

ENV 4417: WATER QUALITY AND TREATMENT

Fall 2015
Exam #2
Tuesday, November 24

University of South Florida
Civil & Environmental Eng.
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Instructions:

1. You may read these instructions, but do not turn the page or begin working until instructed.
2. This exam contains six questions. Answer the first three problems, plus any one of the last three. Answering them in order will probably help, because some information (e.g., flow rate) is passed from one problem to the next
3. If you attempt more than one of the last three questions, make sure that you indicate clearly which one you want me to grade. If it isn't clear, then I will choose which one I feel like grading.
4. Some questions might have multiple parts. In those cases, the point value of each part is indicated. The total number of points possible is 100.
5. Unit conversion factors and other potentially useful information are provided on page 2.
6. Answer each question in the space provided. If you need more space, you can attach additional pages as needed, but make sure to put your name on them.
7. Show your work and state any important assumptions you make. I cannot award partial credit if I can't follow what you did.
8. Report a reasonable number of significant digits in your answers.
9. Include units in your answers. An answer without proper units is not correct!
10. The exam is closed-book, but you are allowed one personal note sheet of standard 8.5-by-11 or A4 paper. You may write anything you want on it, both front and back, but it must be hand-written.
11. A hand-held calculator is recommended. Other electronic devices are not permitted. Calculators may not be pre-programmed with formulae from the class.
12. Time limit: 60 minutes (or until the end of the class period). Stop working when asked. If you continue working after time has been called, you will be penalized at a rate of 1 point per minute.
13. Don't cheat. Cheating will result in appropriate disciplinary action according to university policy. More importantly, cheating indicates a lack of personal integrity.
14. Please print your name legibly in the space provided below, and turn in this exam at the end of the period.
15. Hints:
 - Read each question carefully and answer the question that is asked.
 - Watch your units. If you take good care of your units, they will take good care of you.
 - Work carefully and don't rush.

Name: ANSWER KEY

Potentially useful constants:

Ideal gas constant, R :	$8.314 \text{ Pa}\cdot\text{m}^3\cdot\text{mol}^{-1}\cdot\text{K}^{-1} = 82.06\times 10^{-6} \text{ atm}\cdot\text{m}^3\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$
Gravitational acceleration, g :	9.81 m/s^2
Molecular weight of water, H_2O :	18.01 g/mole
Density of water at 25°C :	$0.9970 \text{ g/mL} = 997.0 \text{ kg/m}^3$
Viscosity of water at 25°C :	$0.890\times 10^{-3} \text{ Pa}\cdot\text{sec}$
Density of water at 15°C :	$0.9991 \text{ g/mL} = 999.1 \text{ kg/m}^3$
Viscosity of water at 15°C :	$1.136\times 10^{-3} \text{ Pa}\cdot\text{sec}$

Potentially useful conversion factors:

Pressure:	$1 \text{ atm} = 760 \text{ mm Hg} = 760 \text{ torr} = 14.7 \text{ lb}_{\text{force}}/\text{in}^2 = 101,325 \text{ Pa}$ $1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg}/(\text{m}\cdot\text{sec}^2)$ $1 \text{ bar} = 10^5 \text{ Pa}$
Mass:	$1 \text{ kg} = 1000 \text{ g} = 10^6 \text{ mg} = 10^9 \mu\text{g}$ $1 \text{ kg} = 2.207 \text{ lb}_{\text{mass}}$ $1 \text{ t (metric tonne)} = 1000 \text{ kg} = 2207 \text{ lb}_{\text{mass}}$ $1 \text{ ton (English ton)} = 2000 \text{ lb}_{\text{mass}}$
Length:	$1 \text{ km} = 1000 \text{ m} = 10^5 \text{ cm} = 10^6 \text{ mm} = 10^9 \mu\text{m}$ $1 \text{ ft} = 12 \text{ in} = 30.48 \text{ cm} = 0.3048 \text{ m}$
Temperature:	$25^\circ\text{C} = 298.15 \text{ K}$
Volume:	$1 \text{ m}^3 = 1000 \text{ L} = 10^6 \text{ mL} = 10^6 \text{ cm}^3$ $1 \text{ gal} = 3.785 \text{ L}$
Work/Energy:	$1 \text{ BTU} = 1.055 \text{ kJ}$
Power:	$1 \text{ MW} = 10^6 \text{ W} = 10^6 \text{ J/s} = 10^6 \text{ N}\cdot\text{m/s}$
Area :	$1 \text{ ha} = 10^4 \text{ m}^2$

