SOLUTIONS

1) A wastewater treatment plant discharges 1.0 m$^3$/s of effluent having an ultimate BOD of 40 mg/L into a stream flowing at 10.0 m$^3$/s. Just upstream from the discharge point, the stream has an ultimate BOD of 3.0 mg/L. The deoxygenation constant $k_d$ is estimated at 0.22/day.
   a. Assuming complete and instantaneous mixing, find the ultimate BOD of the mixture of waste and river just downstream from the outfall.
   b. Assuming a constant cross-sectional area for the stream equal to 55 m$^2$, what BOD would you expect to final at a point 10,000 m downstream.

2) The wastewater in Problem 1 has DO equal to 4.0 mg/L when it is discharged. The river has its own DO, just upstream from the outfall, equal to 8.0 mg/L. Find the initial oxygen deficit of the mixture just downstream from the discharge point. The temperatures of sewage and river are both 15°C.

3) Two point sources of BOD along a river (A and B) cause the oxygen sag curve shown in the following image.

   a. Sketch the rate of reaeration vs. distance downriver.
   b. Sketch $L_t$ (that is, the BOD remaining) as a function of distance downriver.
4) Untreated sewage with a BOD of 240 mg/L is sent to a wastewater treatment plant where 50 percent of the BOD is removed. The river receiving the effluent has the oxygen sag curve shown in the following figure (the river has no other sources of BOD). Notice that downstream is express in both miles and days required to reach a given spot.

a. Suppose the treatment plant breaks down and it no longer removes any BOD. Sketch the new oxygen sag curve a long time after the breakdown. Label the coordinate of the critical distance downriver.

b. Sketch the oxygen sag curve, as it would have been only four day after the breakdown of the treatment plant.

5) The ultimate BOD of a river just below a sewage outfall is 50.0 mg/L and the DO is at the saturation value of 10.0 mg/L. The deoxygenation rate coefficient $k_d$ is 0.30/day and the reaeration rate coefficient $k_r$ is 0.90/day. The river is flowing at the speed of 48.0 miles per day. The only source of BOD ion this river is the single outfall.

a. Find the critical distance downstream at which DO is minimum.

b. Find the minimum DO.

c. If a wastewater treatment plant is to be build, what fraction of the BOD would have to be removed from the sewage to assure a minimum of 5.0 mg/L everywhere downstream?

6) A city of 200,000 people deposits 37 cubic feet per second (cfs) of sewage having a BOD of 28.0 mg/L and 1.8 mg/L of DO into a river that has a flow rate of 250 cfs and a flow speed of 1.2 ft/s. Just upstream of the release point, the river has a BOD of 3.6 mg/L and a DO of 7.6 mg/L. The saturation value of DO is 8.5 mg/L. The deoxygenation coefficient $k_d$ is 0.61/day and the reaeration coefficient $k_r$ is 0.76/day. Assuming complete and instantaneous mixing of the sewage and river find

a. The initial oxygen deficit and ultimate BOD just downstream of the outfall

b. The time and distance to reach the minimum DO

c. The minimum DO

d. The DO that could be expected 10 miles downstream
7) The town of Martins Creek, PA, has filed a complaint with the Department of Environmental Protection (DEP) citing the town of Portland, PA, for the discharge of raw sewage into the Delaware River. The raw sewage is considered to be the cause of high fecal coliform counts and reduced levels of dissolved oxygen (DO), which have lead to foul odors along the river between Portland and Martins Creek. The coliform counts and reduced DO levels have lead to restrictions of recreational areas within the Portland/Martins Creek reach of the Delaware River.

The DEP water quality criterion for the Delaware River is 5 mg/L of DO (i.e. at no point shall the DO concentration drop below 5 mg/L).

Martins Creek is 15.55 km down stream of Portland.

