Fundamentals of River Hydraulics & Engineering

Chapter 5. Environmental Hydraulics (Contaminant Transport in Surface Water)

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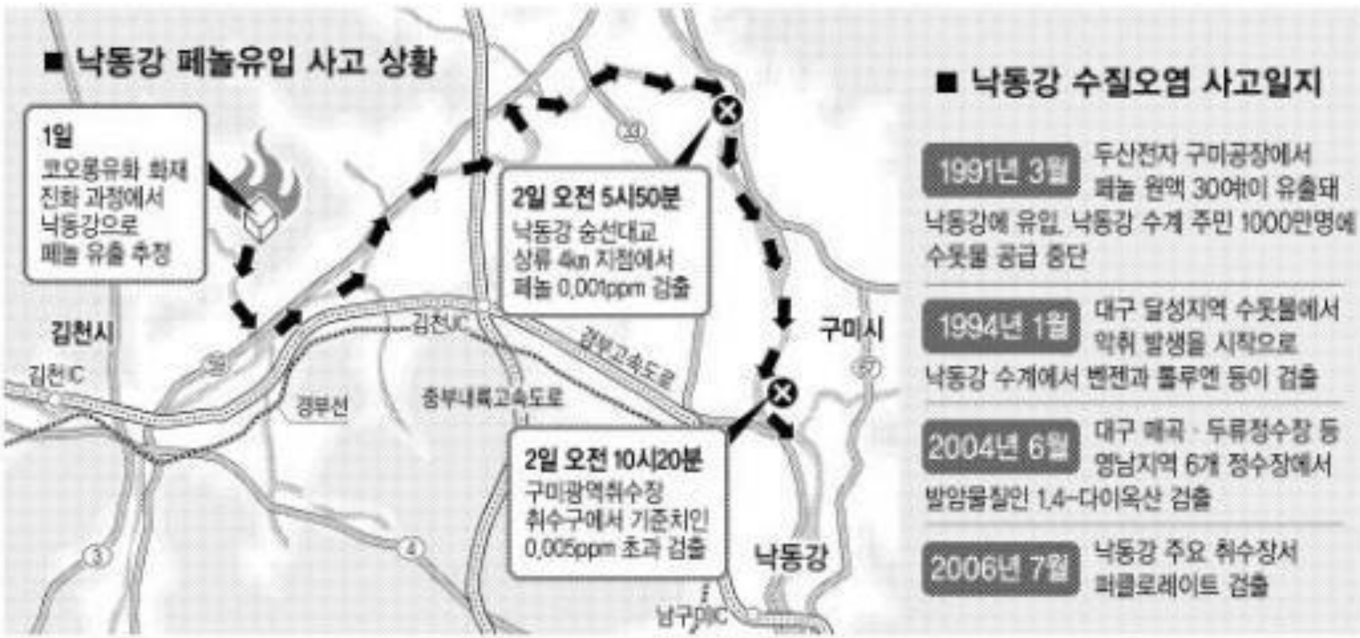
Accidental Release of a Chemical in Nakdong-gang River

- An industrial plant released accidentally a phenol solution in Mar. 14, 1991.
- It was recorded as a historical event that contaminated the source of drinking water in the south-eastern part of Korea.
- A leakage took place in the 30 m long pipeline from the storage tank to production line in a plant of an electronic company.
- About 30 ton of phenol was leaked during 8 hours during the midnight, which was not detected so long.

08년 낙동강 페놀 유출 사고



- A fire broke out in a plant in Gimcheon.

- A staff in the city was dispatched to extinguish the fire and build a dam to prevent the mixing of water and chemicals from flowing into the Daegwang-cheon Stream, located 600 m away.

95년 씨프린스호 사고로 인한 기름 유출

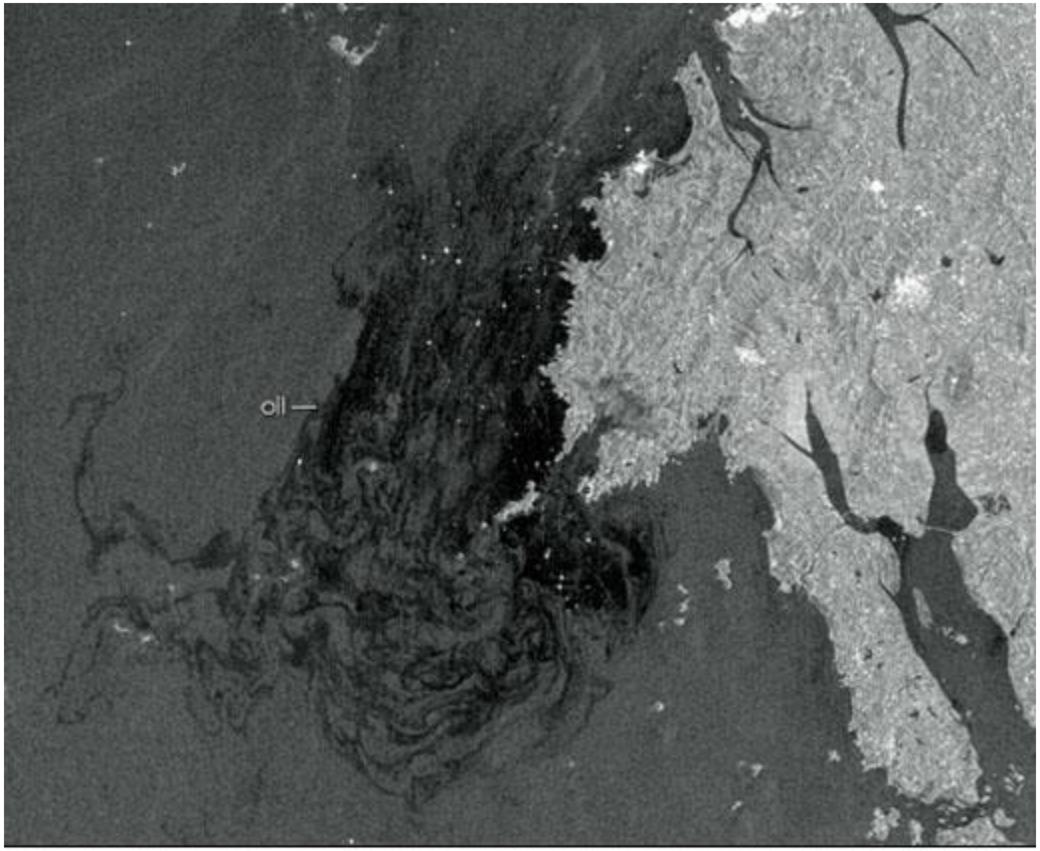
- On July 23, 1995, in the sea off Sori Island, Yeocheon-gun, Jeollanam-do, Typhoon Fei (940 hpa, wind speed 40 m, waves 8-10 m) caused a stranding.
- About 5,000 tons of oil was spilled in the accident, and 3,826 ha of farms were damaged.
- Disaster prevention costs and damage from fishing and tourism were about 73.5 billion won.
- The sea area around Yeosu and 73.2 km of coast have been transformed into the “sea of death”. After the accident, control work was carried out for about two years, but until now (February 2008), oil bands have been found in the tidal flats.

Oil Spill from Tanker at West Coast of Korea in 2007 (1)

- On Dec. 7, 2007, an oil tanker from Hong Kong released 15,000 tons of oil through 3 apertures after the crash with ship with offshore crane.