Atomic Masses:

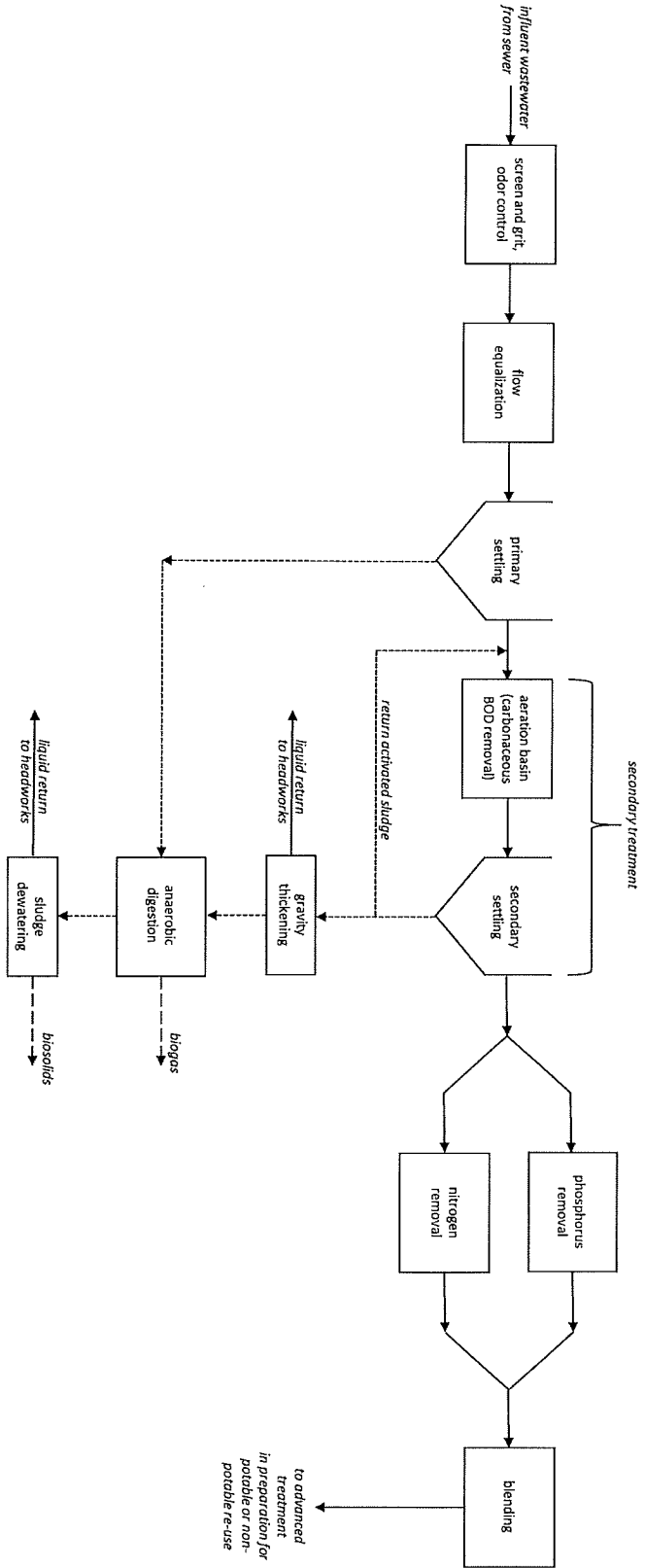
H = 1.008 g/mole	C = 12.01 g/mole	N = 14.01 g/mole	O = 16.00 g/mole
Na = 22.99 g/mole	Mg = 24.31 g/mole	Al = 26.98 g/mole	P = 30.97 g/mole
S = 32.06 g/mole	Cl = 35.45 g/mole	Ca = 40.08 g/mole	Fe = 55.85 g/mole

pK_A values of some common acids (at ambient temperature):

$\text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^-$	pK _A = 6.35
$\text{HOCl} \leftrightarrow \text{H}^+ + \text{OCl}^-$	pK _A = 7.54
$\text{NH}_4^+ \leftrightarrow \text{H}^+ + \text{NH}_3$	pK _A = 9.2
$\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}$	pK _A = 10.33

