Chapter 1 Concepts and Definitions

Water quality
= water quantity
+ hydrodynamics of transport and mixing
+ chemistry and biology of natural water systems

1.1 The Role of Hydrology and Hydraulic Engineering in Environmental Management

atmosphere - air motion
hydrosphere - water motion

◆ Fluid motions transport and disperse disposal of residuals

- massive discharges of wastewater into rivers and oceans

◆Without fluid motion, there is no transport and dispersion

(ex)

1.1.1 Overall Framework for Environmental Management

•Environmental Fluid Mechanics

- study of fluid motions in the lower atmosphere, in the ground, and in rivers, lakes, and seas that relate to problems connected to human activities within the environment.

•Environmental Hydraulics

- study of water motions in the ground, and in rivers, lakes, and seas that relate to problems connected to human activities within the environment.

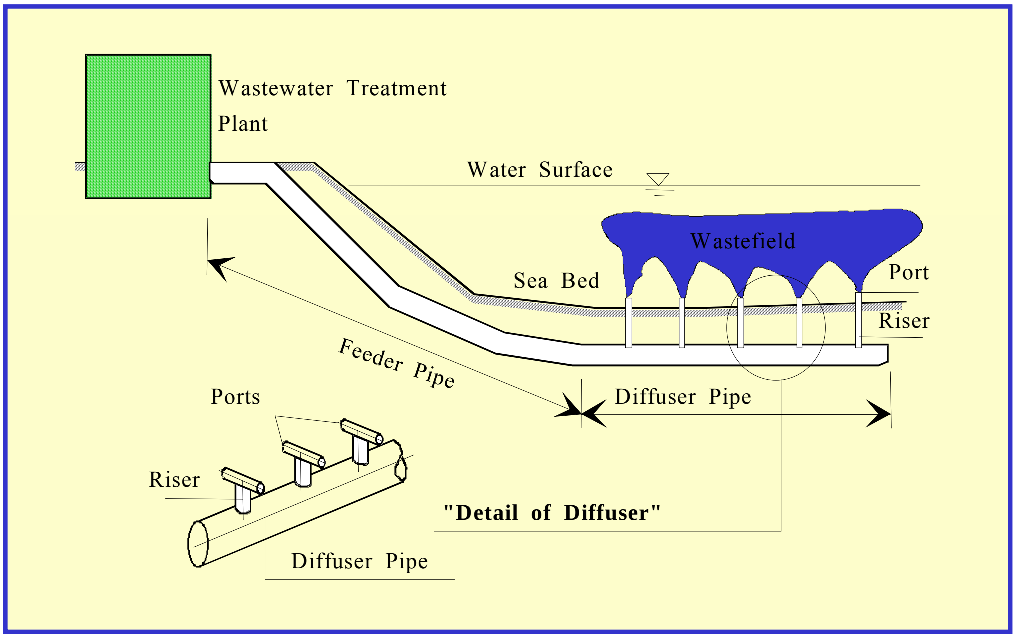
•Transport - Hydraulic engineer

Transformation - Chemist
Accumulation - Biologist
⇒ processes that takes places between the point where a pollutant is discharged into the water environment and some other sites (downstream site in rivers) where the ambient water quality is observed.

