Civil Engineering Department

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CVG2132 – FUNDAMENTALS OF ENVIRONMENTAL ENGINEERING

Homework 4: Solutions Professor: Rob Delatolla

Due Date: Dec. 1, 2017 (3:45 pm) – Drop box « CVG 2132 », Mezzanine A (0.5) CBY

Question 1. A sample of river water was acquired as an attempt to characterize the health of the water source. Part of this characterization was to determine the biological oxygen demand (BOD) of the river water with precision. The measurement was repeated four time using four different dilutions to determine an accurate BOD_5 of the river water.

All four BOD_5 had a total volume of 300 mL and had the same initial dissolved oxygen (DO) concentration of 8.2 mg O_2/L.

The dilution water was non-seeded distilled water. No seed was added as it was assumed there would be an adequate microbial population in the sample water.

(a) Based on the measurement results below, determine which of the tests enable one to determine an accurate BOD_5 measurement of the river:
Sample A – 300 mL of sample water was used and a final DO concentration of 0.06 mg O_2/L was measured;
Sample B – 10 mL of sample water was used and a final DO concentration of 7.6 mg O_2/L was measured;
Sample C – 100 mL of sample water was used and a final DO concentration of 3.1 mg O_2/L was measured;
Sample D – 150 mL of sample water was used and a final DO concentration of 0.74 mg O_2/L was measured;
Blank – 300 mL of dilution water was used and a final DO concentration of 8.2 mg O_2/L was measured.

(b) Determine the BOD_5 of the river water.

(c) What are two storage based factors that could invalidate the BOD test. Why do they invalidate the test?

Solution: The objective of this problem is to familiarise you with the BOD process and what factors can interfere with the process.

Step 1: Determine which samples are valid
Samples A and D are not valid because the residual dissolved oxygen concentrations are below 2 mg O_2/L and therefore cannot be used to accurately measure the BOD. This is because the precision of the DO probe decreases at lower DO concentrations and the test could be limited by the oxygen concentration rather than the BOD.

Sample B is not valid because the decrease in dissolved oxygen was less than 2 mg O_2/L meaning that the decrease in oxygen may not entirely be attributed to changes in DO due to the precision limitations of the DO probe.

Sample C is within the measurement range that ensures accuracy because it had a final DO concentration of greater than 2 mg O_2/L and a total decrease of more than 2 mg O_2/L.

Step 2: Determine the BOD_5 of the river

$BOD_5 = [(DO_i - DO_f) - (DO_{Bi} - DO_{Bf})(1-P)] / (P)$

For Sample C V_s = 100 mL and V_t = 300 mL

$P = V_s/V_t$ = 100 mL/300 mL = 0.333

BOD_5 = [(8.2 mg O_2/L – 3.1 mg O_2/L) – (8.2 mg O_2/L – 8.2 mg O_2/L)(1-0.333)]/ 0.3333

BOD_5 = 15.3 mg O_2/L

Therefore the BOD_5 of the river water is 15.3 mg O_2/L

Step 3: Determine other factors which could invalidate the BOD test

Two storage based factors that could invalidate the BOD test are that it could have been stored at the wrong temperature (i.e not 20˚C) which would affect incubation of the bacteria and consumption of the oxygen, it could have been stored in a location that is not dark which could cause the growth of algae, or the bottle could have been improperly sealed which would cause reaeration.

Question 2. A treated wastewater effluent contains carbonaceous compounds that can be approximated by 43 mg of glucose ($C_6H_{12}O_6$) per litre and nitrogen compounds that can be expressed as 16 mg NH_3-N/L. What is the carbonaceous UBOD, nitrogen UBOD and the total UBOD? If the carbonaceous BOD rate constant is 0.17 1/d, does the treated wastewater meet the federal effluent guideline of 25 mg BOD_5/L?

$$C_6H_{12}O_6 + 6\,O_2 \leftrightharpoons 6\,CO_2 + 6\,H_2O$$
$$NH_3 + 2\,O_2 \leftrightharpoons NO_3^- + H^+ + H_2O$$

Solution: The objective of this problem is to familiarise you with the determination of UBOD and BOD_5 from chemical constituents

Step 1: Determine the carbonaceous UBOD

The first step to determine the carbonaceous UBOD is to determine the molar concentration of glucose.

