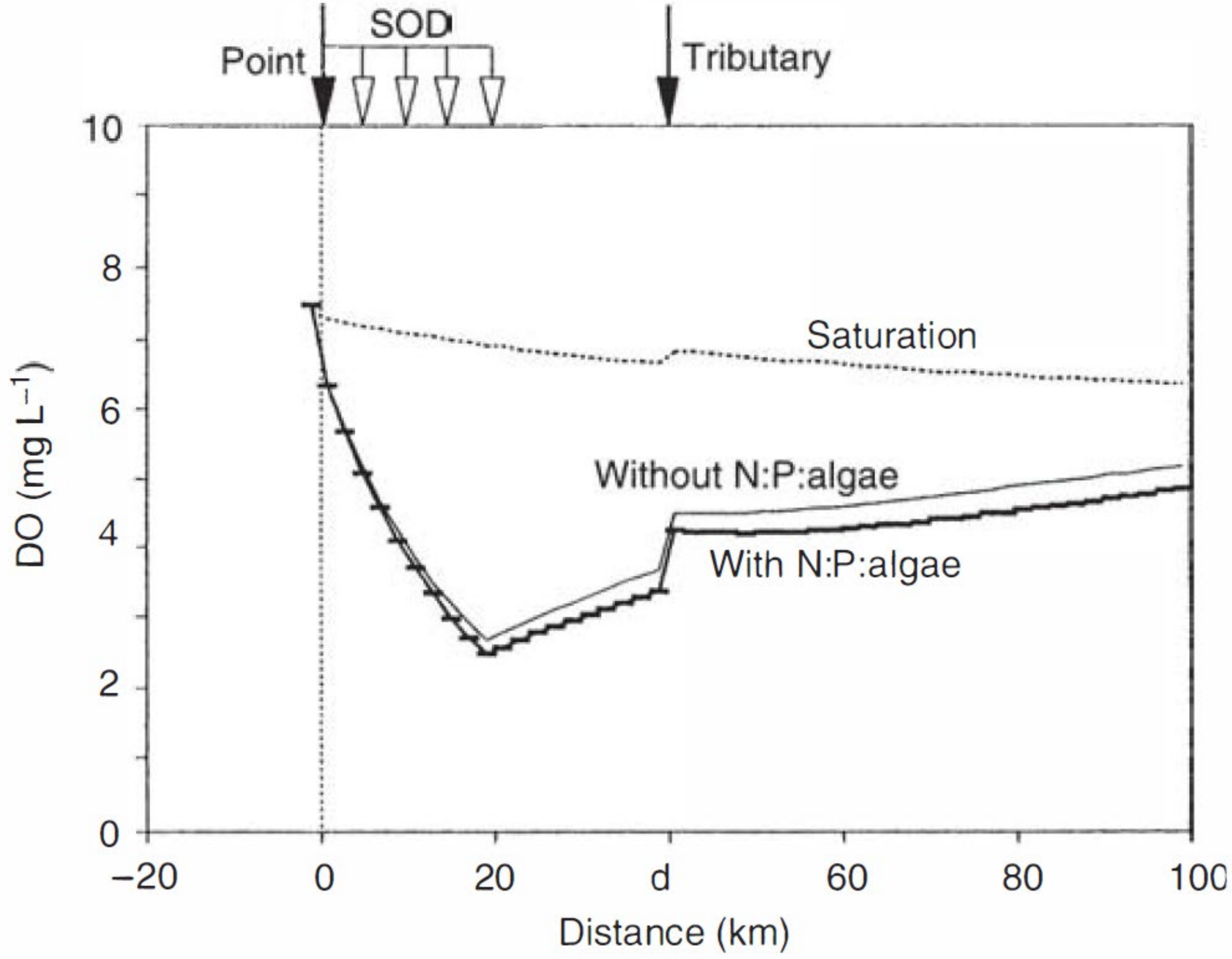