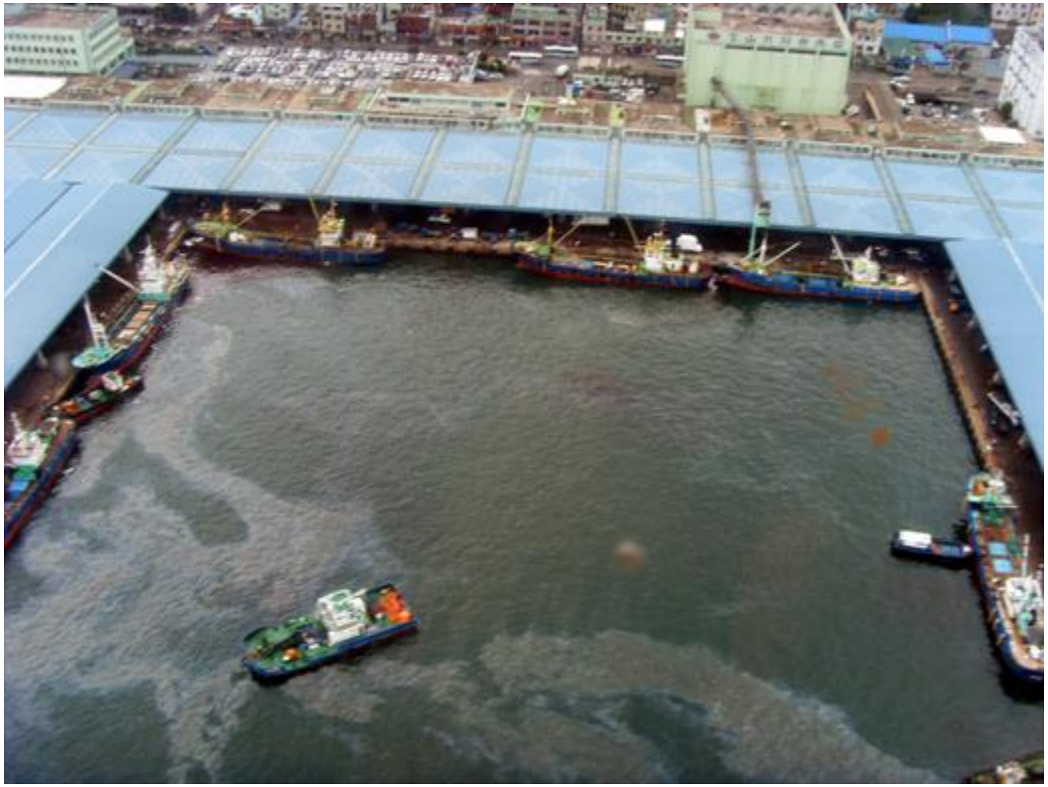
- The amount of oil released was three times larger than 5,000 t of oil by the Sea Prince, which was the worst accident before in Korea.

07년 태안 앞바다 유조선 기름 유출 (2)



충남 태안 앞바다의 기름 유출 사고 현장이 위성 사진에 포착되었다. 유럽우주국의 위성 엔비셋이 이 사진을 촬영한 시각은 우리나라 기준 11일 오전 10시 40분. 위성사진은 사고 현장을 한 눈에 보여준다. 기름은 넓은 바다를 뒤덮고 있다. 그 모양새가 섬뜩하다. 위력도 대단해 보인다. 바다 위에 떠있는 기름은 급속히 그 세를 확장할 태세이다.

08년 부산항 기름 유출



지난 23일 오후 7시께 부산 서구 남부민동 남항일자방파제로부터 140m 떨어진 해상에서 233t급 어선인 제105 통영호(승선원 10명)와 147t급 유조선인 일해호가 충돌하면서 유조선에 실려있던 480t의 벙커C유 중 30t 가량의 기름이 바다에 유출되는 사고가 발생했다. 이에 부산해경은 사고해역 인근에 3000m에 달하는 오일펜스를 설치했고, 30여 척의 방제정과 경비정, 민간 방제업체 선박 등을 동원해 방제작업을 펼치고 있다. /부산해경 제공

꿀벌과 개미의 지혜를 팔아라

- In 1989, a tanker of Exxon Mobil released 42,000 t of oil along the coast of Alaska due to wreckage.
- Oil freezes due to low temperature and cannot be removed.
- Destruction of nearby ecosystem for over 20 years without removing oil.

- The problem was solved by Innocentive, a service provider that connects knowledge users and providers on the Internet.
- In 2007, a cement company craftsman used a vibration device to remove oil while stirring to prevent freezing.

꿀벌과 개미의 지혜를 팔아라

- 굴지의 정유회사 Exxon Mobil의 유조선이 1989년 알래스카 근해에서 좌초되면서 대량의 기름 유출 사고 발생 (42,000 t)
- 낮은 기온 때문에 기름이 얼어붙어 제거 불가능
- 기름을 제거하지 못한 채 20여년간 인근 생태계 파괴

- 인터넷 상에서 지식의 사용자와 공급자를 연결해 주는 서비스 제공 회사 Innocentive 에 의해 문제 해결

- 2007년 시멘트 회사 기능공에 의해 진동기기를 활용하여 기름이 얼지 않도록 저어주면서 기름을 제거

Introduction

The objective of this chapter is to provide transport and fate principles in the hydro-environment, i.e., to predict the concentration as a function of space and time through water body.

본 장의 목적은 하천에 유입된 물질*의 거동을 파악, 즉 시간과 공간의 함수인 물질의 농도를 예측하는 것

여기서 물질은 반드시 유해한 것만을 의미하지는 않음

Some Terms

- mass concentration (ppm=g/m^3=mg/L)