The following data pertain to the 7-year, 10-day low flow at Portland

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<th>Delaware River just above Portland</th>
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</thead>
<tbody>
<tr>
<td>Flow (m³/sec)</td>
<td>0.1507</td>
<td>1.08</td>
</tr>
<tr>
<td>BOD₅ at 16°C (mg/L)</td>
<td>128.00</td>
<td>Not provided</td>
</tr>
<tr>
<td>BOD₅u at 28°C (mg/L)</td>
<td>Not provided</td>
<td>11.40</td>
</tr>
<tr>
<td>DO (mg/L)</td>
<td>1.00</td>
<td>7.95</td>
</tr>
<tr>
<td>k at 20°C (day⁻¹)</td>
<td>0.4375</td>
<td>k of BOD in river is based on WW</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>16.00</td>
<td>28.00</td>
</tr>
</tbody>
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Data of river after WWTP

<table>
<thead>
<tr>
<th>Parameter</th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Average Speed (m/sec)</td>
<td>N/A</td>
<td>0.390</td>
</tr>
<tr>
<td>Average Depth (m)</td>
<td>N/A</td>
<td>2.80</td>
</tr>
<tr>
<td>Bed-activity coefficient</td>
<td>N/A</td>
<td>0.200</td>
</tr>
</tbody>
</table>

A) What is the DO concentration as mg/L at Martins Creek?

**WWTP**

\[ \text{BOD}_5 = 128 \text{ mg/L at 16 C} \]

Flow = 0.1507 m³/sec
DO = 1.0 mg/L
T = 16 C
k = 0.4375

**River before Portland**

\[ \text{BOD}_5 = 11.40 \text{ mg/L} \]

Flow = 1.08 m³/sec
DO = 7.95 mg/L
T = 28 C

**River after Portland**

Speed = 0.390 m/s
Depth = 2.8 m
Bed Activity = 0.20

Distance between Portland and Martins Creek is 15.55 km

B) Does your answer make sense based on the complaint received?
A wastewater treatment plant discharges 1.0 m³/s of effluent having an ultimate BOD of 40.0 mg/L into a stream flowing at 10.0 m³/s. Just upstream from the discharge point, the stream has an ultimate BOD of 3.0 mg/L. The deoxygenation constant $k_d$ is estimated at 0.22/d.

(a) Assuming complete and instantaneous mixing, find the ultimate BOD of the mixture of waste and river just downstream from the outfall.

(b) Assuming a constant cross-sectional area for the stream equal to 55 m², what ultimate BOD would you expect to find at a point 10,000 m downstream?

\[ L_r = 3 \text{ mg/L} \]
\[ Q_r = 10 \text{ m}^3/\text{s} \]
\[ L_w = 40 \text{ mg/L} \]
\[ Q_w = 1 \text{ m}^3/\text{s} \]

\[ k_d = 0.22/\text{d} \]

**a. just downstream:**

\[ L_o = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r} = \frac{1 \text{ m}^3/\text{s} \times 40 \text{ mg/L} + 10 \text{ m}^3/\text{s} \times 3 \text{ mg/L}}{10 + 1 \text{ m}^3/\text{s}} = 6.4 \text{ mg/L} \]

**b. at 10,000 m downstream:**

\[ t = \frac{\text{distance}}{\text{speed}} = \frac{10,000 \text{ m}}{1 \text{ m}^3/\text{s} / 55 \text{ m}^2} \times \frac{\text{hr}}{3600 \text{ s}} \times \frac{\text{day}}{24 \text{ hr}} = 0.578 \text{ days} \]

\[ L_t = L_o e^{-kt} = 6.4 \text{ mg/L} e^{-0.22/\text{d} \times 0.578} = 5.6 \text{ mg/L} \]
2.) The wastewater in Problem 5.21 has DO equal to 4.0 mg/L when it is discharged. The river has its own DO, just upstream from the outfall, equal to 8.0 mg/L. Find the initial oxygen deficit of the mixture just downstream from the discharge point. The temperatures of sewage and river are both 15°C.

\[ \text{DO}_r = 8 \text{mg/L} \quad \text{Q}_r = 10 \text{ m}^3/\text{s} \]
\[ \text{DO}_w = 4 \text{ mg/L} \quad \text{Q}_w = 1 \text{ m}^3/\text{s} \quad \text{DO}_{sat} = 10.08 \text{mg/L} \]

\[ \text{a. just downstream:} \]
\[ \text{DO} = \frac{4.0 \text{mg/L} \times 1 \text{ m}^3/\text{s} + 8 \text{mg/L} \times 10 \text{m}^3/\text{s}}{1 + 10 \text{ m}^3/\text{s}} = 7.64 \text{mg/L} \]

From Table 5.11, \( \text{DO}_{sat} = 10.08 \text{ mg/L} \)

Initial deficit \( \Delta \text{DO} = \text{DO}_{sat} - \text{DO} = 10.08 - 7.64 = 2.44 \text{ mg/L} \)

3.) Two point sources of BOD along a river (A and B) cause the oxygen sag curve shown in Figure P5.25.