• Role of Hydraulic Engineer

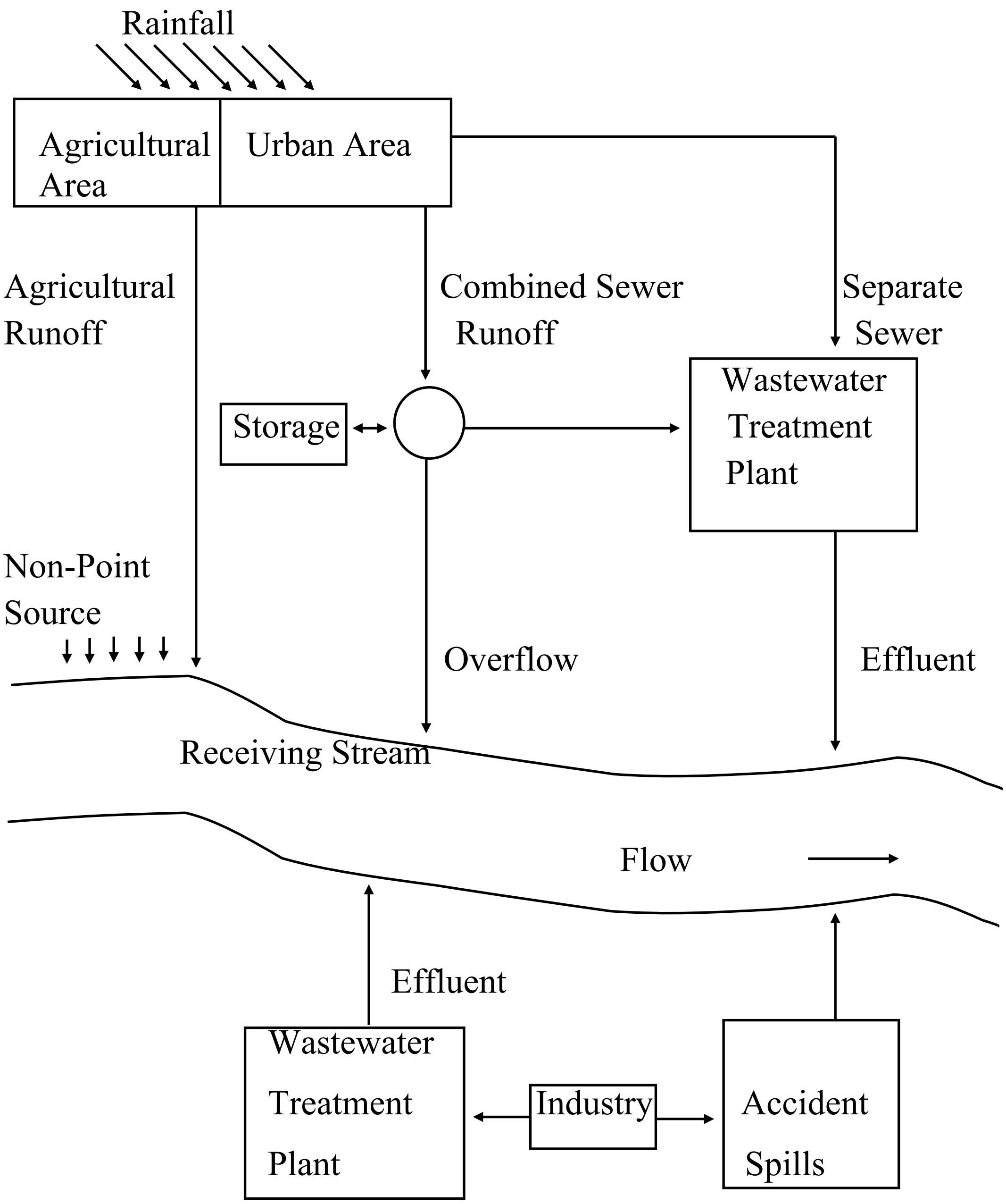
1) design of hydraulic structure (outfalls, diffusers)

-> **jets and plumes**



2) analyze water quality processes -> **diffusion and dispersion**

Conceptual View of Pollutant Inputs



Point

Non-point

Instantaneous

Continuous

Conservative

Reactive

Dissolved

Suspended

miscible

immiscible

Organic

Inorganic

- Environmental Control System

- optimization of

(a) control of pollutants at the source (pre-treatment, clean technology)

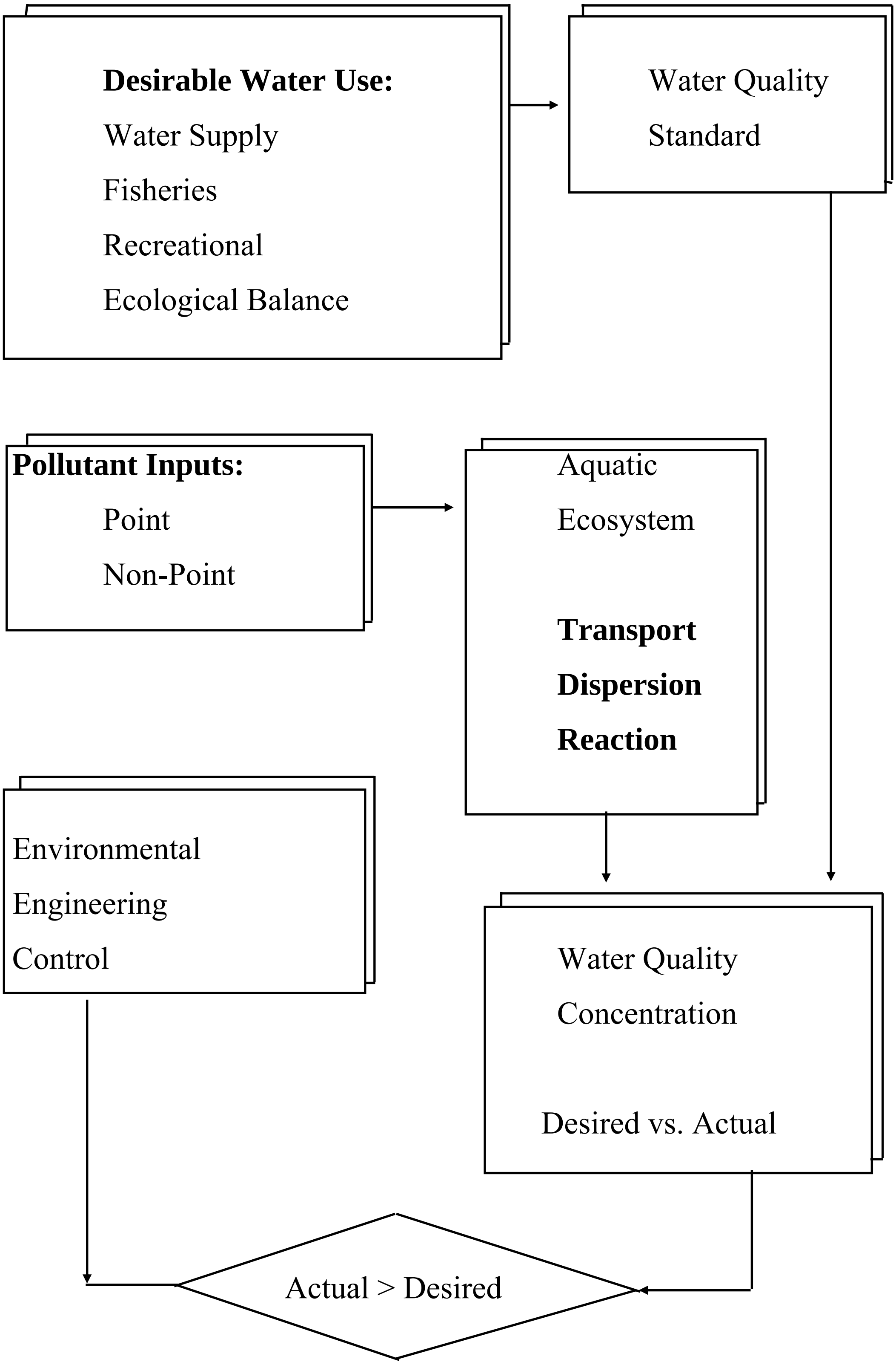
(b) wastewater treatment (primary, secondary treatment)