  c = mass of constituent/volume of fluids

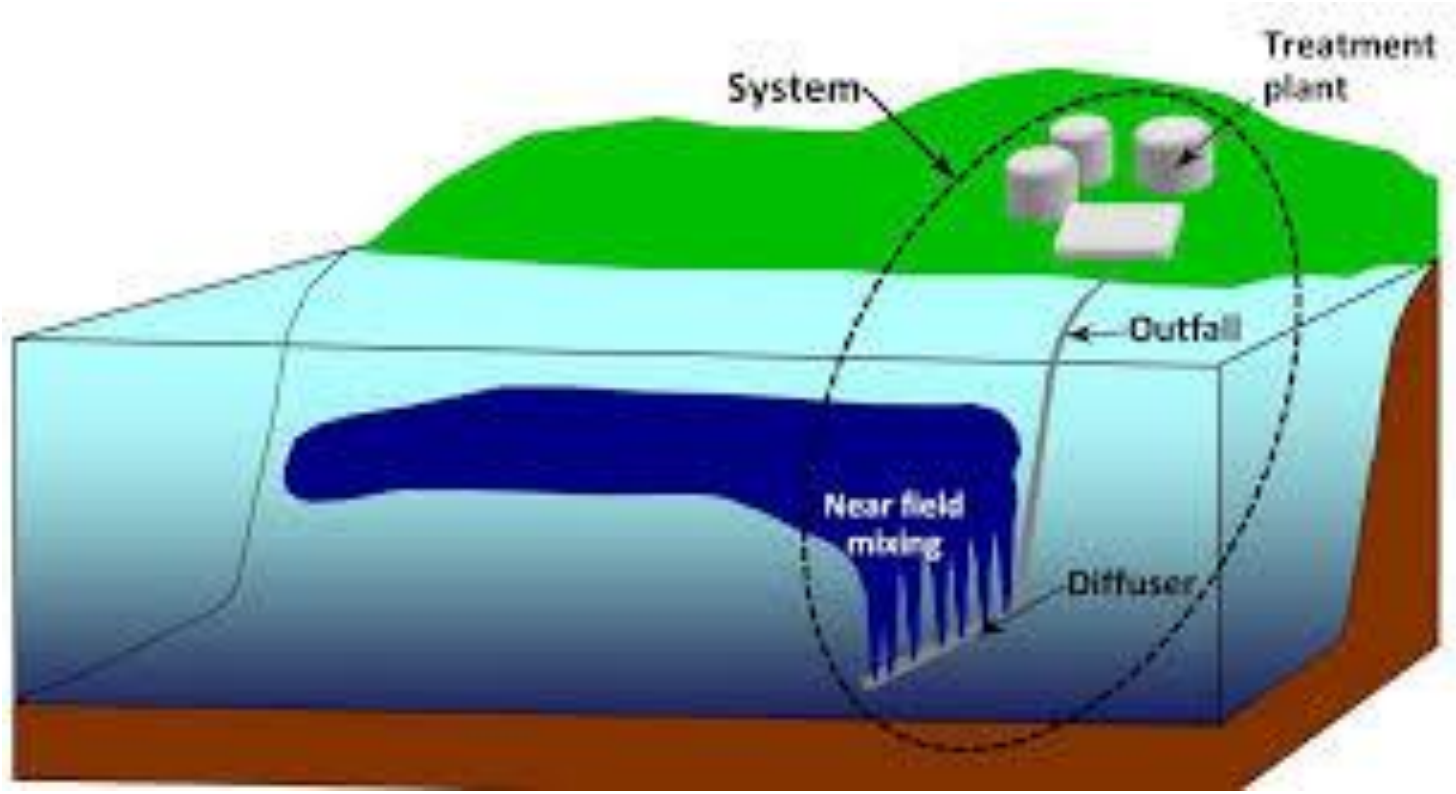
- M = c V

  L = c Q: pollutant load (오염부하량)

- steady problem: Mixing under steady flow condition, Ex: Streeter-Phelps model (QUAL2 by US Corps of Engineers)
- unsteady problem: Mixing during flood

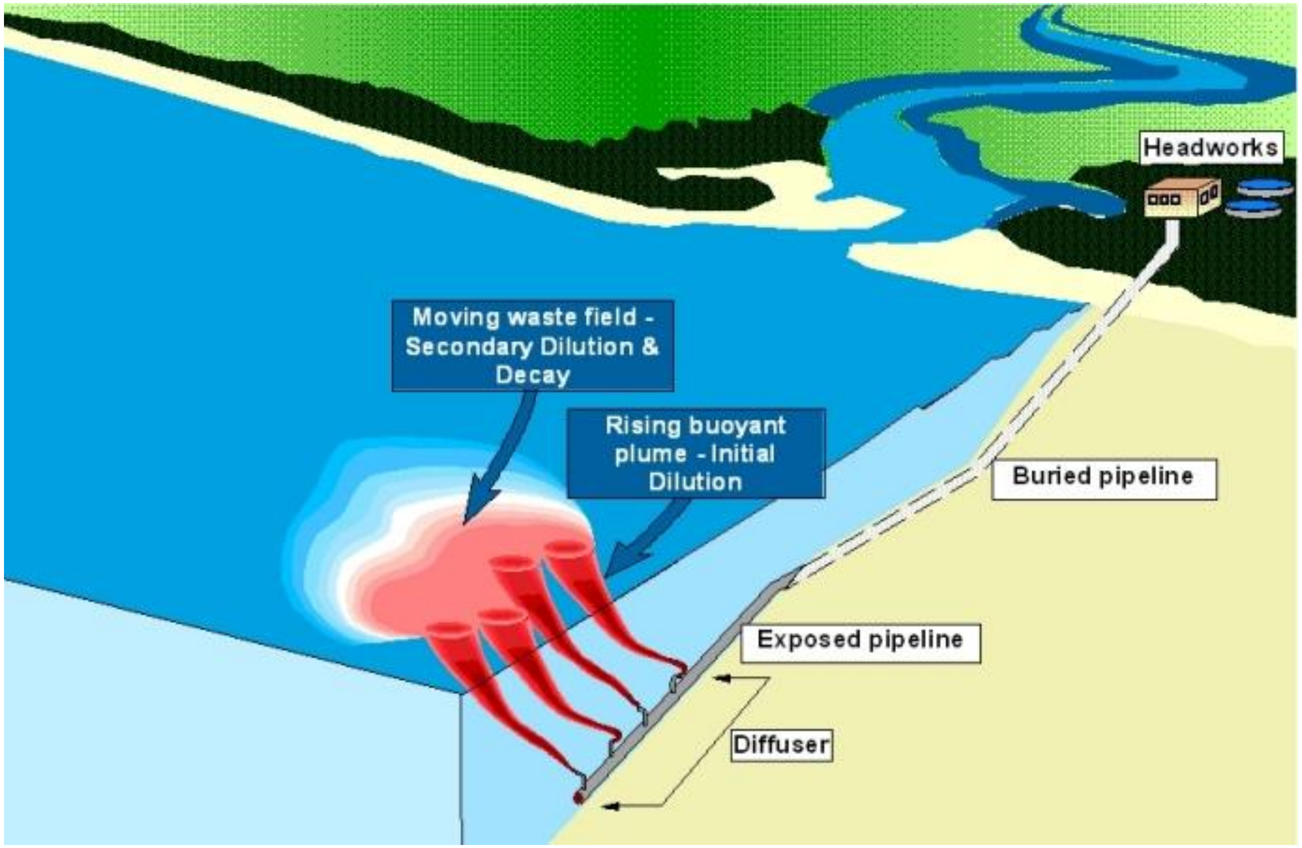
- near-field problem: Mixing is affected by the shape of outlet
- far-field problem: Mixing is affected by ambient water (주변수체), not by the shape of outlet

Near-Field and Far-Field Problems



Ocean Outfall

A **marine or ocean outfall** is a pipeline or tunnel that discharges municipal or industrial wastewater, stormwater, combined sewer overflows, cooling water, or brine effluents from water desalination plants to the sea. Usually they discharge under the sea's surface (submarine outfall).



Contaminant Source

- **point source (점오염원): a source that discharges through a pipe at a known location (from industry or waste water treatment plant)**

- **non-point source (비점오염원): the constituents that originated from the flow distributed over the land surface. This is brought out from the rainfall events.**

- **First Flush (초기세정효과): The pollutograph shows considerably higher concentration at the beginning of the storm.**

First Flushing (초기세정효과)