(a) Sketch the rate of reaeration vs. distance downriver.
(b) Sketch \( L_r \) (that is, the BOD remaining) as a function of distance downriver.
Untreated sewage with a BOD of 240 mg/L is sent to a wastewater treatment plant where 50 percent of the BOD is removed. The river receiving the effluent has the oxygen sag curve shown in Figure P5.25 (the river has no other sources of BOD). Notice that downstream is expressed both in miles and days required to reach a given spot.

(a) Suppose the treatment plant breaks down and it no longer removes any BOD. Sketch the new oxygen sag curve a long time after the breakdown. Label the coordinates of the critical distance downstream.

(b) Sketch the oxygen sag curve as it would have been only four days after the breakdown of the treatment plant.

a. Long after treatment plant breaks down, deficit is doubled since the BOD is doubled.

b. Only 4 days after the breakdown, the first 4 days beyond the outfall have been affected, beyond that, the DO is same as before the breakdown:
The ultimate BOD of a river just below a sewage outfall is 50.0 mg/L and the DO is at the saturation value of 10.0 mg/L. The deoxygenation rate coefficient \( k_d \) is 0.30/day and the reaeration rate coefficient \( k_r \) is 0.90/day. The river is flowing at the speed of 48.0 miles per day. The only source of BOD on this river is this single outfall.

(a) Find the critical distance downstream at which DO is a minimum.
(b) Find the minimum DO.
(c) If a wastewater treatment plant is to be built, what fraction of the BOD would have to be removed from the sewage to assure a minimum of 5.0 mg/L everywhere downstream?

\[ t_c = \frac{1}{k_r - k_d} \ln \left( \frac{k_r}{k_d} \right) = \frac{1}{0.90 - 0.30/\text{day}} \ln \left( \frac{0.9}{0.3} \right) = 1.83 \text{ days} \]

assuming \( x = v t \): distance = 48.0 miles/day \( \times \) 1.83 days = 87.9 miles

\[ D_{\text{max}} = \frac{k_d L_0}{k_r - k_d} (e^{-k_d} - e^{-k_r}) \]

\[ = \frac{0.3/\text{day} \times 50.0 \text{ mg/L}}{(0.9 - 0.3)/\text{day}} (e^{0.3 \times 1.83} - e^{0.9 \times 1.83}) = 9.6 \text{ mg/L} \]

\[ D_{\text{O min}} = D_{\text{O sat}} - D_{\text{max}} = 10.0 - 9.6 = 0.4 \text{ mg/L} \]

(c) when \( D_O = 0 \), D is proportional to \( L_0 \):

\[ \frac{D_{\text{max,wall}}}{D_{\text{max,here}}} = \frac{10.0 - 5.0}{9.6} = 0.52 \]

therefore, need to remove \( 1.0 - 0.52 = 48\% \) of the BOD.

A city of 200,000 people deposits 37 cubic feet per second (cfs) of sewage having a BOD of 28.0 mg/L and 1.8 mg/L of DO into a river that has a flow rate of 250 cfs and a flow speed of 1.2 ft/s. Just upstream of the release point, the river has a BOD of 3.6 mg/L and a DO of 7.6 mg/L. The saturation value of DO is 8.5 mg/L. The deoxygenation coefficient \( k_d \) is 0.61/day and the reaeration coefficient \( k_r \) is 0.76/day. Assuming complete and instantaneous mixing of the sewage and river find