(c) disposal in the environment (post-treatment, wastewater outfalls)

- Role of Hydraulic Engineer (Environmental Hydraulics)

- make interface between man's activities and the natural environment
- draw water supply from natural water bodies
    - develop technology how wastewater is returned → design of outfalls

Flow Diagram of Water Quality Engineering



1.1.2 Using the Water Environment for Waste Assimilation

◆ Types of pollutant (from the least dangerous to the most hazardous)

(1) **natural inorganic salts and sediments**

- not toxic unless in excessive doses

(2) waste heat or **heated water discharges**

- cooling water for electric generating plants
- decrease water's assimilative capacity for oxygen

(3) **organic wastes**

- domestic sewage → biochemical oxygen demand (BOD)
- carbon, nitrogen, phosphorous: nutrients → eutrophication

• BOD

- amount of dissolved oxygen for bacteria to oxidize the organic wastes in the water

$$\text{Organic waste} + O_2 \rightarrow CO_2 + H_2O$$

• COD

- amount of dissolved oxygen to oxidize the organic wastes using chemicals

$$\text{COD} > \text{BOD}$$

- drinking water quality

class	BOD
1	< 1ppm
2	< 3ppm
3	< 6ppm
4	< 8ppm

- ppm = parts per million = mg/ℓ

1ppm = 1g of BOD/1,000,000g of water

(4) **trace metals**

- industrial wastewater – electro-planting, battery manufacturing, mining, smelting, refining
- lead, mercury, cadmium, selenium
- toxic in high concentration (accumulation)

(5) **synthetic organic chemicals**

- slow to degrade in environment
- bioaccumulate in the aquatic food chain
- industrial chemicals: phenol, benzenes, PCB(Poly-Chlorinated Biphenyls),
- agricultural chemicals: pesticides, herbicides, DDT

* biological process (multiplying the concentration by a factor of 10^5 in successive food chain steps)
⇔ physical process of mixing (= high dilution reduces the concentration)

(6) **radioactive materials**

- resulting from production of nuclear energy, nuclear weapons, and production of radioactive materials for industrial use
- plutonium - 239/240, strontium-90, cesium-137
- long-term storage of radio-active wastes w/o leakage

<cf> radioisotopes for tracer materials: I-131 (half-life - 8.3 days)

(7) **chemical and biological warfare agents**

- exceedingly toxic can not be dispersed in the environment

◆ Strategy of wide dispersal

- "Dilution is the solution to pollution."
- suitable only for heat and natural organic materials

◆ Toxic substances: trace metals, synthetic chemicals, radioactive materials

- results in acute effects of mortality and long-term chronic effect

- tendency to sorb to particulates in the water body

- tendency to be toxic at relatively low concentrations of μg/l or ng/l

- tendency to be concentrated by aquatic organisms and transferred up the food chain

• The safest strategy = non production and nonuse

1.1.3 Mass Balance Concepts in Residual Management

◆ **Conservation of mass**

- Flux of substance source must balance the fluxes for subsequent transport and diffusion with adjustments for chemical and biological conversions and sinks, such as deposition on the river bed or sea floor.

