Lecture 5: River Water Quality

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Objective: To introduce river water quality concepts and fundamentals

Previous class

- Discussion on parameters
  - Pathogens
  - Inorganic ions
  - Heavy metals
  - Organic compounds
  - Suspended solids
  - Excess nutrients

Implications of wastewater discharge on river water quality

- What happens when wastewater is discharged in river?
- Which parameter to study first?
- How to track trend of important parameter with time and distance along the movement of river?
- What other parameters to measure?

Dissolved oxygen (DO)

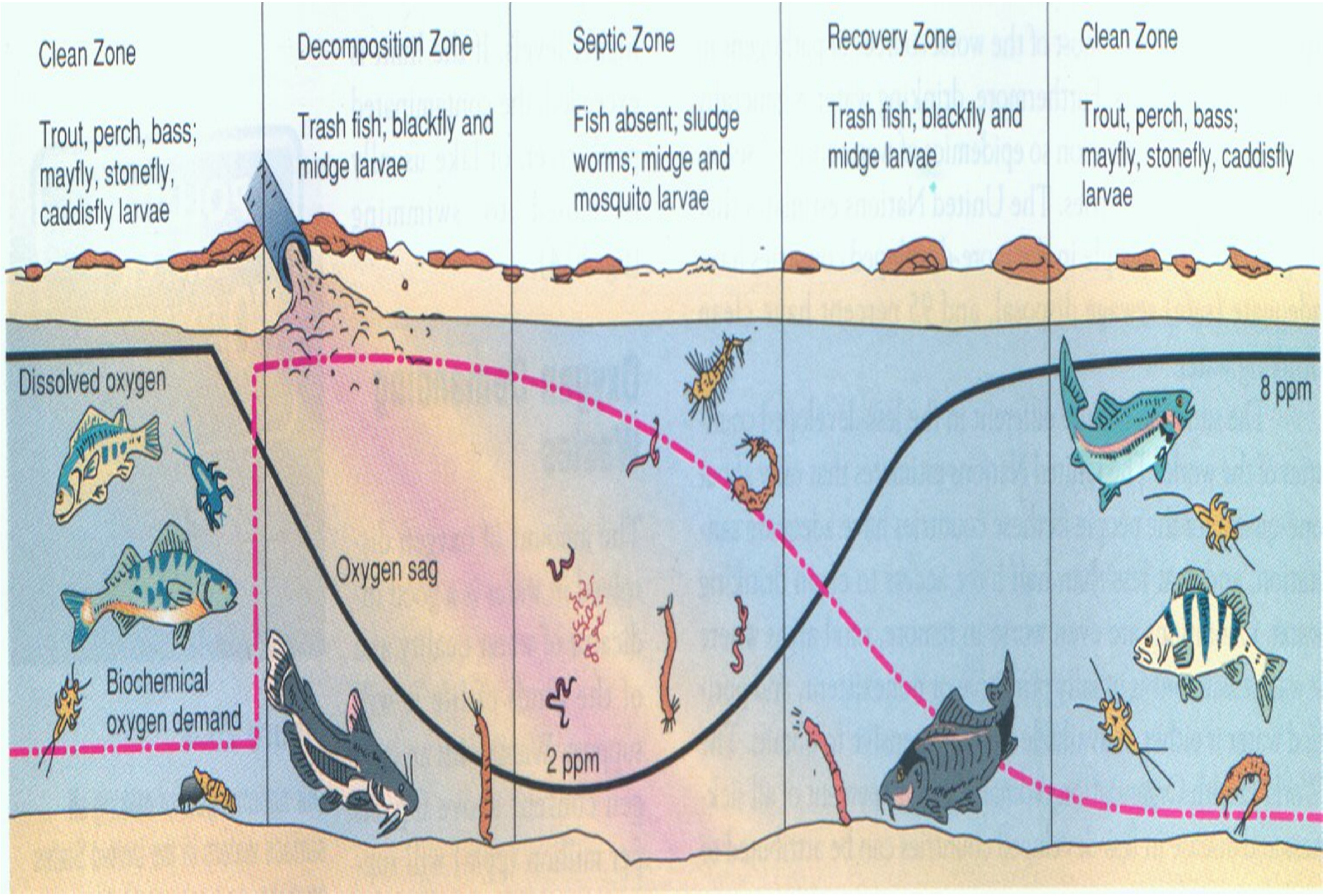
- Important for aquatic species-need some minimum level of DO
- Important for aquatic plants
- Lack of DO can result in development of anaerobic conditions which can be result in anaerobic breakdown; generation of methane and carbon dioxide