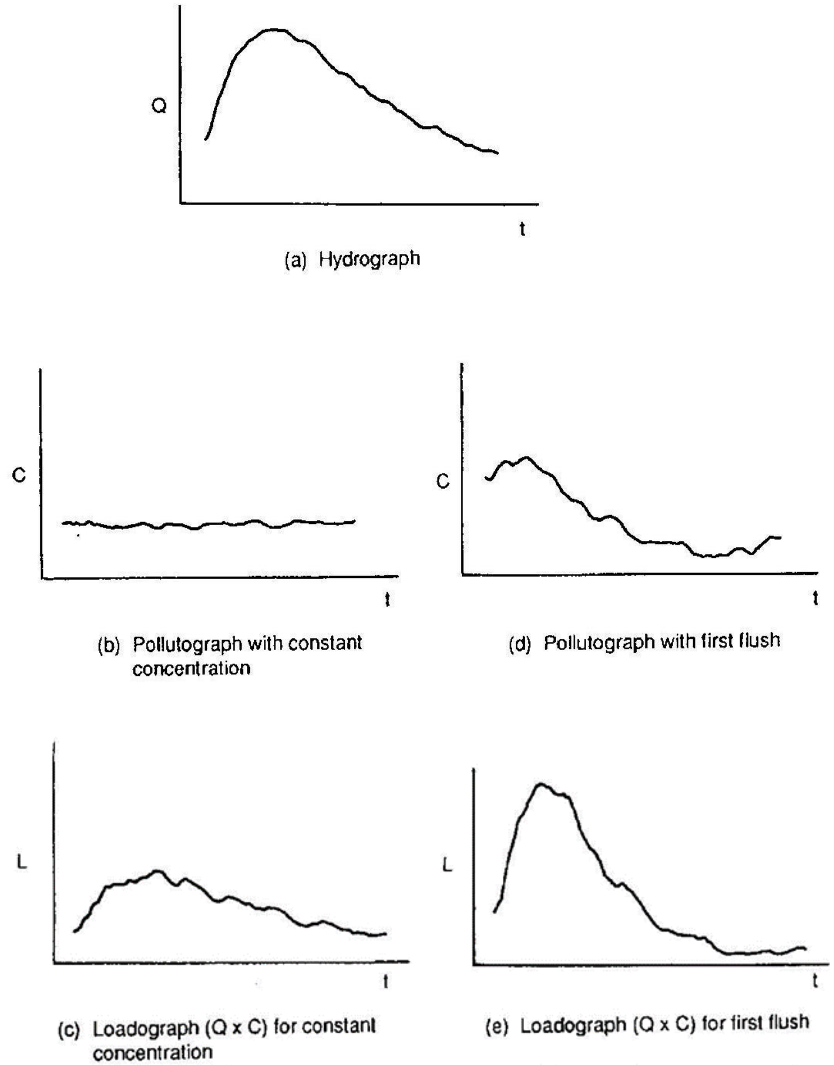


FIGURE 14.2.1 Effect of first flush on shapes of pollutograph and loadograph: (*a*) hydrograph (Q vs. T), (*b*) pollutograph (C vs. t), and (*c*) loadograph (load vs. t). Load = $Q \times C$.

Transport

- Transport (**이송**) is a process of a physical quantity moved by advection and diffusion.
- Advection (**이류**): This results from flow that is unidirectional and does not change the identity of the substance being transported.(convection **대류**)
- diffusion (**확산**): This refers to the movement of mass to random water motion or mixing.
    - molecular diffusion (**분자확산**)
    - turbulent diffusion (**난류확산**)

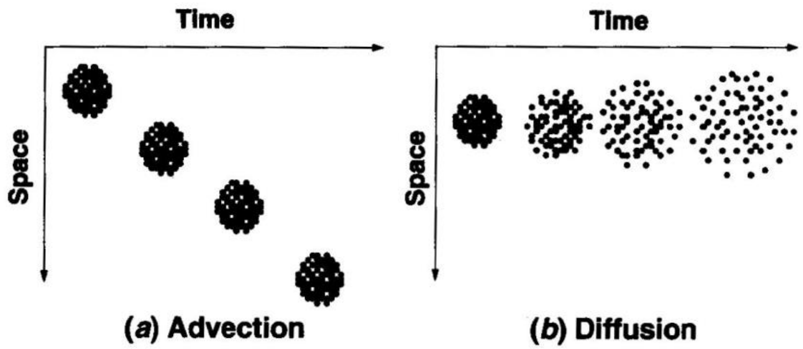
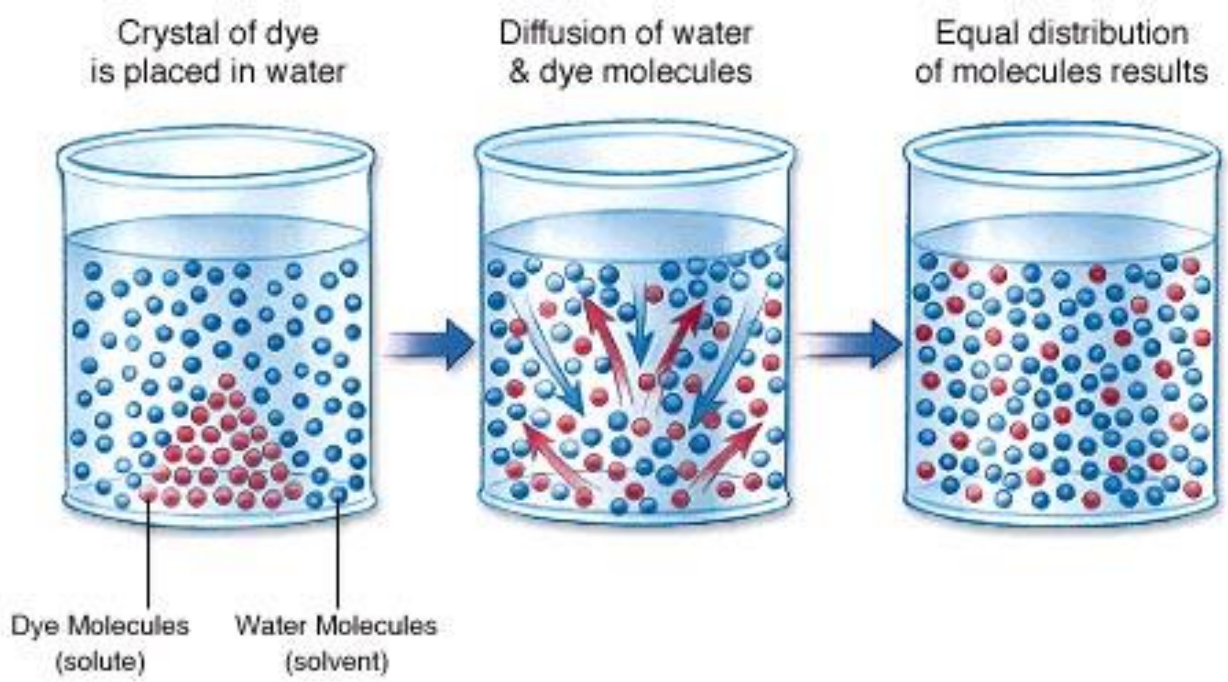


FIGURE 8.1 The transport of a dye patch in space and time via (*a*) advection and (*b*) diffusion.

Molecular Diffusion



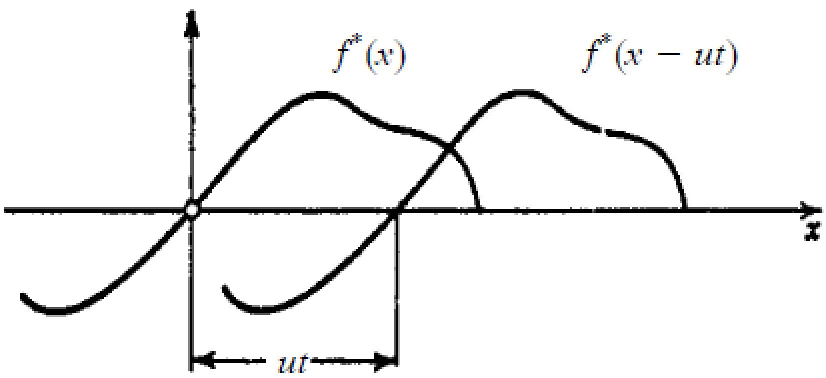
- **The distribution of the dye molecules becomes homogeneous in the cup without water flow.**

Advection 1

- **The transport by advection of a physical quantity *f* at a speed *u* is given by (1d wave equation)**

$$\frac{\partial f}{\partial t}+u\frac{\partial f}{\partial x}=0$$

which describes the wave propagation without deformation.