• **flux of solute mass** = mass of a solute crossing a unit area per unit time in a given direction

• For steady state, total influx = total efflux

◆ Types of pollutant source

1) point source

- discharge from a structure which is specially designed for the outflow of wastewater or accidental spill

(ex) - industrial and municipal sewerage system

- accidental spill of chemicals or oil from a ship

- release of heated water from power plant

2) nonpoint source

- widely distributed points where pollutants are introduced into the hydrologic cycle

(ex) runoff of salts, soil erosion, acid rainfall, street drainage

<cf> classification by input period

continuous input - municipal sewerage system, heated water from power plant

instantaneous input - accidental spills

1.1.4 Impacts of Some Traditional Activities of Hydraulic Engineers

◆ Adverse effects of traditional hydraulic works on water quality

(1) man-made reservoirs → summertime thermal stratification → oxygen depletion in the lower layer

(2) diversion water for <u>consumptive uses</u> → reduce river flow (inflow) and its ability to provide natural flushing

(3) canals → transport huge amount of dissolved salts, sediment, nutrients and parasites

(4) agricultural drainage system → accelerate the leaching of nutrients and salts from land to natural hydrologic systems

(5) breakwater for harbors → interfere with natural nearshore circulation which could otherwise carry away pollutants

(6) estuarine modification or barriers → radically change the circulation patterns decreasing flushing of pollutants

1.2 Environmental Hydraulics

1.2.1 Hydrologic transport processes

◆ Hydrologic transport processes

- physical processes of flow of natural water bodies which cause pollutants or natural substances to be transported and mixed, or exchanged with other media

⇔ man-made unit process (chemical plant)

(1) Advection: transport by an imposed current system of receiving (ambient) water bodies

(2) Convection: vertical transport induced by hydrostatic instability (buoyancy)

(ex) - flow over a heated plate

- flow below a chilled water surface in a lake (winter time)

(3) Molecular diffusion

- scattering of particles by random molecular motion
- Brownian motion
- described by Fick's law
- molecular diffusivity

(4) Turbulent diffusion

- random scattering of particles by turbulent motion
- analogous to molecular diffusion
- molecular diffusion ≪turbulent diffusion

(ex) mixing in coffee cup: in rest vs. stirring

(5) Shear(shear flow)

- advection of fluid at different velocities (direction and magnitude) at different positions

(ex) - velocity distribution over stream bed

- complex flow in estuary or coastal areas

(6) Dispersion

- scattering of particles or cloud of contaminants by the combined effects of shear and diffusion
- shear advection + vertical and/or transverse diffusion
- molecular diffusion $\ll$ turbulent diffusion $<$ dispersion

(7) Mixing

- diffusion or dispersion
- turbulent diffusion in buoyant jets and plumes
- any process which causes one parcel of water to be mixed with or diluted by another

(8) Evaporation

- transport of water vapor from a water or soil surface to the atmosphere

(9) Radiation

- flux of radiant energy at a water surface

(10) Particle settling

- sinking (or rising) of particles having densities different from the ambient fluid (ex) sand grains, dead plankton → downward transport of nutrients in lakes and ocean

(11) Particle entrainment

- picking up of particles (sand, organic detritus) from the bed by turbulent flow past the bed

- flow analysis - mean velocity is important
- pollutant analysis - fluctuation and irregularities in hydrologic systems are equally important

1.2.2 Buoyant Jets and Plumes

- submerged (momentum) jet

- increase the dilution of effluent discharge with the surrounding waters

- submerged buoyant jet

- when discharge fluid is lighter or heavier than surrounding waters
- heated water discharge vs. wastewater discharge

- plume

- initial momentum is not important

●Analysis of buoyant jets and plumes

a) jet parameters : initial momentum flux, mass flux, buoyancy flux
b) ambient conditions : ambient density stratification, ambient velocity profile
c) geometric factors : jet shape, angle, orientation

1.2.3 Density-Stratified Flows in a Natural Environment and Geophysical Fluid Mechanics

⇒ video film『Stratified Flow』

- Density stratification

→ lake, reservoirs : due to temperature variation

→ estuary - salinity profiles
- internal structure causes effect on both mean flow fields and turbulent mixing and dispersion

1.2.4 Sedimentation and Erosion

- hydrologic transport processes

- particle setting and entrainment
- stream morphology
- erosion, transport and deposition → 『Advance River Engineering』

1.2.5 Interdisciplinary Modeling

- fate of pollutants - governed by combination of physical, chemical and biological processes