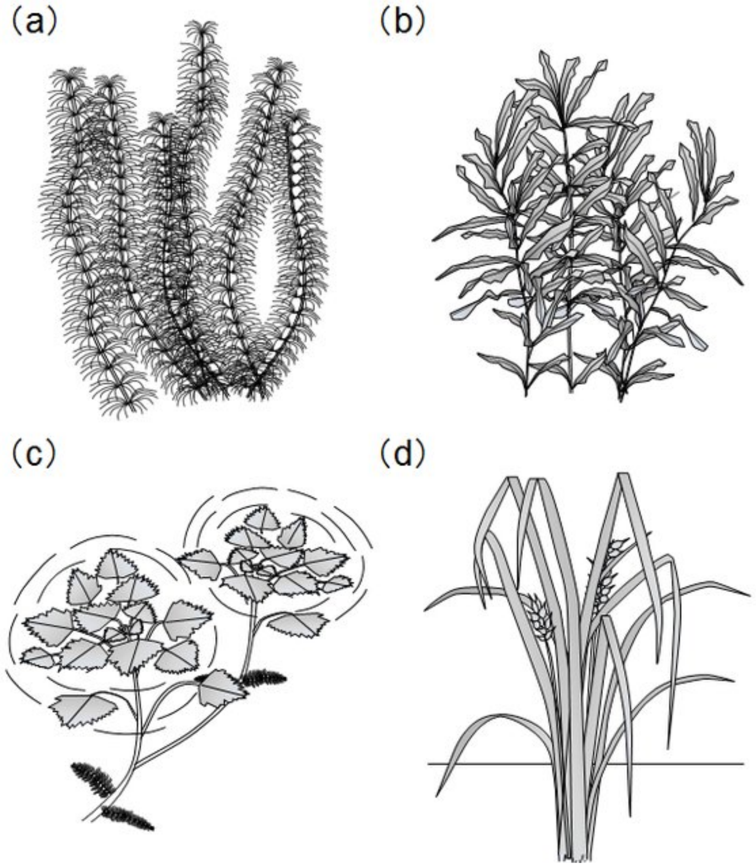