Interpretation of 1D Wave Equation

Advection 2

- **The analytical solution is given by**

$$f = f^*(x - ut)$$

where *f is any arbitrary function. The solute concentration *c* in a 3d form is**

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} = 0$$

Fick's First Law

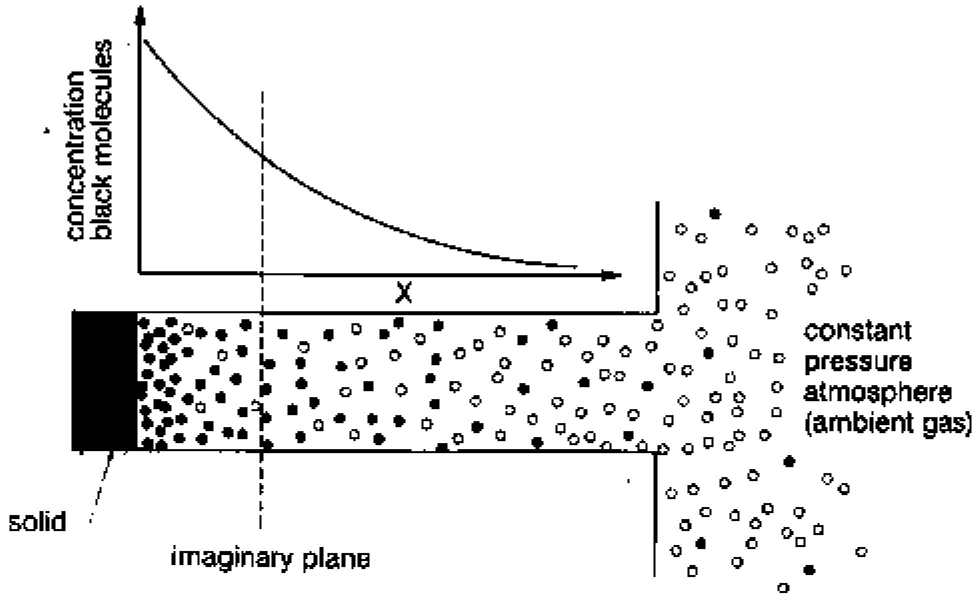


Figure 6.3. Simple one-dimensional binary gas diffusion: Diffusion from an evaporating solid in a tube open to a pure constant-pressure atmosphere.

The mass flux is proportional to the concentration gradient.

$$F_x \propto \frac{\partial c}{\partial x} \qquad \text{or} \qquad F_x = -E_x \frac{\partial c}{\partial x}$$

- **What is the dimension of Ex?**

Fick's Second Law

- Applying the mass conservation leads to

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(E_x \frac{\partial c}{\partial x}\right)$$

known to be "diffusion equation."

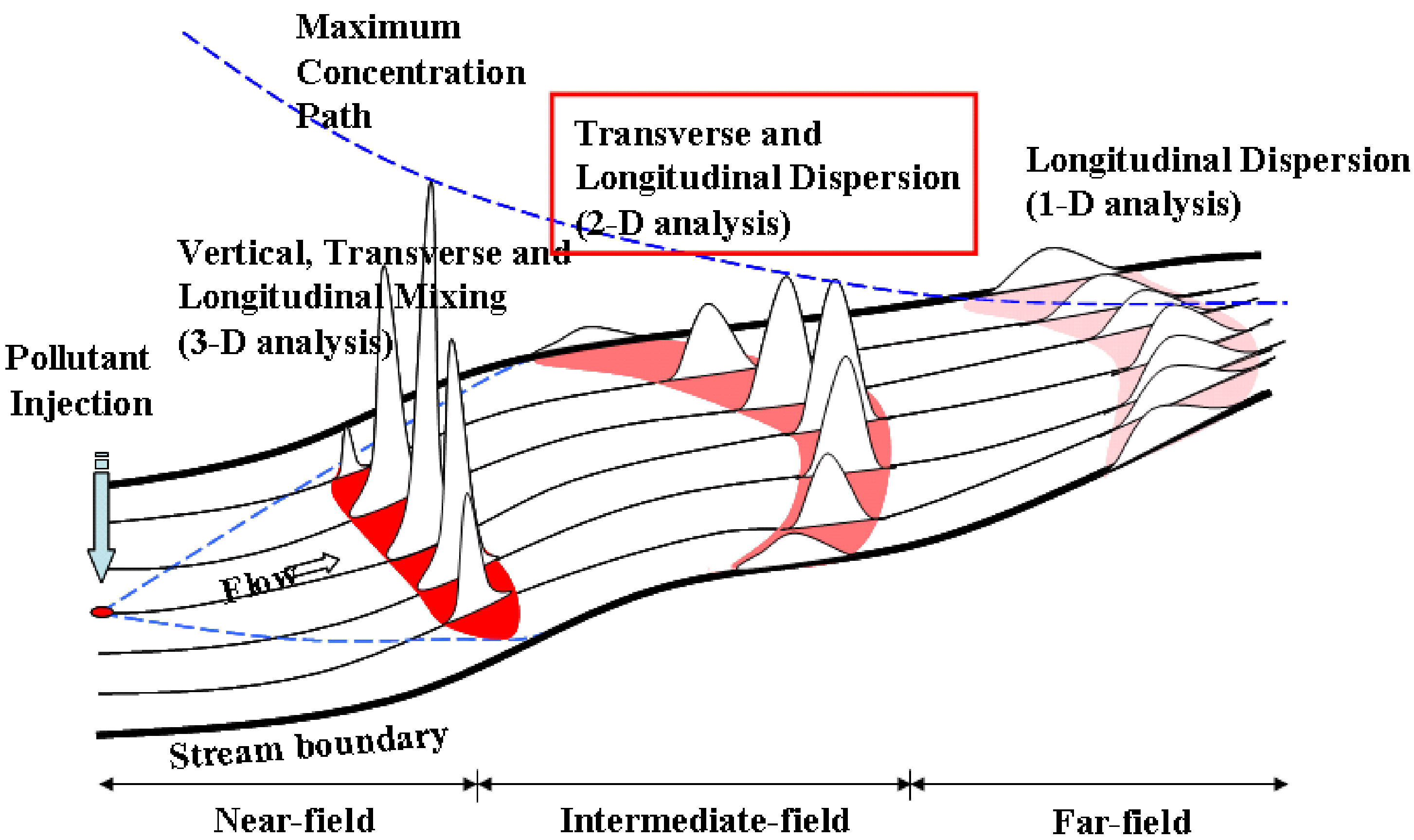
- Three-dimensional form is

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(E_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(E_z \frac{\partial c}{\partial z}\right)$$

- Fick's first and second laws are valid only for laminar flows. However, G.I. Taylor later showed they are valid for turbulent flows.

Mixing in River

✓ When a pollutant is introduced into a river, it undergoes different mixing stages.