MW_C = 12 g/mol

MW_H = 1 g/mol

MW_O = 16 g/mol

MW_{O2} = 32 g/mol

$MW_{C6H12O6} = 6*MW_C + 12*MW_H + 6*MW_O$

$MW_{C6H12O6}$ = 6*12 g/mol + 12*1 g/mol + 6*16g/mol = 180 g/mol

$[C_6H_{12}O_6]$ = 43 mg/L * 1g/1000 mg/ 180 g/mol = $2.39\text{x}10^{-4}$ M

From the stoichiometric equation, 6 mols of oxygen gas are consumed per mol of glucose oxidised.

Therefore $[O_2]_{req}$ = $2.39\text{x}10^{-4}$ M * 6 mols O_2/mol * 32 g O_2/mol O_2 * 1000 mg/g= 45.87 mg O_2/L

Therefore the carbonaceous UBOD is 45.87 mg O_2/L

Step 2: Determine the nitrogen UBOD

As with step 1, we need to determine the molar concentration of ammonia nitrogen.
Note that in the problem the ammonia concentration was given as nitrogen meaning that MW = 14 g/mol instead of 17 g/mol
Therefore $[NH_3\text{-}N]$ = 16 mg/L *1g/1000mg/ 14 g/mol = 1.14×10^{-3}M
From the stoichiometric equation 2 mols of oxygen gas are consumed per mol of ammonia nitrogen converted
Therefore $[O_2]_{req}$ = 1.14×10^{-3}M*2 mol O_2/mol*32 g/mol *1000 mg/g = 73.14 mg O_2/L
Therefore the nitrogen UBOD is 73.14 mg O_2/L

Step 3: Determine the total UBOD

The UBOD is the total of the carbonaceous BOD and the nitrogen BOD
Therefore $UBOD_t$ = cUBOD + nUBOD
$UBOD_t$ = 45.87 mg O_2/L + 73.14 mg O_2/L = 119.01 mg O_2/L
Therefore the total UBOD is 119.01 mg O_2/L

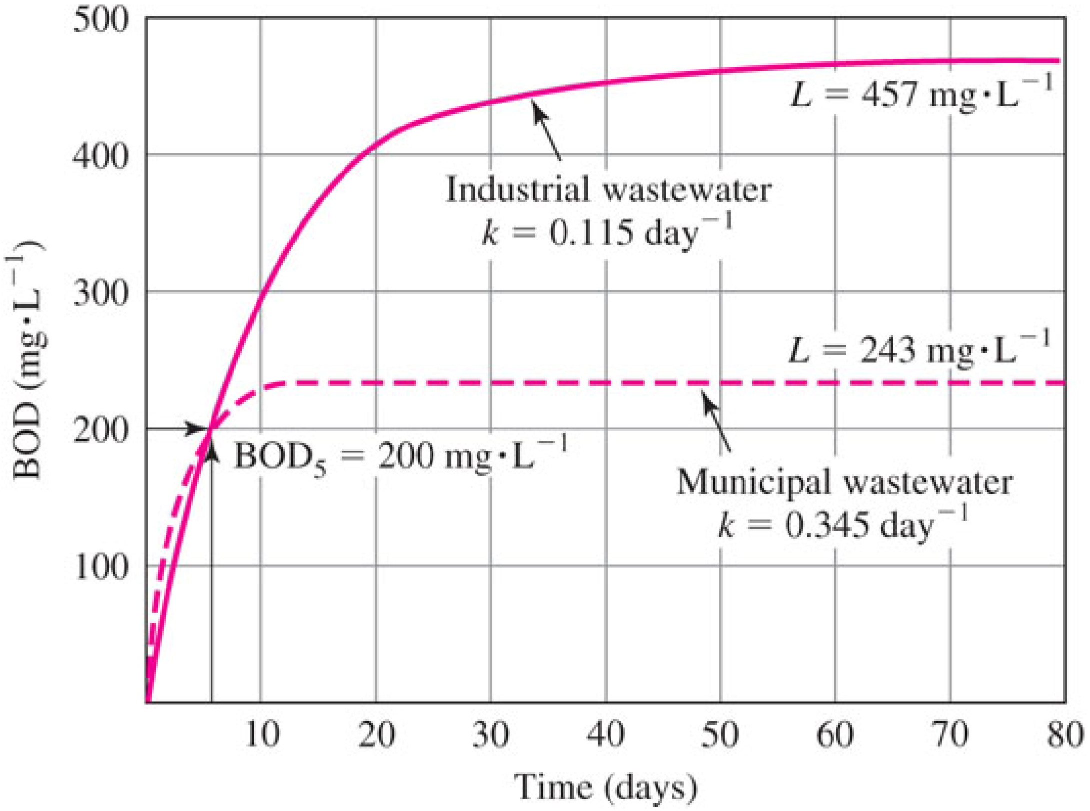
Step 4: Determine the BOD_5 and see if it exceeds 25 mg O_2/L