FIGURE 36.8
QUAL2E output for dissolved oxygen with and without algae and nutrients.

Fixed Plants in Streams

Now that we have incorporated phytoplankton dynamics in flowing waters, the next simulation is to incorporate fixed plants which have prevalence in shallow systems (ranging from large macrophytes to periphyton).

Periphyton on rocks (USGS)



Illustrations of the four macrophyte species: (a) Elodea nuttallii, (b) Potamogeton crispus, (c) Trapa japonica, and (d) Carex idzuroei. Sato et al. 2013 Limnology 15

Simple Attached Plant/Nutrient Analysis

For fixed plants, Thomann and Mueller (1987) used an approach assuming roots have fixed biomass and plants act as a zero-order sink for nutrients,

$$H\frac{dn}{dt^*} = -a_{na}k_g(T, I)a'$$

$$H\frac{dp}{dt^*} = -a_{pa}k_g(T, I)a'$$

where *a*’ = fixed biomass in areal units (μ gChl m^{-2}) and *H*= depth (m).

Simple Attached Plant/Nutrient Analysis

Using boundary conditions of $n = n_0$ and $p = p_0$ at the mixing point, the equations yield:

$$n = n_0 - \frac{a_{na} k_g a'}{H} t^*$$

$$p = p_0 - \frac{a_{pa} k_g a'}{H} t^*$$

Where critical travel time is

$$t_n^* = \frac{n_0 - 100}{a_{na} k_g a'} H$$

$$t_p^* = \frac{p_0 - 25}{a_{pa} k_g a'}$$

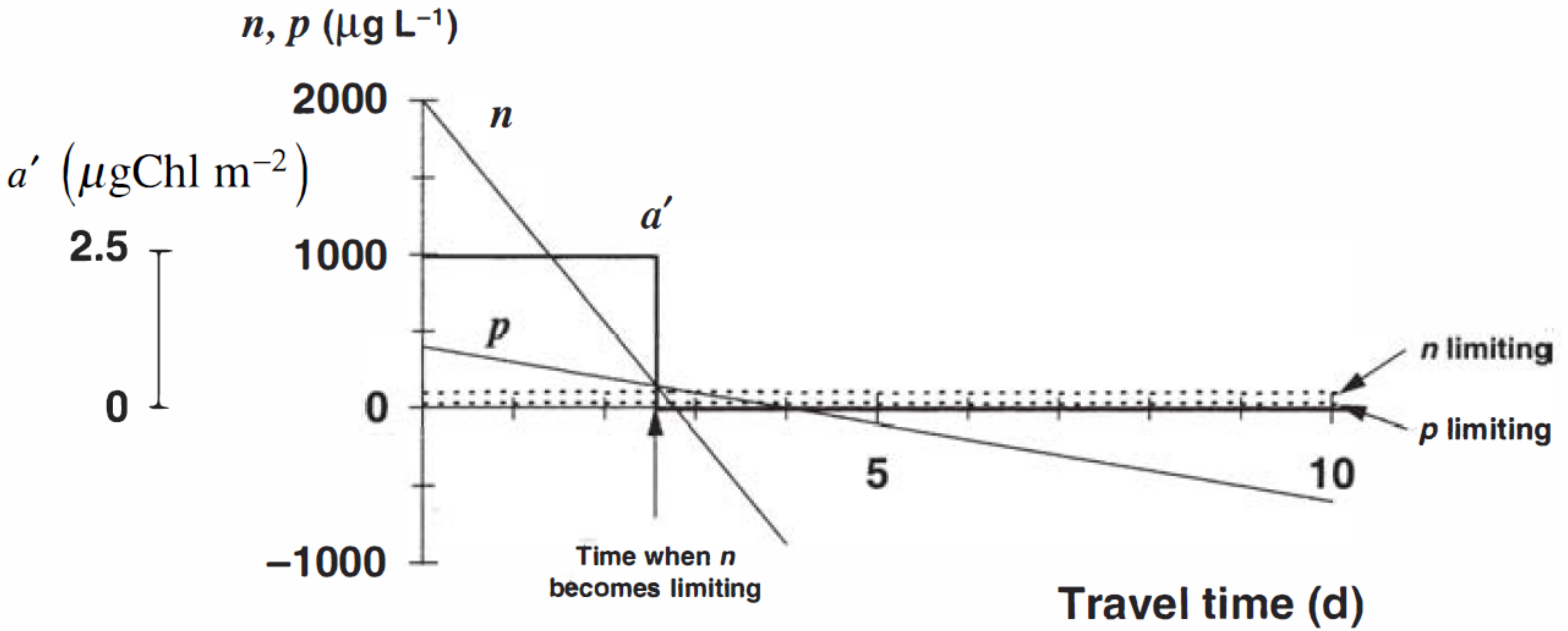


FIGURE 36.9
A simple nutrient balance for a stream including fixed-plant growth.

Modeling Attached Plants

Attached plants differ from floating plants:

- Fixed plants do not advect/settle

- Most fixed plants reside on or near the bottom. Light attenuation must be handled differently.

$$\phi_l = \frac{\int_0^{fT_p} F(I)\,dt}{T_p}$$

where *F(I)* is one of the growth models for light.