Conceptual diagram of pollutant mixing in rivers
(after Kilpatrick and Wilson, 1989)

Transport in the Environment: A Simple Analysis of Turbulent Diffusion

- The 3d unsteady transport equation

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=\frac{\partial}{\partial x}\left(E_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(E_y\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(E_z\frac{\partial c}{\partial z}\right)$$

- 1d form of transport equation

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}=\frac{\partial}{\partial x}\left(E_x\frac{\partial c}{\partial x}\right)$$

- Reynolds decomposition $u=\bar{u}+u'$

$$\frac{\partial c}{\partial t}+\bar{u}\frac{\partial c}{\partial x}=\frac{\partial}{\partial x}\left(E_x\frac{\partial c}{\partial x}\right)-u'\frac{\partial c}{\partial x}$$

$$\frac{\partial c}{\partial t}+\bar{u}\frac{\partial c}{\partial x}=\left(E_x+\varepsilon_x\right)\frac{\partial^2 c}{\partial x^2}$$

- The turbulent diffusion dominates over the molecular diffusion (ε>>E).

• This is not a rigorous analysis of turbulent diffusion since c is also an instantaneous variable. However, it gives an insight how important turbulent diffusion is.

Transport in the Environment

- For 3d transport,

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial c}{\partial z}\right)$$

- If we assume that $u \gg v, w$ and $\epsilon_x >> \epsilon_y$, ε_z, then

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial c}{\partial x}\right)$$

- It can be noted that 1d equation is still valid for mixing in the river.

Shear Flow Dispersion (전단류확산)

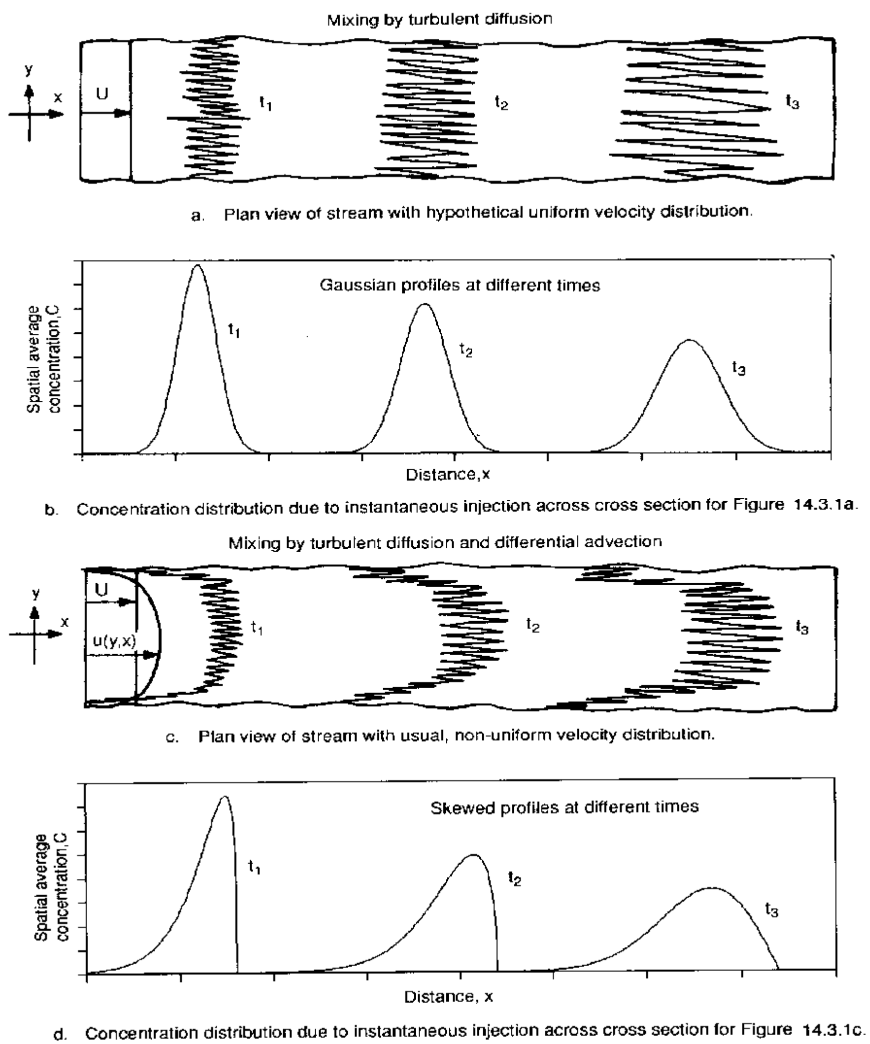


FIGURE 14.3.1 Definition sketch for longitudinal dispersion: (*a*) plan view of stream with hypothetical uniform velocity distribution, (*b*) concentration distribution due to instantaneous injection across cross section of Fig. 4.3.1 (*a*), (*c*) plan view of stream with usual nonuniform velocity, (*d*) concentration distribution due to instantaneous injection across cross section for Fig. 14.3.1(*c*).

Transport in the Environment

- The river is 1d in nature. So 1d model for contaminant transport is very convenient. The mean velocity and concentration are

$$U = \frac{Q}{A} = \frac{1}{A}\int_A u \, dA$$

$$C = \frac{1}{A}\int_A c \, dA$$

which are section-averaged variables.

- The 1d equation commonly applied to the stream is

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{1}{A}\frac{\partial}{\partial x}\left(A E_L \frac{\partial C}{\partial x} \right) - KC$$

where E_L = longitudinal dispersion coeff. and K = first-order rate coeff.

- E_L is typically in the order of 100-1,000 times greater than turbulent diffusivity.

Longitudinal Dispersion Coefficient

$$E_L = \frac{0.011 U^2 W^2}{h U_*}$$ empirical

- Eddy diffusivity

$$\varepsilon_t = 0.15 h U_*$$ straight, empirical

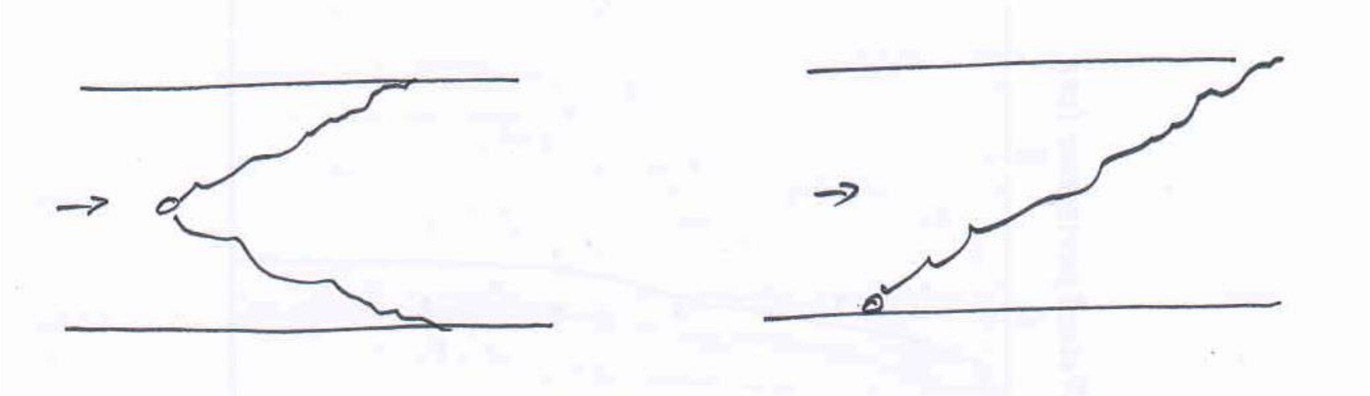
$$= 0.6 h U_*$$ curved, empirical

$$\varepsilon_v = 0.067 h U_*$$ theoretical

Distance to Complete Mixing

$$L_m = \frac{0.1 U W^2}{\varepsilon_t}$$ for centerline mixing

$$L_m = \frac{0.4 U W^2}{\varepsilon_t}$$ for sidebank mixing



Ex.5.1

Ex.5.1: Mixing in a River

- **The Cuyahoga River: S_0 = 0.002, h = 4 m, U = 0.8 m/s, & W = 110 m.**

(1) Find ε_t, ε_v, and E_L.