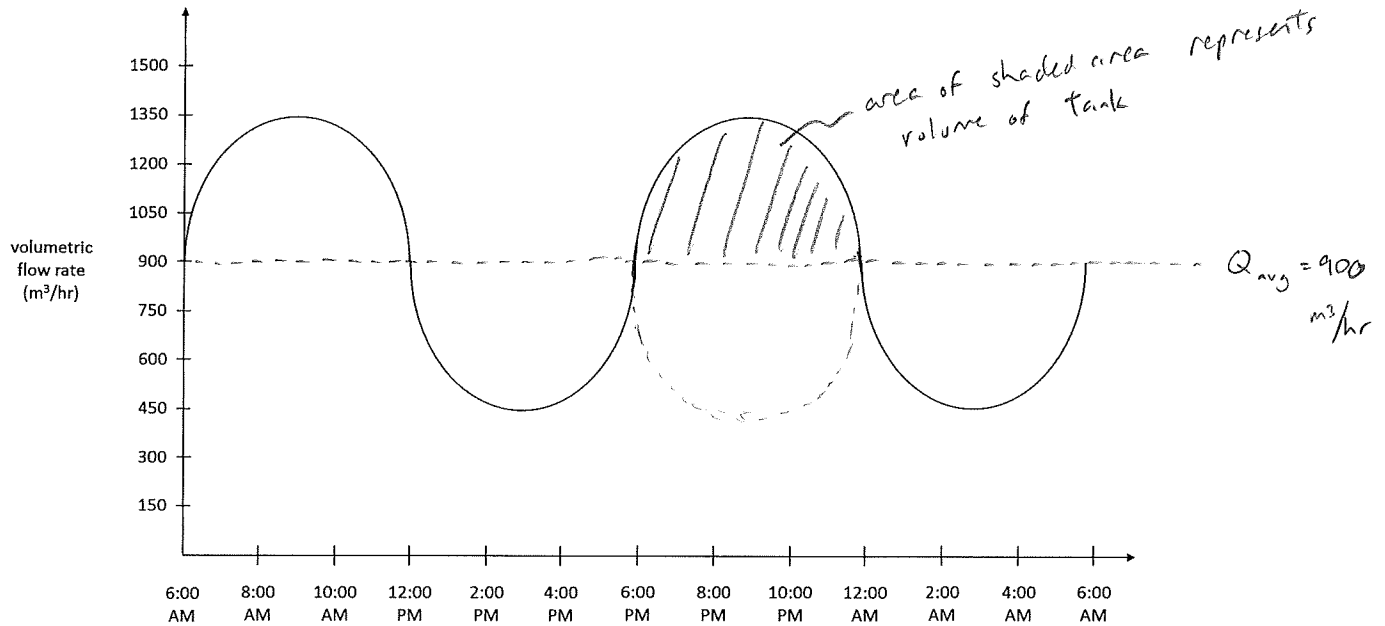
Let's design a water reclamation facility!

The city of Sprawlville has experienced a lot of population growth recently, and developers are building many new housing developments on the far outskirts of town. The new developments are many miles from the existing centralized wastewater treatment plant, so a new water reclamation facility will be built. The engineering firm at which you are an employee has been hired to design and build the new facility. A schematic diagram of the planned facility is provided below. Your job today is to help with some parts of the design that have not yet been worked out.



1. FLOW EQUALIZATION (20 pts)

The following figure shows the expected flow rate in to the treatment plant as a function of time.



You want to design a flow equalization basin to smooth out the flow rate, so that the rest of the plant can operate at (or close to) steady state.

- a. (15 pts) Recommend a volume for the flow equalization tank. Hint: the area of an ellipse is $(\pi/4)ab$, where a and b are the lengths of the major axis and the minor axis of the ellipse. Therefore the area of half an ellipse is $(\pi/8)ab$.

$$\text{Area of ellipse} = \left(\frac{\pi}{4}\right)(6 \text{ hr})\left(1350 \frac{\text{m}^3}{\text{hr}} - 450 \frac{\text{m}^3}{\text{hr}}\right) = 4241 \text{ m}^3$$

$$\therefore \text{Shaded area} = \text{tank volume} = \underline{2120 \text{ m}^3}$$

But add in some extra volume for high-flow events, etc... maybe 20-30% extra volume

$$\text{Recommended tank volume} = \underline{\underline{2700 \text{ m}^3}}$$

- b. (5 pts) At what volumetric flow rate (in m^3/hr) will water flow from the equalization basin to the rest of the treatment plant?

$$Q = Q_{\text{avg}} = \underline{\underline{900 \text{ m}^3/\text{hr}}} \text{ by inspection}$$

2. PRIMARY SETTLING (20 pts)

Water flowing from the equalization tank to the primary settling basins is expected to contain approximately 250 mg/L of suspended solids, 80 mg/L of soluble BOD₅, and 230 mg/L of total BOD₅ (both soluble and particulate). It is expected that the primary settling basin will be able to remove 60% of suspended matter, and that the primary sludge will be 5.0% solids by mass and will have a density of 1030 g/L.