Dissolved oxygen (DO)

- What are factors that affect the amount of dissolved oxygen concentration in a river?
- What is the approximate dissolved oxygen concentration in a healthy natural water body?
- Which are the steps in developing a DO sag curve?
- How is the lowest DO concentration point in the sag curve called?
- If there was no change in the waste addition in a stream throughout the year, will the DO be higher in winter or summer?

Effect of Oxygen Demanding Wastes on Rivers

- Amount of dissolved oxygen (DO) in water is the most commonly used indicator of a river's health.
- The solubility of oxygen depends on temperature, pressure, and salinity and the dissolved oxygen concentration in a healthy stream ranges from 7-9 mg/L.
- As DO drops below 4 or 5 mg/L the forms of life that can survive begin to be reduced.
- In an extreme case, when anaerobic conditions exist, most higher forms of life are killed.



(Source: Environmental Science: A Global Concern, 3rd ed. by W.P Cunningham and B.W. Saigo, WC Brown Publishers, © 1995)

Dissolved Oxygen Depletion

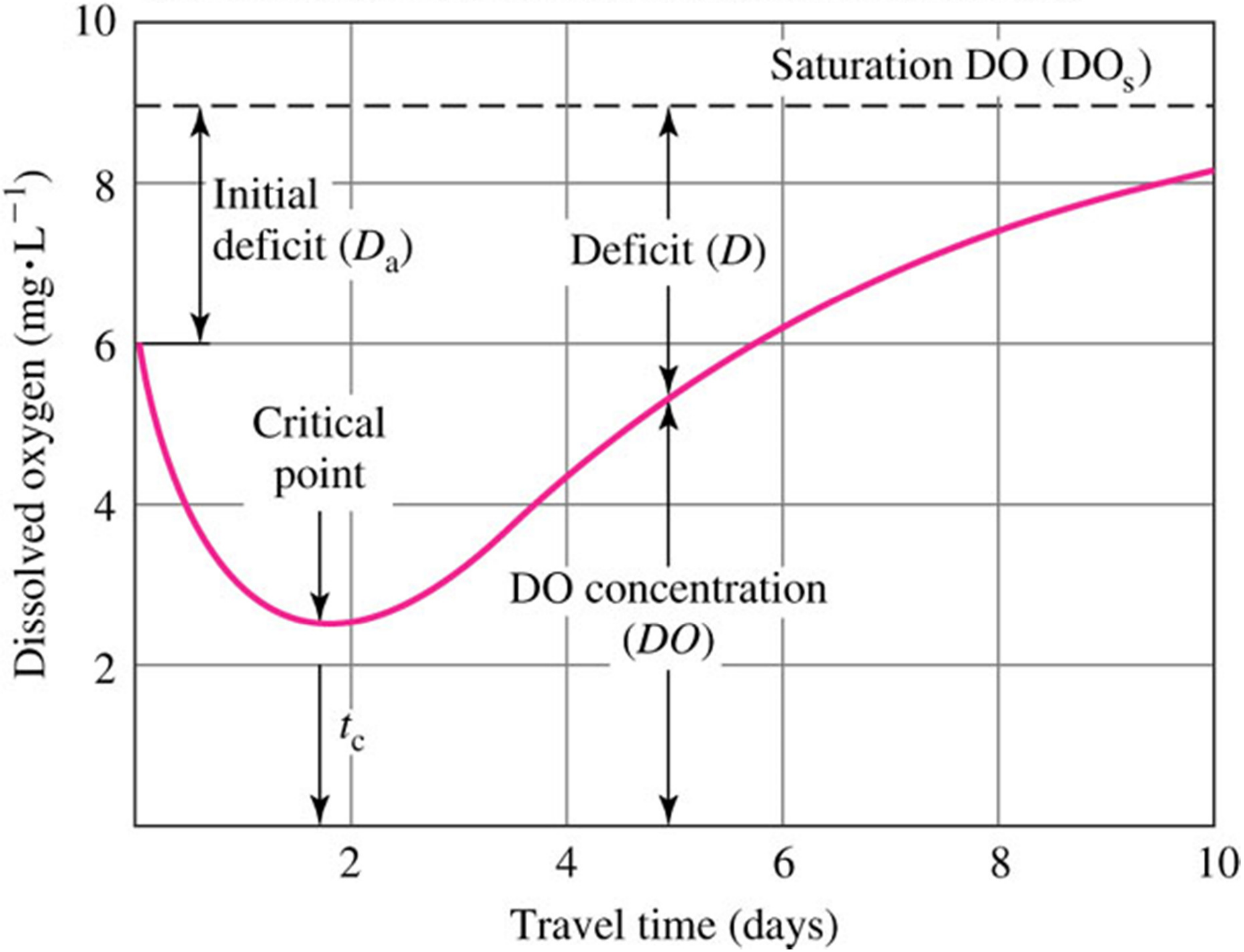
Factors Affecting Amount of DO Available in Rivers