(2) Find the channel length for complete mixing.

Reaction Kinetics

- The production or loss of a constituent, with or without interaction with another constituent, is a kinetic process. This is different from advection or diffusion.
- Example of kinetic processes

process	gain/loss
Decay of bacteria	Loss
Oxidation of carbonaceous material	Loss
Re-aeration of dissolved oxygen	Gain

- A general equation

$$\frac{dc_i}{dt} = f(c_i, c_j, T), \quad j = 1, 2, \ldots$$

where c_i is the conc. of constituent i at T.

Examples 1

- First-order kinetics

$$\frac{dc}{dt} = -Kc$$

where K = the first-order rate coeff. [T^{-1}].

- Analytical solution of the first-order kinetics is

$$c(t) = c_0 e^{-Kt}$$

- Second-order kinetics

$$\frac{dc}{dt} = -Kc^2$$

- Analytical solution of the second-order kinetics is

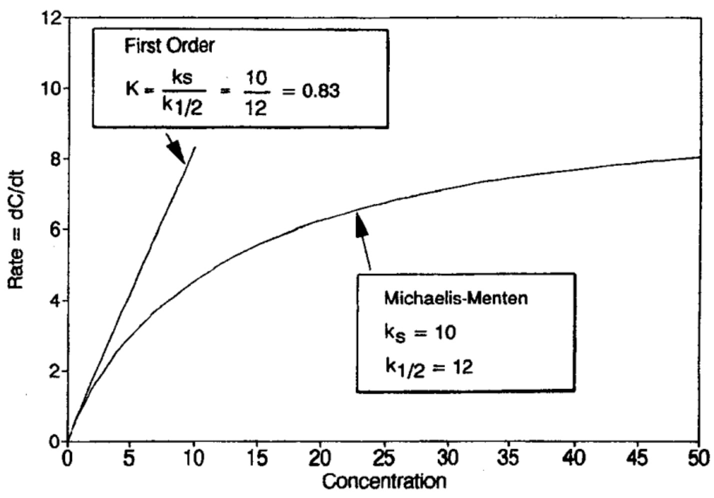
$$c(t) = c_0 \frac{1}{1 + Kc_0 t}$$

Examples 2

- Monod kinetics

$$\frac{dc}{dt} = -\frac{k_s c}{k_{1/2} + c}$$

where k_s = the limiting reaction rate const. and $k_{1/2}$ = the half-saturation const. Monod kinetics is often applied to nutrients (nitrogen & phosphorous) especially in eutrophication studies.

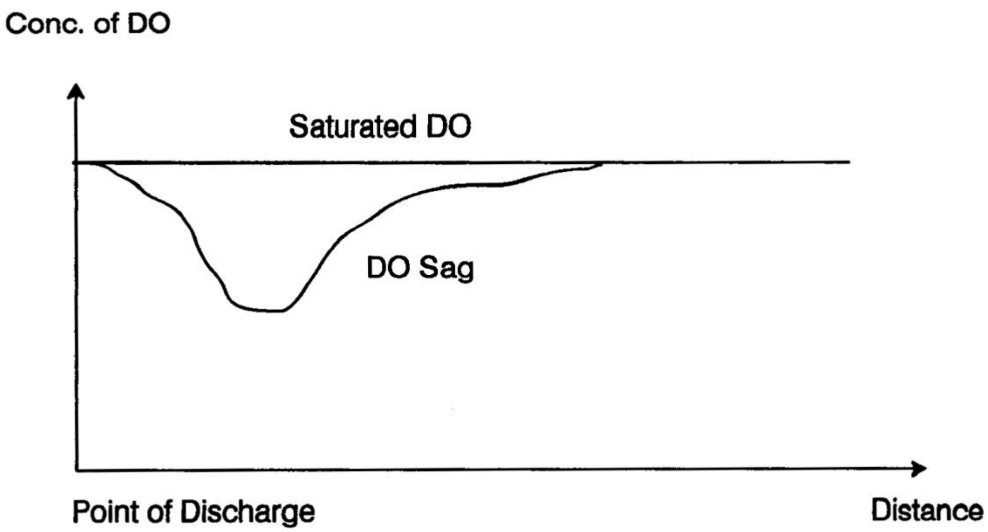


Example of Monod Kinetics

Oxygen Balance 1

- Biochemical Oxygen Demand (BOD)

The quantity of oxygen used in aerobic stabilization of wastes and polluted waters.



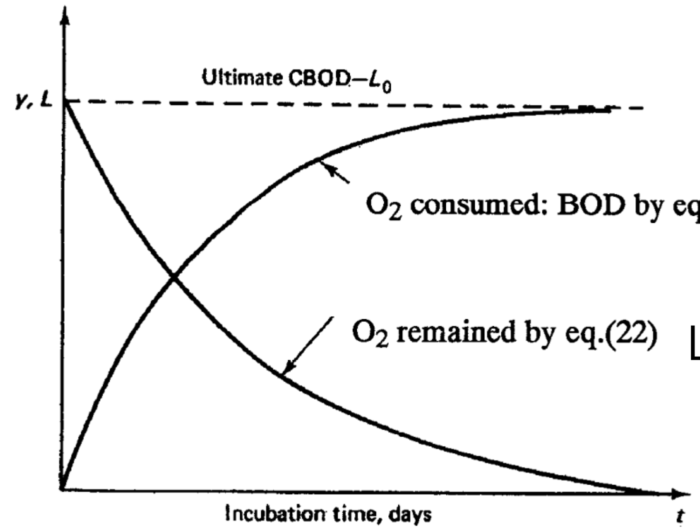
Oxygen Sag Curve

Oxygen Balance 2

- Sources of DO
  - Re-aeration from the atmosphere (재폭기)
  - Photosynthetic oxygen production (광합성)
  - DO in incoming tributaries and effluents (지천 혹은 유출수 유입)

- Sinks of DO
  - Oxidation of carbonaceous waste material (탄소화합물의 산화)
  - Oxidation of nitrogeneous waste materials (질소화합물의 산화)
  - Oxygen demand of sediment of water body (유사)
  - Use of oxygen for respiration by aquatic plants (수생식물 호흡)

Oxygen Sag Curve 1



- DO remained

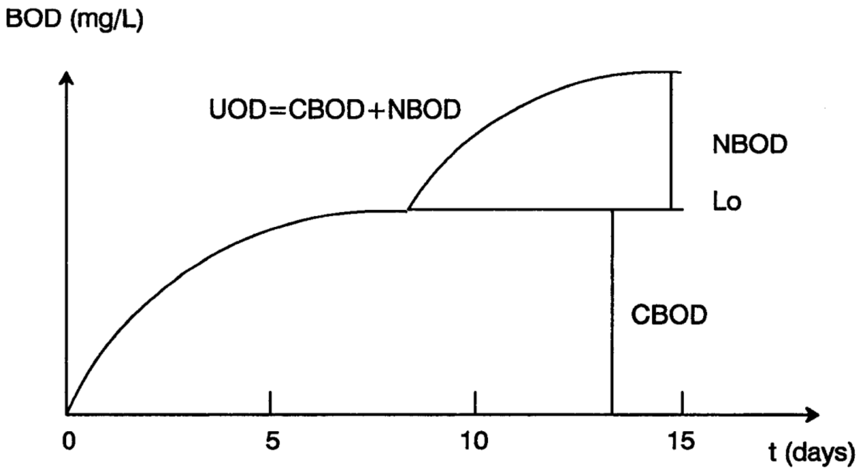
$$\frac{dL}{dt} = -K_1 L \rightarrow L = L_0 \exp(-K_1 t)$$