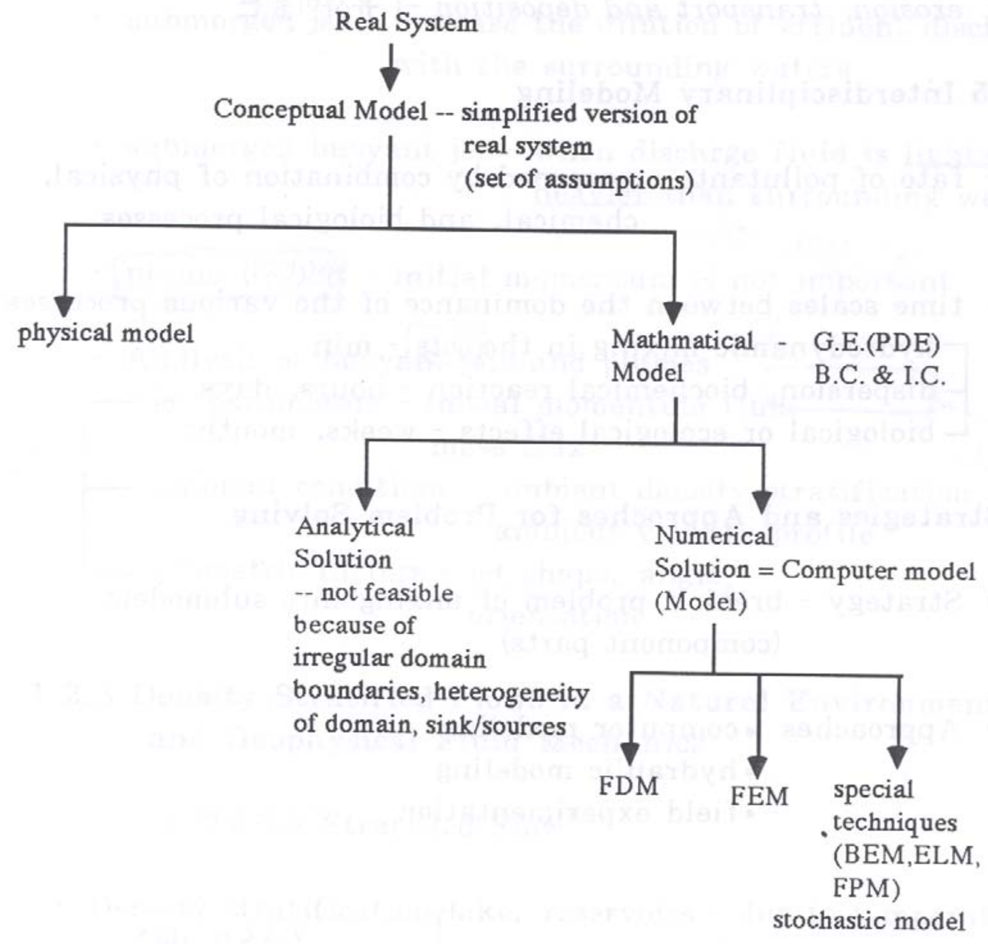
- time scales between the dominance of the various processes

- hydrodynamic mixing in the jets - min
- dispersion, biochemical reaction - hours, days
- biological or ecological effects - weeks, months

1.3 Strategies and Approaches for Problems Solving

- Strategy - break a problem of mixing into submodels (component parts)

- Approaches - computer modeling
  - hydraulic modeling
  - field experimentation



1.3.1 Strategies

◆ Problem identification

a) For acute toxic effects

- predict maximum instantaneous point concentration of a pollutant

b) For long-term ecological effects

- predict changes in monthly averages over broad areas

<Table 1.1> Effluent flow from a sewer outfall (ocean)

phase	phenomenon	length scale (m)	time scale (sec)
1	initial jet mixing	$< 10^2$	$< 10^3$
2	establishment of sewage field	$10 \sim 10^3$	$10^2 \sim 10^3$
3	natural lateral diffusion / dispersion	$10^2 \sim 10^4$	$10^3 \sim 10^5$
4	advection by currents	$10^3 \sim 10^5$	$10^3 \sim 10^6$
5	large scale flushing (by tidal motion)	$10^4 \sim 10^6$	$10^6 \sim 10^8$

◆ Definition of submodels

- **omnibus model** - cover all steps
- **component models** - break problems into components for different length and time scales

- simplifying (idealized) representations can be made

- concentrate on the dominant processes and important features of the environment

a) near-field model: initial jet and plume mixing occurs

b) far-field model: heat loss, natural lateral dispersion and advection by currents are dominant

- results from near-field model are used as input of far-field model

- probable errors in predictions of 25-50% are not unusaul

1.3.2 Approaches

◆ Order-of-magnitude analysis

- quick approximate solution (quick-and-dirty)
- scaling
- powers of ten
- show the correct dependence on the most important parameters
- based on dimensional analysis

(ex) Find longitudinal distance required for complete vertical mixing of surface discharge pollutants

mixing time $T = \alpha \dfrac{d^2}{\varepsilon_v}$ (time scale)

d = depth (cm)