- Oxygen demanding wastes affect available DO
- Tributaries bring their own oxygen supply
- Photosynthesis adds DO during the day but the same plants remove oxygen at night
- Respiration of organisms living in water as well as in sediments remove oxygen
- In the summer rising temperatures reduce solubility of oxygen
- In the winter oxygen solubility increases, but ice may form blocking access to new atmospheric oxygen

Modeling DO in a River

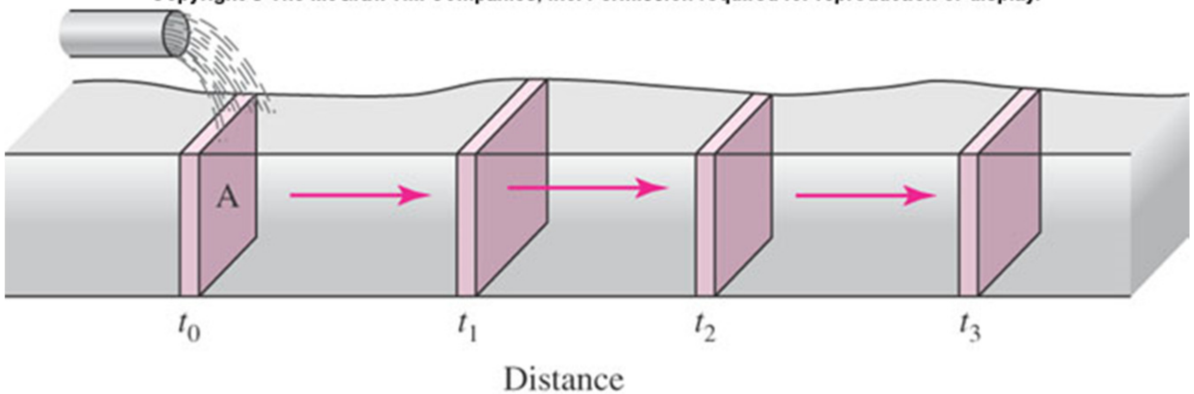
- To model all the effects and their interaction is a difficult task
- The simplest model focuses on two processes:
  - The removal of oxygen by microorganisms during biodegradation (de-oxygenation)
  - The replenishment of oxygen at the interface between the river and the atmosphere (re-aeration)