(a) The initial oxygen deficit and ultimate BOD just downstream of the outfall
(b) The time and distance to reach the minimum DO
(c) The minimum DO
(d) The DO that could be expected 10 miles downstream
DO = 7.6 mg/L  
Lr = 3.6 mg/L  
Qr = 250 cfs  
DOw = 1.8 mg/L  
Lw = 28 mg/L  
Qw = 37 cfs

u = 1.2 ft/s  
DOSat = 8.5 mg/L  
kr = 0.76/d  
kd = 0.61/d

a. initial conditions:

\[ \text{DO}_0 = \frac{37 \text{cfs} \times 1.8 \text{mg/L} + 250 \text{cfs} \times 7.6 \text{mg/L}}{37 + 250 \text{ cfs}} = 6.85 \text{mg/L} \]

Initial deficit = \( \text{D}_c = 8.5 \text{mg/L} - 6.85 \text{mg/L} = 1.65 \text{mg/L} \)

Initial BOD = \( L_0 = \frac{37 \text{cfs} \times 28 \text{mg/L} + 250 \text{cfs} \times 3.6 \text{mg/L}}{37 + 250 \text{ cfs}} = 6.75 \text{mg/L} \)

b. critical point:

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

\[ = \frac{1}{0.76 - 0.61/\text{d}} \ln \left( \frac{0.76}{0.61} \left[ 1 - \frac{1.65 (0.76 - 0.61)}{0.61 \times 6.75} \right] \right) = 1.05 \text{ days} \]

critical distance = \[ x_c = 1.2 \frac{\text{ft}}{\text{s}} \times 3600 \frac{\text{s}}{\text{hr}} \times 24 \frac{\text{hr}}{\text{d}} \times 5280 \frac{\text{ft}}{\text{mi}} \times 1.05 \text{day} = 20.7 \text{miles} \]

c. minimum DO:

\[ D_{\text{max}} = \frac{k_d L_0}{k_r - k_d} \left( e^{-k_r t} - e^{-k_d t} \right) + D_0 e^{-k_d t} \]

\[ = \frac{0.61/d \times 6.75 \text{ mg/L}}{(0.76 - 0.61)/\text{d}} \left( e^{-0.76 \times 1.05} - e^{-0.76 \times 0.51} \right) + 1.65 e^{-0.76 \times 0.51} = 2.85 \text{ mg/L} \]

\[ \text{DO}_{\text{min}} = \text{DO}_{\text{Sat}} - D_{\text{max}} = 8.5 - 2.85 = 5.6 \text{ mg/L} \]

d. 10 miles downstream:

\[ t = \frac{10 \text{mi} \times 5280 \text{ft/mi}}{1.2 \text{ft/s} \times 3600 \text{s/hr} \times 24 \text{hr/d}} = 0.51 \text{days} \]

\[ D = \frac{k_d L_0}{k_r - k_d} \left( e^{-k_r t} - e^{-k_d t} \right) + D_0 e^{-k_d t} \]

\[ = \frac{0.61 \times 6.75}{0.76 - 0.61} \left( e^{-0.61 \times 0.51} - e^{-0.76 \times 0.51} \right) + 1.65 e^{-0.76 \times 0.51} = 2.6 \text{ mg/L} \]

\[ \text{DO} = 8.5 - 2.6 = 5.9 \text{ mg/L} \]
7) The town of Martins Creek, PA, has filed a complaint with the Department of Environmental Protection (DEP) citing the town of Portland, PA, for the discharge of raw sewage into the Delaware River. The raw sewage is considered to be the cause of high fecal coliform counts and reduced levels of dissolved oxygen (DO), which have lead to foul odors along the river between Portland and Martins Creek. The coliform counts and reduced DO levels have lead to restrictions of recreational areas within the Portland/Martins Creek reach of the Delaware River.