ε_v = vertical eddy diffusivity (m^2 / s)

set $\varepsilon_v = 0.07 u^* d$

u^* = shear velocity = $\bar{u}\sqrt{\frac{f}{8}}$

f = Darcy – Weisbach friction factor

then $T = \alpha \frac{d^2}{0.07 d\bar{u}}\sqrt{\frac{8}{f}}$

$$\sqrt{\frac{8}{f}} \approx 15$$

$$\alpha \approx 0.35$$

$$\therefore T \approx 75\frac{d}{\bar{u}}$$

substitute $X = \bar{u}T$

$$\therefore \frac{x}{d} \approx 75 \approx 10^2$$

x = longitudinal distance required for complete vertical mixing

◆ Computer model:

- numerical solutions

- include meteorological factors

- avoid scaling errors

◆ Physical model:

- reproduce complex 3-D flows

- scaling errors → viscous effects are too strong in reduced laboratory models

- scaling based on Froude laws

1) Reynolds numbers are much reduced from the prototype

2) alter turbulence and resistance characteristics

- distorted model - big estuary (river) model

◆ Field Studies

- Eulerian-type measurements:
  - fixed-location recording meter

- Lagrangian experiments

- track flow trajectories and dispersion
- verify or adjust numerical models

◆ Mixed Approaches

- interweaving of all of the approaches

- better than single approach, computer model, hydraulic model, and field studies

1.4 Basic Definitions and Concepts

1.4.1 Concentration

- Concentration

\- units of mass of tracer or contaminant per unit volume

$$C = \lim_{\Delta V \to 0} \frac{\Delta M}{\Delta V}$$

where ΔM = tracer mass in elemental volume ΔV

- Time average of C

$$C = C(x, y, z, t)$$

$$\bar{C}(x, y, z, t_0) = \frac{1}{T}\int_{t_0}^{t_0+T} C(x, y, z, t)dt$$

where T = averaging time interval

\- sec, min for turbulence fluctuation

\- hours, day for unsteady flow

- Spatial average of C

$$\bar{C}_v(x_0, y_0, z_0, t) = \frac{1}{V}\iiint_{\Delta V} C(x, y, z, t)dV$$

\- wipes out turbulent fluctuations occurring on scales smaller than $V^{\frac{1}{3}}$

- Flux average of $C = \overline{C}_f$

◦ flux = mass per unit area per unit time

Flux of contaminant mass through AA

= $\overline{C}_f$ • (flux of water through AA)

$$\int_A C\ u\ dA = \overline{C}_f \int_A u\ dA = \overline{C}_f\ Q$$

$$\therefore\ \overline{C}_f(t) = \frac{1}{Q}\int_A C\,u\,dA$$

- Total mass M

$$M = \int_0^T \overline{C}_f(t)\ Q dt = \int_0^T \int_A C\ u\ dA dt$$

1.4.2 Dilution

- Dilution: rate at which tracer is diluted, S

$$S = \frac{total\ volume\ of\ sample (= vol.\ of\ mixture)}{volume\ of\ effluent\ contained\ in\ the\ sample}$$

S=1 → undiluted effluent

p = volume fraction of effluent in a sample

= 1/S = relative concentration

- mixture of effluent with ambient water of background concentration C_a

items	effluent	ambient water	mixture
vol.	vol_e	vol_a	$vol_e + vol_a$
conc. of contaminant	C_e	C_a	$\frac{vol_e C_e + vol_a C_a}{vol_e + vol_a}$ (harmonic mean)

$$\therefore\ C = \frac{vol_e C_e + vol_a C_a}{vol_e + vol_a} = \frac{(vol_e + vol_a)C_a + vol_e(C_e - C_a)}{vol_e + vol_a}$$