Dissolved Oxygen Sag Curve



Mass Balance Approach

- River described as "plug-flow reactor"



- Mass balance
- Oxygen is depleted by BOD exertion (de-oxygenation)
- Oxygen is gained through re-aeration

Steps in Developing the DO Sag Curve

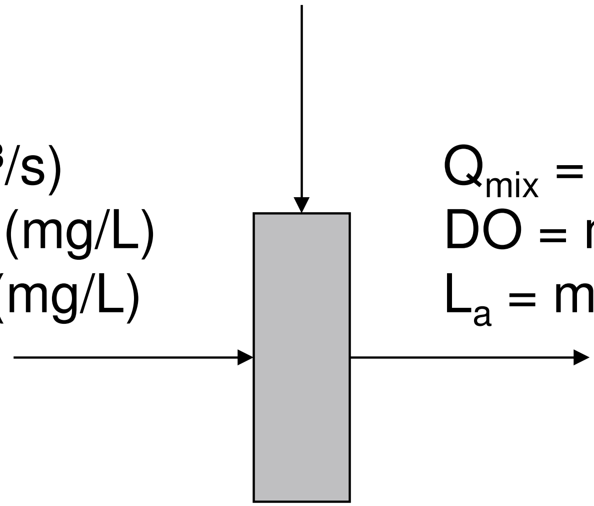
1. Determine the initial conditions
2. Determine the de-oxygenation rate from BOD test and stream geometry
3. Determine the re-aeration rate from stream geometry
4. Calculate the DO deficit as a function of time
5. Calculate the time and deficit at the critical point (worst conditions)

1. Determine Initial Conditions

Mass Balance for Initial Mixing

Q_w = waste flow (m^3/s)
DO_w = DO in waste (mg/L)
L_w = BOD in waste (mg/L)

Q_r = river flow (m^3/s)
DO_r = DO in river (mg/L)
L_r = BOD in river (mg/L)



Q_{mix} = combined flow (m^3/s)
DO = mixed DO (mg/L)
L_a = mixed BOD (mg/L)

a. Initial dissolved oxygen concentration:

$$DO = \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r}$$

b. Initial DO deficit:

$$D_a = DO_s - DO$$

where:

D_a=initial DO deficit (mg/L)

DO_s=saturation DO conc.(mg/L)

Therefore, the initial deficit after mixing is

$$D_a = DO_s - \frac{Q_w DO_w + Q_r DO_r}{Q_{mix}}$$

where D_a is the initial deficit (mg/L)

Note: DO_s is a function of temperature, atmospheric pressure, and salinity. Values of DO_s are found in tables.

Solubility of Oxygen in Water ($DO_s = DO_{saturation}$)

DO_s is a function of temperature, atmospheric pressure and salinity

	Chloride concentration in water (mg/L)			
Temperature (°C)	0	5000	10,000	15,000
0	14.62	13.73	12.89	12.10
5	12.77	12.02	11.32	10.66
10	11.29	10.66	10.06	9.49
15	10.08	9.54	9.03	8.54
20	9.09	8.62	8.17	7.75
25	8.26	7.85	7.46	7.08
30	7.56	7.19	6.85	6.51

Source: Thomann and Mueller (1987).

c. Initial ultimate BOD concentration:

If, the BOD data for the waste or river are in terms of BOD_5, calculate L for each

$$L = \frac{BOD_t}{1 - e^{-kt}}$$

Therefore, initial *ultimate* BOD concentration

$$L_a = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r}$$

2. Determine De-oxygenation Rate

rate of de-oxygenation = $k_d L_t$

where: k_d = de-oxygenation rate coefficient (day^{-1})