- DO consumed (DO deficit)

$$D = L_0 - L = L_0 \left[1 - \exp(-K_1 t)\right]$$

where K_1 = deoxydation coeff. (**탈산소계수**)

Oxygen Sag Curve 2



Carbonaceous (BOD), nitrogenous (NOD), and ultimate (UOD) oxygen demand

- A simpler way is to combine CBOD and NBOD into UOD. That is,

  UOD = CBOD + NBOD

- Oxygen is replenished by reaeration, i.e.,

$$\frac{dL}{dt} = K_2\left(L_0 - L\right) = K_2 D$$

where K_2 = reaeration coeff. (**재폭기계수**)

Streeter-Phelps Model

- Deoxydation process

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

- Reaeration process

$$\frac{dL}{dt} = K_2 D$$

- Combined process

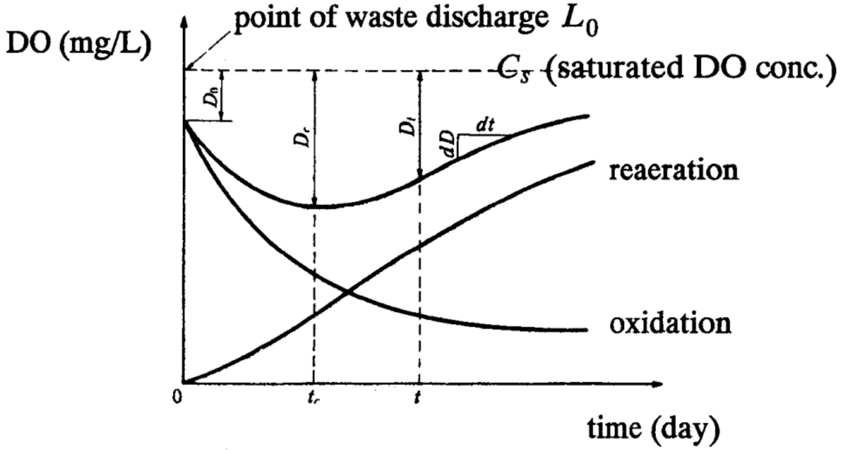
$$\frac{dL}{dt} = -K_1 L + K_2 D$$

or

$$\frac{dD}{dt} = K_1 L - K_2 D$$

- Solution

$$D(t) = \frac{K_1 L_0}{K_2 - K_1}\left(e^{-K_1 t} - e^{-K_2 t}\right) + D_0 e^{-K_2 t}$$



Oxygen Sag Curve by Streeter-Phelps Model

Order of Kinetics

EXAMPLE 2.1. INTEGRAL METHOD. Employ the integral method to determine whether the following data is zero-, first-, or second-order:

t (d)	0	1	3	5	10	15	20
c (mg L^{-1})	12	10.7	9	7.1	4.6	2.5	1.8

If any of these models seem to hold, evaluate k and c_0.

Solution: Figure 2.4 shows plots to evaluate the order of the reaction. Each includes the data along with a best-fit line developed with linear regression. Clearly the plot of $\ln c$ versus t most closely approximates a straight line. The best-fit line for this case is

$$\ln c = 2.47 - 0.0972t \qquad (r^2 = 0.995)$$

Therefore the estimates of the two model parameters are

$$k = 0.0972 \text{ d}^{-1}$$

$$c_0 = e^{2.47} = 11.8 \text{ mg L}^{-1}$$

Thus the resulting model is

$$c = 11.8e^{-0.0972t}$$

The model could also be expressed to the base 10 by using Eq. 2.15 to calculate

$$k' = \frac{0.0972}{2.3025} = 0.0422$$

Order of Kinetics

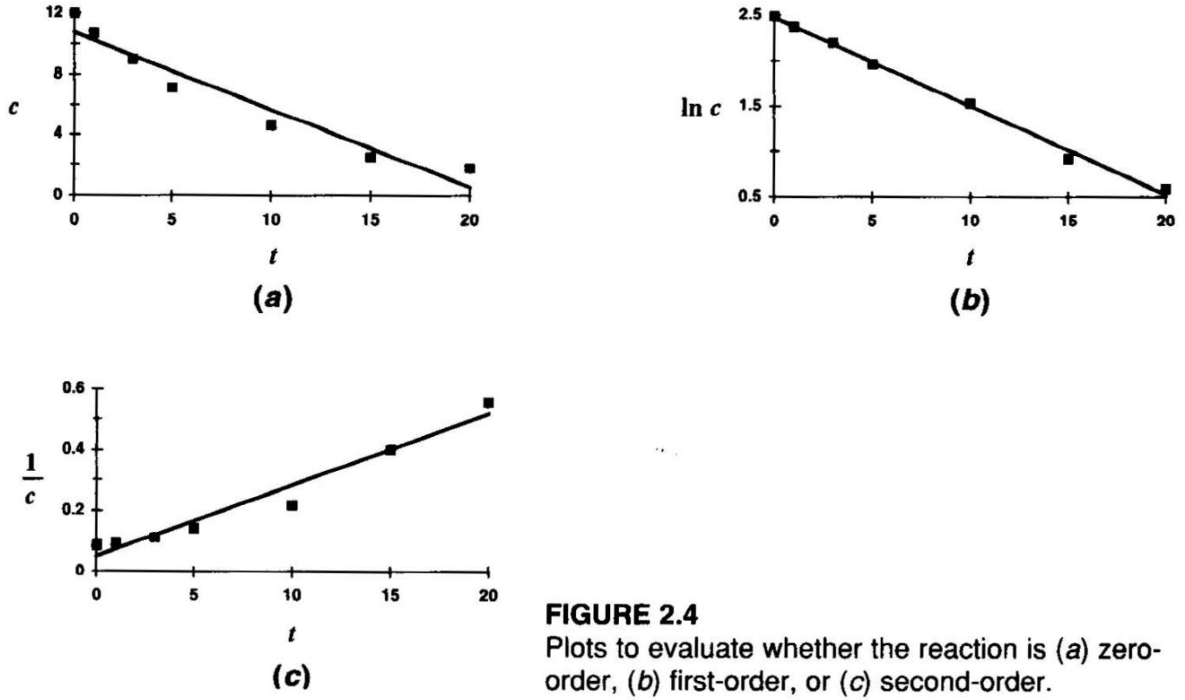


FIGURE 2.4
Plots to evaluate whether the reaction is (*a*) zero-order, (*b*) first-order, or (*c*) second-order.

which can be substituted into Eq. 2.16,

$$c = 11.8(10)^{-0.0422t}$$

The equivalence of the two expressions can be illustrated by computing c at the same value of time,

$$c = 11.8e^{-0.0972(5)} = 7.26$$

$$c = 11.8(10)^{-0.0422(5)} = 7.26$$

Thus they yield the same result.