$$= C_a + \frac{vol_e}{vol_e + vol_a}(C_e - C_a)$$

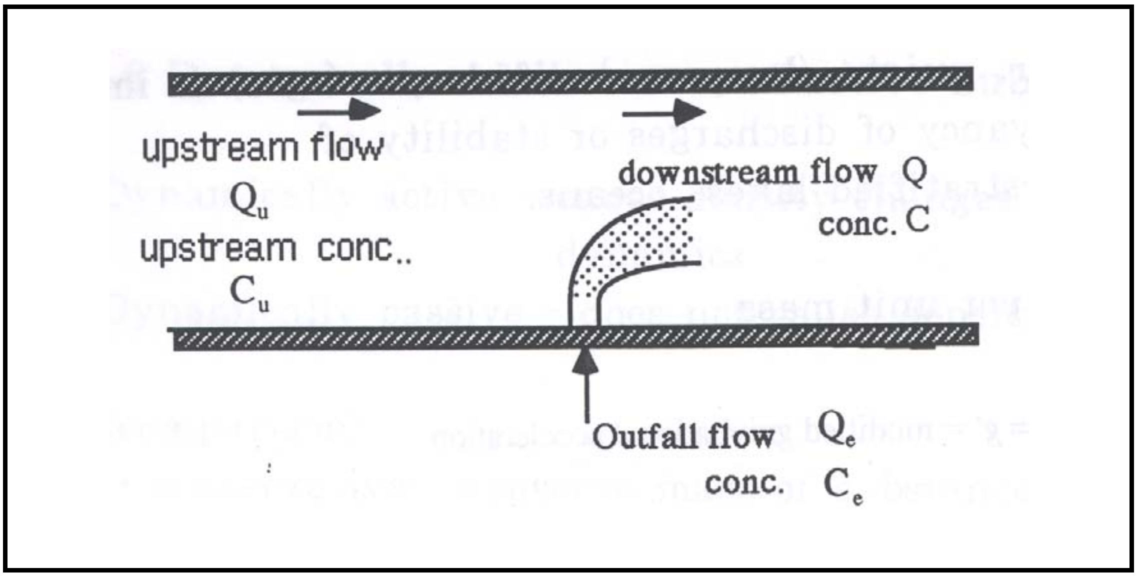
$$= C_a + P(C_e - C_a)$$

$$= C_a + \frac{1}{S}(C_e - C_a)$$

→ increment of concentration above background is reduced by the dilution factor *S* or *p* from the point of discharge to the point of measurement of e

$$\therefore\ p = \frac{C - C_a}{C_e - C_a}$$

$$S = \frac{C_e - C_a}{C - C_a}$$



Mass balance at effluent outfall

● After effluent is fully mixed across the section,

mass rate of substance upstream + mass rate added by outfall

= mass rate of substance downstream from outfall

$$Q_u C_u + Q_e C_e = QC$$

$w \Rightarrow Q_e C_e$ = impact waste load [M/T]

1.4.3 Average Dilution

- dilution of a composite sample

$$\overline{S} = \frac{total \quad vol.}{total \;\; effluent \;\; vol.} = \frac{1}{P} = \frac{\sum_{i=1}^{N} vol_i}{\sum_{i=1}^{N} vol_i \dfrac{1}{S_i}}$$

1.4.4 Density

- weight density of water plays an important role in mixing in water body

weight density = weight per unit volume

$= \rho g$ = weight/vol.

where ρ = mass density = *M/vol.*

g = gravitational acceleration

- Variation of ρ is less than 3% in estuary and ocean

$\Rightarrow$ unimportant for fluid acceleration

$\Rightarrow$ however, weight (buoyancy) difference ($= g\Delta\gamma$) is important for buoyancy of discharges of stability of density-stratified flows.

- buoyancy per unit mass

$$g\frac{\Delta\rho}{\rho} = g' = \text{ modified gravitational acceleration}$$

- $\sigma_t = \sigma - units$ for water density

$$\rho = 1 + \frac{\sigma_t}{1000}\ (g/cm^3)$$

$$= 1000 + \sigma_t (kg/m^3)$$

$$\sigma_t = \sigma - units$$

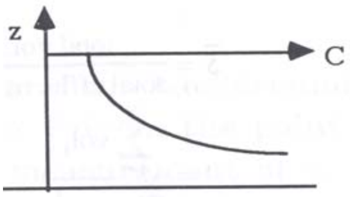
$$= f_n(temperature,\ salinity) \rightarrow See\ App.1$$

1.4.5 Density Stratification

· density profile $\rho_a(z)$

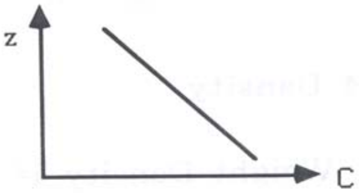
z = vertical coordinates

$$\frac{d\rho_a}{dz} < 0$$



· linear density stratification

$$-g\frac{d\rho_a}{dz} = const.$$



1.4.6 Dynamically Active versus Passive Substances

• Dynamically active substance:

- cause significant density changes to affect the flow dynamics
- heated water discharge
- need to recalculate flow fields at each time step → coupled model

• Dynamically passive substance:

- does not cause density changes
- wastewater discharge
- flow fields are separately calculated and used as given input to mixing analysis

→ scalar transport model

<cf> conservative substance: conserve mass

non-conservative substance: reactive, BOD

1.4.7 Velocity Distribution in Turbulent Shear Flow

- turbulent shear flow in a long pipe or channel

- driving force: pressure gradient and gravity

- resisting force: shear stresses at the wall

- velocity contour map (Fig.5.11)
- $u = u(y, z)$

- Vertical velocity distribution

- approximated by a logarithmic function

a) Pipe : $u = \bar{u} + \frac{3}{2}\frac{u^*}{\kappa} + \frac{2.30}{\kappa} u^* \log_{10} \frac{z}{R}$ (1.27)

b) Wide channel : $u = \bar{u} + \frac{u^*}{\kappa} + \frac{2.30}{\kappa} u^* \log_{10} \frac{z}{d}$ (1.28)

where z = distance from the wall
R = pipe radius
d = channel depth
κ = Von Karman constant ≈ 0.4