- a. (10 pts) Estimate the concentrations of soluble BOD₅ and total BOD₅ that will exit the primary settling basin and flow to secondary treatment.

Concentration of soluble BOD₅ is not affected by primary settling.

$$\therefore \text{Soluble BOD}_5 = \underline{S_0 = 80 \text{ mg/L}}$$

What about BOD₅ from suspended matter?

$$\text{Entering BOD}_5^{\text{ss}} = 230 \text{ mg/L} - 80 \text{ mg/L} = 150 \text{ mg/L}$$

About 60% of that will be removed \Rightarrow 90 mg/L removed, 60 mg/L remain

$$\text{Total BOD}_5 = 80 \text{ mg/L} + 60 \text{ mg/L} = \underline{140 \text{ mg/L}}$$

- b. (10 pts) Estimate the volumetric flow rate of primary sludge produced, in units of L/hr.

Entering S.S. = 250 mg/L, 60% removed \Rightarrow 150 mg/L solids removed

$$(900 \text{ m}^3/\text{hr}) (1000 \text{ L}/1 \text{ m}^3) (150 \text{ mg/L solids}) (1 \text{ kg}/10^6 \text{ mg}) = 135 \text{ kg/hr solids removed}$$

But sludge is only 5.0% by mass

$$\frac{135 \text{ kg/hr solids}}{0.05} = 2700 \text{ kg/hr sludge}$$

$$\frac{(2700 \text{ kg sludge/hr}) (1000 \text{ g/kg})}{1030 \text{ g/L}} = \underline{2600 \text{ L/hr primary sludge}}$$

3. SECONDARY TREATMENT (40 pts)

You want to design the secondary treatment system so that the total BOD₅ in the secondary effluent (i.e., effluent of the secondary clarifier) is no greater than 15 mg/L. You expect that the suspended solids concentration in the secondary effluent will be about 10 mg/L.

The bacteria that metabolize the carbonaceous BOD₅ in the aeration basin are expected to have the following properties.

- concentration of MLVSS in the aeration basin $X = 2500$ mg/L
- half-velocity coefficient $K_S = 60$ mg/L BOD₅
- bacterial death rate coefficient $k_d = 0.14$ d⁻¹
- maximum specific growth rate coefficient $\mu_{\max} = 3.0$ d⁻¹
- yield coefficient $Y = 0.60$ mg biomass produced per mg BOD₅ consumed

- a. (8 pts) Estimate the maximum allowable *soluble* BOD₅ concentration in the secondary effluent so that you can meet the criterion of 15 mg/L *total* BOD₅. Hint: how much BOD₅ will be exerted by suspended (particulate) matter?

$$\text{BOD}_5^{\text{ss}} \approx (0.6)(10 \text{ mg/L}) = 6 \text{ mg/L} \quad (\text{estimate})$$

$$\text{BOD}_5^{\text{ss}} + S \leq 15 \text{ mg/L} \Rightarrow 6 \text{ mg/L} + S \leq 15 \text{ mg/L}$$

$$\underline{S \leq 9 \text{ mg/L}} \quad \text{to meet overall criterion of } 15 \text{ mg/L BOD}_5$$

- b. (8 pts) Estimate/calculate the required solids retention time (also called sludge age or mean cell residence time). Hint: use the Monod kinetic parameters given above, along with your answer from part (a).

$$\frac{1}{\theta_c} = \mu - k_d = \mu_{\max} \frac{S}{S + K_S} - k_d$$

$$\frac{1}{\theta_c} = (3.0 \text{ d}^{-1}) \left(\frac{9 \text{ mg/L}}{9 \text{ mg/L} + 60 \text{ mg/L}} \right) - 0.14 \text{ d}^{-1} = 0.2513 \text{ d}^{-1}$$

$$\theta_c = 3.979 \text{ d} \approx \underline{\underline{4.0 \text{ d}}}$$

problem 3 continues →

3. continued

- c. (8 pts) Estimate/calculate the required aeration time (in hr) and the required volume of the aeration basin (in m³).