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Data of river after WWTP
- Average Speed (m/sec) N/A 0.390
- Average Depth (m) N/A 2.80
- Bed-activity coefficient N/A 0.200
A) What is the DO concentration as mg/L at Martins Creek? (35 Points)

**WWTP**

BOD₅ = 128 mg/L at 16 C

Flow = 0.1507 m³/sec

DO = 1.0 mg/L

T = 16 C

k = 0.4375 m³/sec³

River before Portland

BOD₅ = 11.40 mg/L

Flow = 1.08 m³/sec

DO = 7.95 mg/L

T = 28 C

River after Portland

Speed = 0.390 m/s

Depth = 2.8 m

Bed Activity = 0.20

**Distance between Portland and Martins Creek is 15.55 km**

Must Solve for Dt at the appropriate time then solve for DO considering proper temperature.

\[
D_t = \frac{k_d L_r}{k_r - k_d} \left( e^{-k_d t} - e^{-k_r t} \right) + D_a e^{-k_r t}
\]

\[
D_t = DO_s - DO, \text{ therefore}\]

\[
DO = DO_s - D_t
\]

**Time to Martins Creek**

\[
Time = \left[ \frac{15.55 \text{ km} \times (1000 \frac{m}{\text{km}})}{0.390 \frac{m}{\text{sec}}} \right] = 39,871.79 \text{ sec}
\]

Convert to seconds to day = 39,871.79 sec \left[ \frac{60 \text{ sec}}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{day}} \right] = 0.4615 \text{ days}

**Time (t) for a drop of water to travel 15.55 km = 0.4615 days (2 Points)**
Solve for Temperature downstream of WWTP

\[
Temperature \ below \ WWTP = \frac{\left( \frac{0.1507 \ m^3}{\text{sec}} \right) \times 16^\circ C + \left( \frac{1.08 \ m^3}{\text{sec}} \right) \times 28^\circ C}{0.1507 \ m^3 + 1.08 \ m^3} = 26.53^\circ C
\]

\[T \ of \ river \ below \ WWTP = 26.53^\circ C \]

(2 Points)

Solve for \(DO_{s,\text{saturated}}\) at 26.53°C

From Table provided only \(DO_s\) at 25°C and 30°C are provided therefore evaluation through interpolation must be done to calculate the \(DO_s\) at 26.53°C.

\[
Slope \ Formula = \frac{y_2 - y_1}{x_2 - x_1} = \frac{30 - 25}{7.56 - 8.26} \approx \frac{26.53 - 25}{x - 8.26}
\]

\[x = 8.26 + \left[ (26.53 - 25) \times \left( \frac{7.56 - 8.26}{30 - 25} \right) \right] = 8.05 \frac{mg}{L} = DO_s \ at \ 26.53^\circ C
\]

\(DO_s \ @ \ 26.53^\circ C = 8.05 \ mg/L\)

(2 Points)

Solve for variables of \(D_t\) equation; \(D_a, L, k_d, k_r\)

\(D_a = DO_s - DO_o\)

First solve for the initial DO then the initial deficit \((D_o)\)

\[
DO_o = \left( \frac{1.0 \ mg}{L} \times 0.1507 \ m^3 \right) + \left( \frac{7.95 \ mg}{L} \times 1.08 \ m^3 \right) \left( \frac{0.1507 \ m^3}{\text{sec}} + 1.08 \ m^3 \right) = 7.10 \frac{mg}{L}
\]

(2 Points)

Now solve for \(D_a\)

\[D_a = 8.05 \ mg/L - 7.10 \ mg/L = 0.95 \ mg/L\]

(2 Points)
La = \frac{Q_w L_{ow} + Q_r L_{or}}{Q_w + Q_r}

BOD_d (i.e., L_0) at 28^\circ C is the same as BOD_u at 20^\circ C or any other temperature, therefore L_{or} of river at the point of mixing remains as 11.40 mg/L. \quad L_{or} = 11.40 \text{ mg/L} \quad (2 \text{ Points})

BOD of WWTP is given as BOD_5 @ 16^\circ C so we must first solve for BOD_u (i.e., L_{ow}) using a k at 16^\circ C

\quad k_f = k_20 \theta^{(T-20)}, \quad \theta \text{ for } k \text{ and } k_d, \quad 4-20^\circ C = 1.135 \text{ and } 20 - 30^\circ C = 1.056

\quad k_{16} = 0.4375 \times (1.135)^{(16-20)} = 0.2636 \text{ day}^{-1} \quad (3 \text{ Points})

L_{ow} \rightarrow \text{BOD}_i = L_o(1-e^{kt}) \quad \text{or} \quad L_o = \frac{\text{BOD}_i}{1-e^{-kt}}