The carbonaceous BOD rate constant was given to be 0.17 1/d and the carbonaceous UBOD was determined to be 45.87 mg O_2/L
L_0 = 45.87 mg O_2/L
From the lecture 12 notes:
$BOD_t = L_0(1-e^{-kt})$
As we are looking for BOD_5 t = 5 days
BOD_5 = 45.87 mg O_2/L *($1 - e^{-0.17 * 5}$) = 26.26 mg O_2/L
Therefore the BOD_5 just exceeds the limit

Question 3. If two samples from different water sources have the same BOD_5 does that mean that both samples have the same UBOD? Explain your reasoning.

Solution: The purpose of this problem is to familiarise you with how kinetics work

If two samples have the same BOD_5 then they do not necessarily have the same UBOD. This is because the BOD_5 value is effected by both the reaction kinetics and the BOD remaining in the system and therefore a system with a lower reaction kinetic constant but a higher UBOD could have the same BOD_5 as another system with a higher kinetic constant and a lower UBOD.



From Lecture 12 slide 12

Question 4: A municipal wastewater treatment plant discharges 75,000 m^3 per day of secondary effluent containing 20 mg/L of BOD_5 at 25.2°C with a carbonaceous rate constant of 0.22 1/d and a dissolved oxygen concentration of 1.2 mg/L. The receiving stream has a flow of 4.25 m^3/s at a velocity of 0.35 m/s and an average depth of 2.0 m. The temperature of the stream before the wastewater enters is 21°C. The stream is 75% saturated with oxygen and has an ultimate BOD of 2.0 mg/L. The reaeration (k_r) and deoxygenation (k_d) rate coefficients of the stream at 20°C are 0.35 1/d and 0.2 1/d, respectively. Determine the following:

(a) the UBOD of the wastewater stream before mixing

(b) the temperature of the combined wastewater and stream;

(c) the dissolved oxygen concentration of the mixture at the location of initial mixing;

(d) the DO deficit of the mixture at the location of initial mixing;

(e) the ultimate BOD concentration of the mixture at the location of initial mixing;

(f) the distance downstream (x_c) to the point of minimum DO concentration;

(g) the minimum DO concentration in the stream

Solution: The objective of this problem is to walk you through the process of solving a DO sag problem.
Given:
Q_W = 75000 m^3/d
$BOD_{5,W}$ = 20 mg/L
T_W = 25.2˚C
k = 0.22 1/d
DO_W = 1.2 mg/L
Q_R = 4.25 m^3/s
u = 0.35 m/s
H = 2.0m
T_R = 21˚C
$L_{0,R}$ = 2.0 mg/L
$DO_R = 0.75*DO_{S,R}$
k_r = 0.35 1/d
k_d = 0.2 1/d
NOTE: The subscript 0 refers to the mixing point, the subscript W refers to the wastewater treatment plant, the subscript R refers to the receiving waters, the subscript S refers to saturation and the subscript c refers to the critical point

Assumptions:

- There is no change in flow velocity from the addition of the two streams;
- The river is completely mixed in the lateral direction but not in the longitudinal direction;
- 1-dimensional model in the direction of flow;
- Two reaction processes are assumed to be essential i) reaeration is due to stream turbulence and ii) deoxygenation is due to initial DO mixing and BOD effects;
- The temperature of the combined streams is assumed to be constant;
- Steady state, instantaneous mixing and dilute conditions at the point of mixing.