$$\theta = \frac{Y \theta_c (S_0 - S)}{X (1 + k_d \theta_c)} = \frac{(0.60 \text{ mg/mg}) (4.0 \text{ d}) (80 \text{ mg/L} - 9 \text{ mg/L})}{(2500 \text{ mg/L}) [1 + (0.14 \text{ d}^{-1})(4.0 \text{ d})]} = 0.0435 \text{ d}$$

$\theta = 1.0 \text{ hr}$... a bit low, but OK, maybe we have fast bacteria

$$V = Q \theta = (900 \text{ m}^3/\text{hr})(1.0 \text{ hr}) = \underline{\underline{900 \text{ m}^3}}$$

- d. (8 pts) Estimate/calculate the rate at which volatile suspended solids are "wasted," i.e., sent to sludge handling. Report the answer in kg/d. Hint: you can do it based on a material balance for MLVSS around the entire secondary treatment process, but there is a shorter way, if you use your mean cell residence time from part (b).

$$\theta_c = \frac{V X}{Q_E X_E + Q_W X_W} \Rightarrow Q_W X_W = \frac{V X_c}{\theta_c} - Q_E X_E$$

We know V, X, θ_c ... estimate $Q_E \approx Q = 900 \text{ m}^3/\text{hr}$

estimate $X_E \approx 7 \text{ mg/L}$ because some of 10 mg/L is inert

$$Q_W X_W \approx \left[\frac{(900 \text{ m}^3)(2500 \text{ mg/L})}{(4.0 \text{ d})} - (900 \text{ m}^3/\text{hr})(7 \text{ mg/L})(24 \text{ hr/d}) \right] \left(\frac{1000 \text{ L}}{1 \text{ m}^3} \right) \left(\frac{1 \text{ kg}}{10^6 \text{ mg}} \right)$$

$$= \underline{\underline{410 \text{ kg/d}}} \quad \text{VSS wasted in secondary sludge}$$

- e. (8 pts) Assuming that the return activated sludge has a VSS concentration of 9,500 mg/L, what recycle rate is required to maintain the biomass concentration of 2,500 mg/L in the aeration basin?

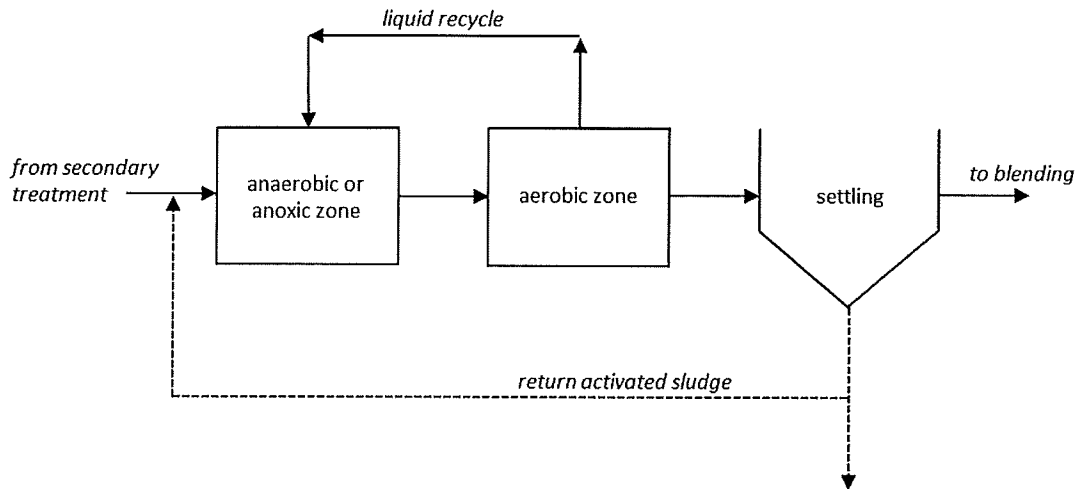
$$\frac{Q_R}{Q_I} = \frac{X}{X_R - X} \left[1 - \frac{\theta}{\theta_c} \right] = \frac{2500 \text{ mg/L}}{9500 \text{ mg/L} - 2500 \text{ mg/L}} \left[1 - \frac{0.0435 \text{ d}}{3.979 \text{ d}} \right]$$

$$= 0.353 = \underline{\underline{35\% \text{ recycle rate}}}$$

$$Q_R = (0.353)(900 \text{ m}^3/\text{hr}) = \underline{\underline{320 \text{ m}^3/\text{hr}}}$$

4. NITROGEN REMOVAL (20 pts)

One of your colleagues at your engineering firm never took ENV 4417 when he was a student, but he is trying to design the nitrogen removal system. He knows that the modified Ludzack-Ettinger (MLE) process is a common process for nitrogen removal. Therefore he designed the following system for nitrogen removal.