\quad L_{ow} = \frac{128 \frac{mg}{L}}{1 - e^{-(0.2636 \text{day}^{-1} \times 5 \text{day})}} = \frac{128}{0.7323} = 174.78 \frac{mg}{L}

\quad L_{ow} = 174.78 \text{ mg/L} \quad (3 \text{ Points})

\quad L_a = \left( \frac{0.1507 \frac{m^3}{sec} \times 174.78 \frac{mg}{L}}{0.1507 \frac{m^3}{sec}} + \frac{1.08 \frac{m^3}{sec} \times 11.40 \frac{mg}{L}}{1.08 \frac{m^3}{sec}} \right) = 31.42 \frac{mg}{L}

\quad L_o = 31.42 \text{ mg/L} \quad (2 \text{ Points})

k_d \text{ and } k_r \text{ at } 26.53^\circ C

k_d \text{ at } 20^\circ C

\quad k_d = k + \frac{u}{h} \eta = k_{d20} = 0.4375 \text{ d}^{-1} + \left( \frac{0.39 \frac{m}{\text{sec}}}{2.8m} \right) \times 0.2 = 0.4654 \text{ d}^{-1} \quad (2 \text{ Points})

k_d \text{ at } 26.53^\circ C

\quad k_{d@26.53} = 0.4654 \times (1.056)^{(26.53-20)} = 0.6643 \text{ day}^{-1}

\quad k_{d@26.53} = 0.6643 \text{ d}^{-1} \quad (2 \text{ Points})
\( k_r \) at 20\(^\circ\)C

\[
k_r = \frac{3.9 u^\frac{1}{2}}{h^\frac{1}{2}} = k_r_{20} = \frac{3.9 \left( \frac{m}{\sec} \right)^{\frac{1}{2}}}{(2.8)^{\frac{1}{2}}} = 0.5198 \, d^{-1}
\]

(2 Points)

\( k_r \) at 26.53\(^\circ\)C, \( \theta \) for \( k_r = 1.024 \)

\[
k_{r@26.53} = 0.5198 \times (1.024)^{26.53-20} = 0.6069 \, day^{-1}
\]

\( k_{r@26.53} = 0.6069 \, day^{-1} \)

(2 Points)

**Variables**

- \( D_a = 0.95 \, mg/L \);
- \( L_a = 31.42 \, mg/L \);
- \( k_d @26.53 = 0.6643 \, d^{-1} \);
- \( k_r @26.53 = 0.6069 \, d^{-1} \);
- \( DO_{s@26.53 C} = 8.05 \, mg/L \)

**Solve for \( D_t \) where \( t = 0.4615 \) days**

\[
D_t = \frac{k_r L_a}{k_r - k_d} \left( e^{-k_d t} - e^{-k_r t} \right) + D_a e^{-k_r t}
\]

\[
D_{0.4615 \, days} = \frac{0.6643 \, d^{-1} \times 31.42 \, mg \, L^{-1}}{0.6069 \, d^{-1} - 0.6643 \, d^{-1}} \left( e^{-0.6643 \, d^{-1} \times 0.4615 \, day} - e^{-0.6069 \, d^{-1} \times 0.4615 \, day} \right) + 0.95 \, mg \, L^{-1} \left( e^{-0.6069 \, d^{-1} \times 0.4615 \, day} \right)
\]

\[
D_{0.4615 \, days} = \frac{20.87 \, d^{-1} \, mg \, L^{-1}}{-0.0574 \, d^{-1}} \left( 0.7359 - 0.7557 \right) + 0.7179 \, mg \, L^{-1} = -363.58 \, mg \, L^{-1} + 0.7179 \, mg \, L^{-1} = 7.92 \, mg \, L^{-1}
\]

\( D_{0.4615 \, day} = 7.92 \, mg/L \)

(4 Points)

**Solve for DO at Martins Creek**

\[
DO_{0.4615 \, day} = DO_{s} - D_t = 8.05 \, mg/L - 7.92 \, mg/L = 0.13 \, mg/L \] (3 Points)

A) DO 15.55 km downstream at Martins Creek is about 0.13 mg/L

B) The answer makes sense because of the DO being close to 0 mg/L at Martins Creek if so, there certainly would be issues of foul odor! (5 Points)