L_t = ultimate BOD remaining at time (of travel down-stream) t

If k_d (stream) = k (BOD test) and $$L_t = L_0 e^{-k_d t}$$

$$\text{rate of de-oxygentation} = k_d L_0 e^{-k_d t}$$

3. Determine Re-aeration Rate

rate of re-aeration = $k_r D$

k_r = re-aeration constant ($time^{-1}$)
D = dissolved oxygen deficit (DO_s-DO)
DO_s = saturated value of oxygen
DO = actual dissolved oxygen at a given location downstream

- O'Connor-Dobbins correlation:

$$k_r = \frac{3.9u^{1/2}}{h^{3/2}}$$

where k_r = re-aeration coefficient @ 20ºC (day^{-1})

u = average stream velocity (m/s)

h = average stream depth (m)

- Correct rate coefficient for stream temperature

$$k_r = k_{r,20}\Theta^{T-20}$$

where Θ = 1.024

4. DO as function of time (Streeter-Phelps equation or oxygen sag curve)

- Rate of increase of DO deficit = rate of deoxygenation – rate of reaeration

$$\frac{dD}{dt} = k_d L_t - k_r D$$

- Solution is:

$$D_t = \frac{k_d L_o}{k_r - k_d}\left(e^{-k_d t} - e^{-k_r t}\right) + D_a\left(e^{-k_r t}\right)$$

5. Calculate Critical time and DO

Critical Point = point where steam conditions are at their worst

$$t_c = \frac{1}{k_r - k_d} \ln\left[\frac{k_r}{k_d}\left(1 - D_a \frac{k_r - k_d}{k_d L_a}\right)\right]$$

$$D_c = \frac{k_d L_a}{k_r - k_a}\left(e^{-k_d t_c} - e^{-k_r t_c}\right) + D_a e^{-k_r t_c}$$

D = dissolved oxygen deficit

Example 1

Q2. Problem # 3-19 (Peavy et al. Text Book). A wastewater treatment plant disposes of its effluent in a surface stream. Characteristics of the stream and effluent are shown below. [5+5+5 points]

Parameter	wastewater	stream
flow (m^3/s)	0.2	5
Dissolved oxygen, mg/L	1	8
Temperature, °C	15	20.2
BOD_5 at 20°C, mg/L	100	2
Oxygen consumption rate (K1 at 20°C) (1/day)	0.2	-
Oxygen reaeration rate (K2 at 20°C) (1/day)	-	0.3

(a) What will be the dissolved oxygen conc. in the stream after 2 days?

(b) What will be the lowest dissolved oxygen concentration as a result of the waste discharge?

(c) Also calculate the maximum BOD_5 (20°C) that can be discharged if a minimum of 4.0 mg/L of oxygen must be maintained in the stream?

Answer:

Parameter	wastewater (given)	stream (given)	Wastewater and stream water mixture
flow (m^3/s)	0.2	5	$=Q_{mixture}=5+0.2=5.2$ m/s
Dissolved oxygen, mg/L	1	8	$DO_{mixture}=(0.2*1+8*5)/(5+0.2)$ =7.73 mg/L
Temperature, °C	15	20.2	$Temp_{mixture}=(0.2*15+20.2*5)/(5+0.2)$ =20 deg C (No temp. correction required)
BOD_5 at 20°C, mg/L	100	2	$BOD_{mixture}=(0.2*100+2*5)/(5+0.2)$ =5.77 mg/L
Oxygen consumption rate (K1 at °C) (1/day)	0.2		0.23 (No temp. correction required) (assumed for stream water)
Oxygen reaeration rate (K2 at °C) (1/day)	-	0.3	0.3 (No temp. correction required)

Ultimate BOD= $Y_{ultimate}$=L_0 = (5-day BOD in mixture water)/[1-exp(-K1$_{mixture}$*5)]
=(5.77 mg/L)/ [1-exp(-0.23*5)] =8.44 mg/L

Initial DO deficit (D_0)
For 20°C stream water temperature, equilibrium concentration of oxygen =9.17 mg/L
D_0 = 9.17 mg/L-7.73 mg/L = 1.44 mg/L