<u>(a) Determine the UBOD (L_0) of the wastewater stream</u>
From lec 12 we know the $BOD_t = L_0(1-e^{-kt})$ therefore we can rearrange the equation to determine L_0
$L_0 = BOD_t/(1-e^{-kt})$
We know that BOD_5 = 20 mg/L, t = 5 d and k = 0.22 1/d
$L_0 = 20 \text{ mg/L}/ (1-e^{-(5d)*(0.22\ 1/d)})$ = 29.98 mg/L = 30 mg/L

<u>(b) Determine the temperature of the combined wastewater and stream</u>
We have the flowrate of the river in units of m^3/s and the flowrate from the wastewater treatment plant in terms of m^3/d so the first thing we must do is make the units match. In this case we can change the units of the wastewater treatment plant

Q_W = 75,000 m^3/d * 1d/24h * 1h/60min * 1min/60 sec = 0.868 m^3/s
Therefore even though the flow from the plant seems very large, it is less than a quarter of that of the receiving waters

To determine the combined temperature we can use the equation from Lec 13
Note that for all mass balance equations we use to solve this problem, we made the assumption above of steady state, instantaneous mixing and dilute conditions at point of mixing.

$T_0 = (Q_W T_W + Q_R T_R) / (Q_W + Q_R)$
$T_0 = (0.868\ m^3/s*25.2^\circ C + 4.25\ m^3/s*21^\circ C)/ (0.868\ m^3/s + 4.25\ m^3/s) = 21.7^\circ C$

<u>(c) Determine the concentration of dissolved oxygen at the point of mixing</u>
To determine the DO concentration at the mixing point we simply need to do a mixing point calculation

$DO_0 = (Q_W DO_W + Q_R DO_R)/(Q_W + Q_R)$

However we do not know the value of DO_R
We do know that $DO_R = 0.75*DO_{S,R}$ meaning that the DO concentration of the river is equal to 75% of the saturation concentration PRE-MIXING.

At 21˚C the saturation concentration is 8.99 mg O_2/L
Therefore $DO_R = 0.75*DO_{S,R} = 0.75*8.99$ mg O_2/L = 6.74 mg O_2/L

$DO_0 = (0.868\ m^3/s * 1.2\ mg\ O_2/L + 4.25\ m^3/s* 6.74\ mg\ O_2/L)/(0.868\ m^3/s + 4.25\ m^3/s)$
$DO_0 = 5.8\ mg\ O_2/L$

<u>(d) Determine the DO deficit at the mixing point</u>
The DO deficit, D_0, is the difference between the DO saturation concentration and the actual DO of the system.
In section (c) we found the actual DO of the system to be 5.8 mg O_2/L however we still need DO_S
In section (b) we found the temperature of the mixed system which can be used to find the DO_S
At 21.7˚C DO_S = 8.8 mg O_2/L
$D_0 = DO_S – DO_0 = 8.8\ mg\ O_2/L – 5.8\ mg\ O_2/L = 3\ mg\ O_2/L$

<u>(e) Determine the UBOD concentration at the mixing point</u>
Like in sections (b) and (c) this is a simple mixing point calculation

$L_W = 30$ mg/L

$L_0 = (Q_W L_W + Q_R L_R)/(Q_W + Q_R)$
$L_0 = (0.868\ m^3/s * 30\ mg/L + 4.25\ m^3/s * 2.0\ mg/L)/(0.868\ m^3/s + 4.25\ m^3/s) = 6.75\ mg/L$

<u>(f) Determine the distance downstream (x_C) to the point of the minimum DO concentration</u>

The first step to solving for these parameters is to adjust the reaeration and deoxygenation coefficients to the new river temperature.

As T_0 is between 20˚C and 25˚C, θ = 1.056

$k_{d(T)} = k_{d(20)}\theta^{(T\text{-}20)}$; $k_{d(21.7)} = k_{d(20)}1.056^{(21.7\text{-}20)} = 0.2\text{x}1.056^{(21.7\text{-}20)} = 0.22$ 1/d

$k_{r(T)} = k_{r(20)}\theta^{(T\text{-}20)}$; $k_{r(21.7)} = k_{r(20)}1.056^{(21.7\text{-}20)} = 0.35\text{x}1.056^{(21.7\text{-}20)} = 0.38$ 1/d

Next we can determine the travel time to the critical point (point at which the DO is at its minimum)

$$t_c = \frac{1}{k_r - k_d} ln\left[\frac{k_r}{k_d}\left(1 - D_0 \frac{k_r - k_d}{k_d L_0}\right)\right]$$

Substituting in the values, we get:

$$t_c = \frac{1}{0.38\frac{1}{d} - 0.22\frac{1}{d}} ln\left[\frac{0.38\frac{1}{d}}{0.22\frac{1}{d}}\left(1 - 3\frac{mg}{L} * \frac{0.38\frac{1}{d} - 0.22\frac{1}{d}}{0.22\frac{1}{d} * 6.75\frac{mg}{L}}\right)\right] = 0.986\ d$$

Now that we have the time it takes to reach the critical point and the velocity of the water, therefore we can find the location of the downstream critical point.