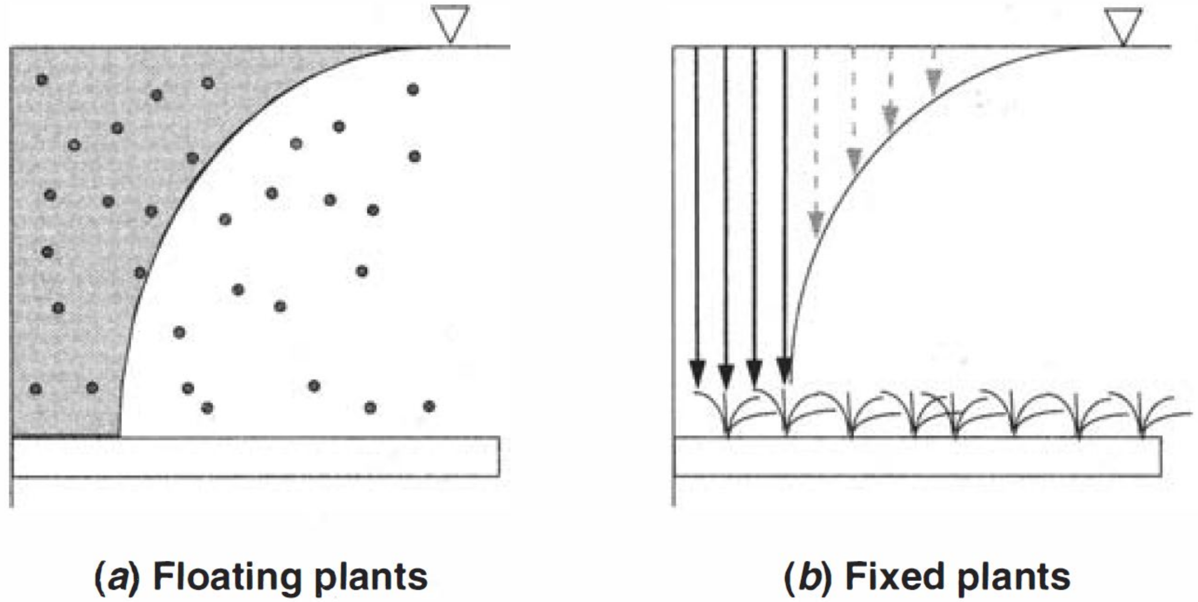
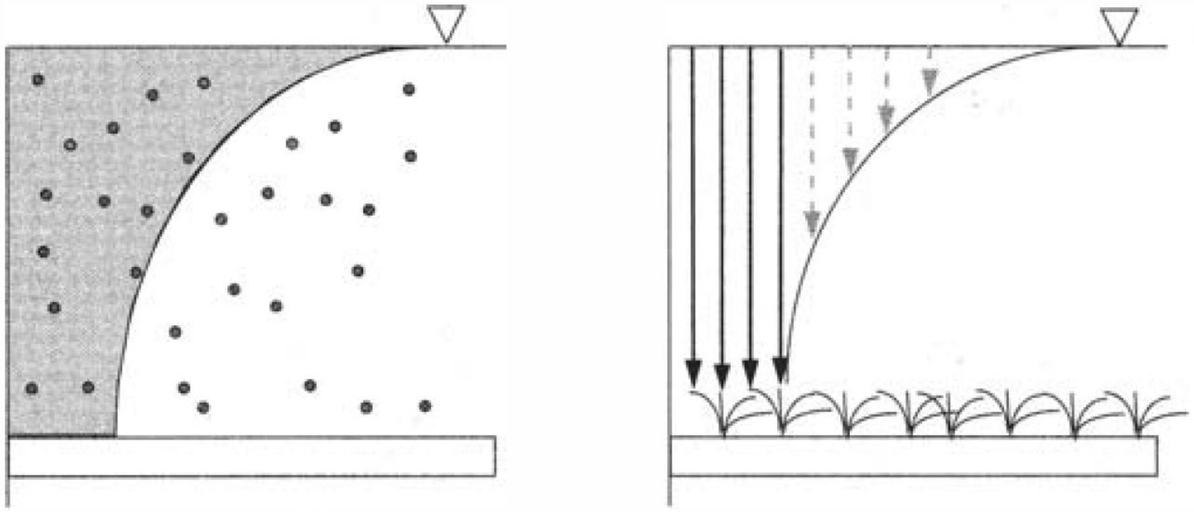


FIGURE 36.10
Contrast between how light is characterized in (*a*) floating (integrated over depth) and (*b*) fixed-plant (level determined at depth of plants) models.

Modeling Attached Plants

If Steele's model is used substitutions can be made to the integral and solved to result as:

$$\phi_l = \frac{f I_a e^{-k_e H}}{I_s} e^{-\frac{I_a e^{-k_e H}}{I_s}+1}$$



(*a*) Floating plants

(*b*) Fixed plants

FIGURE 36.10
Contrast between how light is characterized in (*a*) floating (integrated over depth) and (*b*) fixed-plant (level determined at depth of plants) models.