To get DO after 2 days in stream water after mixing, we need to calculate DO deficit after 2 days first and then calculate DO (at 2days). DO deficit at 2 days is given by
D (t=2 days) = [K1*L_0]*[exp (-K1*t)-exp (-K2*t)]/ (K2-K1) + D_0 exp (-K2*t)
= [0.2*8.44]*[exp (-0.2*2)-exp (-0.3*2)]/ (0.3-0.2) + 1.44 exp (-0.3*2)
= [1.94]*[0.6703-0.5488]/ (0.07) + 0.7903 =3.07 mg/L

D (t=2 days) = DO$_{saturated}$-DO (2day) = 3.07 mg/L
DO (2day) = 9.17-3.07=**6.10 mg/L (answer for part i)**

Time for critical DO deficit (t_c)
= 1/ (K2-K1)*ln [(K2/K1)*(1-D_0 *(K2-K1)/ (K1L_0))]

$= 1/(0.3-0.23)*\ln[(0.3/0.23)*(1-1.44*(0.3-0.23)/(0.23*8.44))]$

$= 14.29*\ln[1.3*(1-1.44*0.036)] = 14.29*\ln[1.23] = 2.95$ days

Critical DO deficit $(D_c) = (K1/K2)*L_0 \exp(-K1*t_c)$

$= (0.23/0.3)*8.44 \exp(-0.23*2.95) = 6.47*0.507 = 3.28$ mg/L

$D_c = DO_{saturated} - DO_{critical} = 3.28$ mg/L => $DO_{critical} = 9.17-3.28$**=5.89 mg/L (answer for part ii)**

Required minimum DO = 4.0 mg/L in stream water. As DO at critical location is 5.89 mg/L, greater than the recommended DO level, no modification in wastewater effluent characteristics is required.

To calculate maximum BOD_5 in effluent water, calculate allowable DO deficit (i.e., $D_{allowable}$) $= DO_{saturated} - DO_{minimum} = 9.17 - 4.0 = 5.17$ mg/L [Note that 5.17 mg/L DO deficit is allowable and we are having 5.89 mg/L critical DO deficit.]

Now with calculated allowable DO deficit (this is assumed to be the critical deficit now) and calculated $t_{critical}$ (assumed to be similar to previous case, i.e., 2.95 days), calculate ultimate BOD in this case. Then calculate 5-day BOD of the mixture stream water and then calculate 5-day BOD of the effluent which will be the desired maximum 5-day BOD value.

$D_{allowable}\ (t=t_{critical}) = D_{critical,new}$

$\Rightarrow 5.17 = (0.23/0.30)*L_0\ [\exp(-0.23*2.95)] = 0.77*0.51L_0 = 0.3927L_0$

$\Rightarrow$ Ultimate BOD of the mixture water = $L_0 = 5.19$ mg/L/ (0.3927) =13.17 mg/L

Now 5-day BOD in mixture water is calculated.

5-day $BOD_{mixture} = L_0 *[1-\exp(-K1_{mixture}*5)] = (13.17 \text{ mg/L})*[1-\exp(-0.23*5)] = 9.0 \text{ mg/L}$

5-day BOD in effluent water is calculated now.

$BOD_{mixture} = (\text{5-day } BOD_{eff} Q_{eff} + \text{5-day } BOD_{stream} Q_{stream}) / (5+0.2)$

$9.0 \text{ mg/L} = (\text{5-day } BOD_{eff}*0.2+2*5)/(5+0.2)$

5-day $BOD_{eff} *0.2+10 = 9.0*5.2 = 46.8$

=> 5-day $BOD_{eff} = (46.8-10)/0.2 =$ **184 mg/L (answer for part iii). This is maximum value of 5-day BOD in wastewater effluent which can be discharged in the stream water without exceeding the minimum required DO value of 4 mg/L.**