$x_c = t_c$*u
x_c = 0.986d * 24h/d *60 min/h *60 s/min * 0.35 m/s = 29816.64 m *1 km/1000m = 29.8 km

<u>(g) Determine the minimum DO concentration in the stream</u>

$$D_c = \frac{k_d L_0}{k_r - k_d}\left(e^{-k_d t_c} - e^{-k_r t_c}\right) + D_0\left(e^{-k_r t_c}\right)$$

Substituting in our values, we get:

$$D_c = \frac{0.22\frac{1}{d} * 6.75\frac{mg}{L}}{0.38\frac{1}{d} - 0.22\frac{1}{d}}\left(e^{-0.22*0.986} - e^{-0.38*0.986}\right) + \frac{3\ mg}{L}\left(e^{-0.38*0.986}\right) = 3.15\ mg/L$$

$DO_c = DO_S - D_c$
DO_c = 8.8 mg/L – 3.15 mg/L = 5.65 mg/L

Therefore the minimum DO concentration is 5.65 mg/L at a distance of 29.8 km downstream

Question 5. The town of Rockland and surrounding municipalities have decided to combine their waste streams and treat all of these streams at the Rockland wastewater treatment plant, therefore Rockland has a need to upgrade the capacity of their wastewater treatment plant. The addition of the outside waste streams increases the UBOD loading on the plant to 52 000 kg per day which corresponds to a concentration of 246 g/m^3 with a flow rate of 212000 m^3/d. In order to avoid interfering with downstream drinking water systems, a minimum DO of 5 mg O_2/L must be attained at a distance of 41.5 km. The Ottawa River has a volumetric flowrate of 5.5 m^3/s, an average temperature of 17˚C, with a flow velocity of 0.4 m/s, an average depth of 2.5 m, no UBOD and a dissolved oxygen concentration equal to the saturation concentration. The wastewater discharged from the wastewater treatment plant is predicted to be at a temperature of 22.5˚C with all of the dissolved oxygen having been consumed; hence having a dissolved oxygen concentration of 0 mg/L. The carbonaceous reaction constant for the mixed river and wastewater is 0.14 1/d at 20˚C. Determine the following:

(a) the deoxygenation (k_d) and reaeration (k_r) constants at 20˚C and at the mixed temperature. Assume a rapid and shallow river with a bed activity coefficient of 0.15.

(b) the effluent UBOD (L_W) required to have a minimum DO concentration of 5 mg O_2/L or above.

(c) the degree of treatment the wastewater treatment plant is required to implement in order to meet the required effluent UBOD. Justify your answer.

Solution: The objective of this problem is to familiarise you with other aspects of DO sag problems not covered in the previous problem.

Given:
$Q_W = 212000\ m^3/d = 2.45\ m^3/s$
$Q_R = 5.5\ m^3/s$
$x_c = 41.5$ km
$T_R = 17^\circ C$
$T_W = 22.5^\circ C$
u = 0.4 m/s
H or h = 2.5 m
$L_R = 0$
$DO_R = DO_{S,R}$
$DO_W = 0$
k = 0.14 1/d

NOTE: The subscript 0 refers to the mixing point, the subscript W refers to the wastewater treatment plant, the subscript R refers to the receiving waters, the subscript S refers to saturation and the subscript c refers to the critical point

Assumptions:

- There is no change in flow velocity from the addition of the two streams;
- The river is completely mixed in the lateral direction but not in the longitudinal direction
- 1-dimensional model in the direction of flow;
- Two reaction processes are assumed to be essential i) reaeration is due to stream turbulence; and ii) deoxygenation is due to initial DO mixing and BOD effects;
- The temperature of the combined streams is assumed to be constant;
- Steady state, instantaneous mixing and dilute conditions at the point of mixing.