- mean velocity in the cross section related to mean wall shear stress

$$\tau_o = \frac{1}{8} f \rho \bar{u}^2 \quad \rightarrow \text{[re1]}$$

where τ_o = mean wall shear stress
f = Darcy-Weisbach friction factor

f - estimated from Moody diagram for circular pipes

- use Moody diagram $R_h = D/4$ with for open channels

$$\bar{u} = \frac{1}{A}\int_A u(y,z)dA$$

$$\sqrt{\frac{\tau_o}{\rho}} = \sqrt{\frac{f}{8}}\bar{u}$$

define

$$\sqrt{\frac{\tau_o}{\rho}} \equiv u^* = \text{ shear (friction) velocity } \rightarrow \text{[re2]}$$

• mean shear stress ← balance of force

$$\tau_o = \rho g R_h S$$

$$\therefore\ u^* = \sqrt{gR_hS} \qquad \rightarrow \text{[re3]}$$

$$\frac{\bar{u}}{u^*} = \sqrt{\frac{8}{f}}$$

[re1]

$$h_L = f\frac{L}{D}\frac{v^2}{2g}, \quad h_L = \frac{\tau_0 L}{\gamma R_h}$$

$$\therefore \tau_o \frac{L}{\gamma \frac{D}{4}} = f\frac{L}{D}\frac{v^2}{2g}$$

$$\therefore \tau_o = \frac{1}{8} f \rho v^2$$

[re2]

Shear velocity $= u^* = \sqrt{\frac{\tau_o}{\rho}} = \sqrt{gRS}$ for steady unsteady flow

$= \sqrt{gD\,(S_o - \frac{\partial D}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial x})}$ for

unsteady flow

- dimensions of velocity
- varies with the boundary friction τ_o

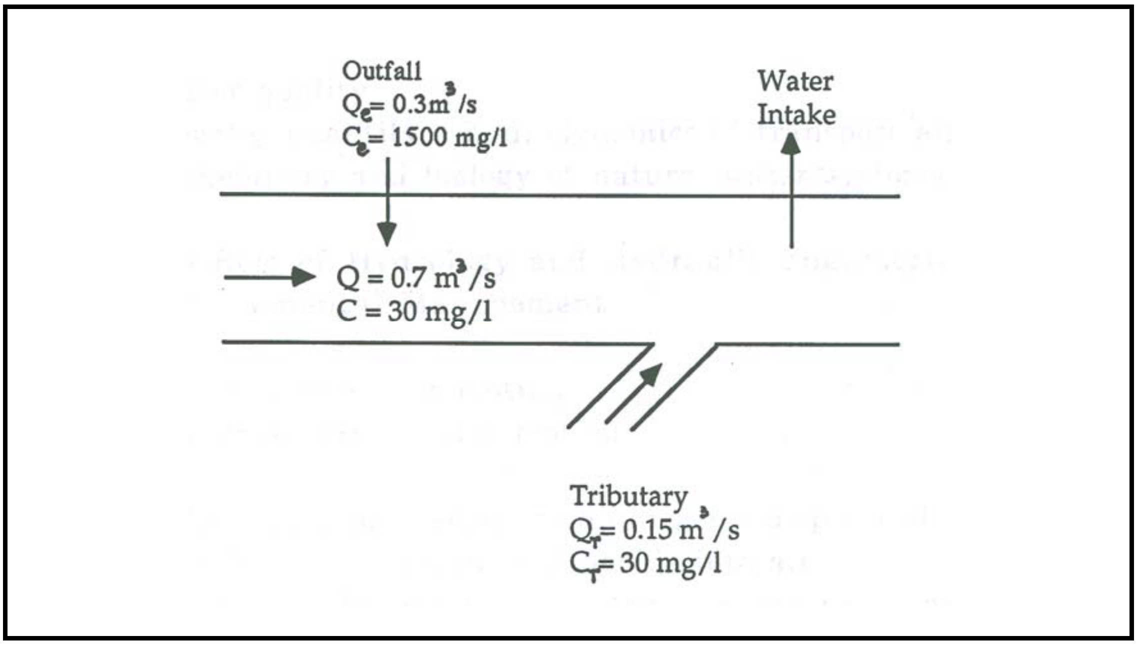
[re3]

$$\tau_o = \gamma R_h \frac{h_L}{l}$$

S_0 = channel slope for uniform flow

Homework #1

Due : 1 Week from Today



Upstream flow with a background level of chlorides, a conservative substance, of 30mg/ℓ is supplemented by an industrial discharge of $0.3m^3/s$ carrying 1,500mg/ℓ chlorides and a downstream tributary of $0.15m^3/s$ with background chlorides concentration of 30mg/ℓ. Assume downstream tributary chlorides concentration does not vary with flow.

To maintain a desired chlorides concentration of 250mg/ℓ at the water intake, determine: (a) the required industrial reduction in chloride concentration (b) the required increase in tributary flow.