(a) Determine the constants k_r and k_d at 20˚C and at the mixed temperature

First we determine the constants at 20˚C.
$k_d = k + \eta(u/h)$
$k_d = 0.14 + 0.15 * (0.4/2.5) = 0.164$ 1/d

$k_r = 3.9u^{1/2}/H^{3/2}$
$k_r = 3.9 *(0.4)^{1/2}/(2.5)^{3/2} = 0.624$ 1/d

Note that these equations determine the constant's value at 20˚C
Now we need to find the mixed temperature

$T_0 = (Q_W T_W + Q_R T_R) / (Q_W + Q_R)$
$T_0 = (2.45\ m^3/s*22.5^\circ C + 5.5\ m^3/s*17^\circ C)/(2.45\ m^3/s + 5.5\ m^3/s)$
$T_0 = 18.7^\circ C$

At 18.7˚C $\theta = 1.135$

$k_{d(T)} = k_{d(20)}\theta^{(T-20)}$; $k_{d(18.7)} = k_{d(20)}1.135^{(18.7-20)} = 0.164x1.135^{(18.7-20)} = 0.14$ 1/d

$k_{r(T)} = k_{r(20)}\theta^{(T-20)}$; $k_{r(18.7)} = k_{r(20)}1.135^{(18.7-20)} = 0.624x1.135^{(18.7-20)} = 0.53$ 1/d

(b) Determine the UBOD L_W required to have a minimum DO concentration of 5 mg O_2/L

Based on the requirement of minimum DO concentration at a location of 41.5 km downstream, we assume the critical location in the river occur at 41.5 km downstream.
$x_c = 41.5$ km *1000m/km = 41500 m
$t_c = x_c/u$
$t_c = 41500$ m/0.4 m/s *1 min/60 s * 1 h/60 min * 1 d/24 h = 1.2 d

At the temperature of 18.7˚C the saturation concentration is 9.34 mg O_2/L
As the DO_c concentration was given as 5 mg O_2/L we can find D_c
$D_c = DO_S - DO_c = 9.34$ mg O_2/L – 5 mg O_2/L = 4.34 mg O_2/L

Now we can solve for L_0 using the following equation

$$D_c = \frac{k_d L_0}{k_r - k_d}\left(e^{-k_d t_c} - e^{-k_r t_c}\right) + D_0\left(e^{-k_r t_c}\right)$$

Before we can continue we need to solve for D_0

$D_0 = DO_S - DO_0$
$DO_0 = (Q_W DO_W + Q_R DO_R)/(Q_W + Q_R)$
We need to find DO_R before we can continue. We know that DO_R is equal to the saturation concentration of the river before mixing.
$DO_{S,R} = DO_R = 9.67$ mg O_2/L at 17˚C
$DO_0 = (2.45\ m^3/s * 0 + 5.5\ m^3/s*9.67\ mg/L)/(2.45\ m^3/s + 5.5\ m^3/s) = 6.69$ mg O_2/L
$D_0 = DO_S - DO_0 = 9.34$ mg O_2/L – 6.69 mg O_2/L = 2.65 mg O_2/L

Now we have all of our unknowns except for L_0
We can rearrange the D_c equation to obtain the following:

$$L_0 = \frac{\left(D_c - D_0\left(e^{-k_r t_c}\right)\right)}{\left(e^{-k_d t_c} - e^{-k_r t_c}\right)k_d}(k_r - k_d)$$

$$L_0 = \frac{\left(4.34 - 2.65\left(e^{-0.53*1.2}\right)\right)}{\left(e^{-0.14*1.2} - e^{-0.53*1.2}\right)*0.14}(0.53 - 0.14) = 25.9\frac{mg}{L}$$

Now that we have L_0, so we can now determine L_W

$L_0 = (Q_W L_W + Q_R L_R)/(Q_W + Q_R)$
As $L_R = 0$ we can rearrange the equation to isolate L_W

$L_W = L_0*(Q_W + Q_R)/Q_W$
$L_W = 25.9\ mg/L*(2.45\ m^3/s + 5.5\ m^3/s)/2.45\ m^3/s = 84\ mg/L$

Therefore the effluent UBOD needs to be a maximum of 84 mg/L to obtain a DO_c of 5 mg O_2/L

(c) Determine the extent of treatment required for the wastewater treatment plant
The initial UBOD was given as 246 g/m^3 or 246 mg/L.
The percent of UBOD that needs to be removed is:
Removed = (246 mg/L – 84 mg/L)/246 mg/L *100% = 65.8%

Therefore 65.8% needs to be removed.
Primary treatment only removes 25-40% of the BOD so that would be insufficient, therefore secondary treatment is required.