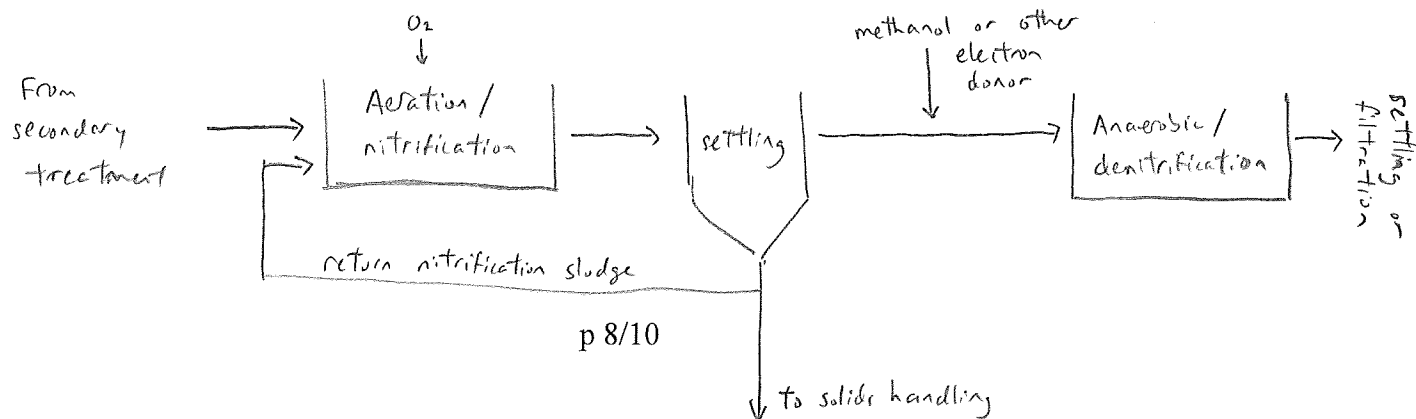


- a. (10 pts) Because you took ENV 4417, you realize that this system will probably not work for nitrogen removal at the treatment plant being proposed for Sprawlville. Explain why not. Hint: look at where the nitrogen removal process is located in the Sprawlville plant; what will *not* be present at that point in the treatment train?

A source of carbon (electron donor) is required for denitrification in the anoxic zone. But if N removal is downstream of secondary treatment, little or no organic carbon remains! Therefore we will not get any denitrification. This system would probably convert NH_4^+ to NO_3^- , but it would not remove the NO_3^- .

- b. (10 pts) Sketch a treatment system that you think would work better for nitrogen removal. It does not need to be very detailed, but you should label streams, processes, and conditions clearly enough that I can assess if your design makes sense.

For N removal downstream of BOD removal, usually a system like this is used:



5. PHOSPHORUS REMOVAL (20 pts)

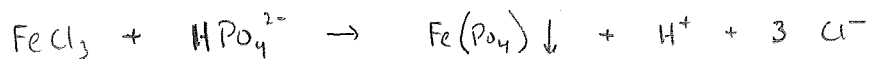
Water exiting secondary treatment is expected to have a total phosphorus concentration of 3.5 mg/L, which will almost all be in the form of orthophosphate (because organic P will be removed with the biomass in secondary settling). Then, the flow is split, with 50% of the flow going to N removal and 50% of the flow going to P removal.

- a. (7 pts) If we assume that no P is removed in the nitrogen removal operation, and the plant's discharge limit for total P will be 2.0 mg/L, then what *fractional removal* of P is required in the P removal operation?

If 50% of the water contains 3.5 mg/L P, then the other 50% must contain 0.5 mg/L or lower, so the blend will be ≤ 2.0 mg/L. Use a material balance around the blending tank if you don't believe me.

$$\therefore \frac{3.0 \text{ mg/L removed}}{3.5 \text{ mg/L from secondary}} = 0.857 = \underline{\underline{86\% \text{ removal}}} \text{ of P in the phosphorus removal system}$$

- b. (13 pts) P will be removed via chemical precipitation. Assume that FeCl_3 is selected as your chemical coagulant, and that 50% excess FeCl_3 is required to ensure adequate P removal (i.e., 50% more than would theoretically be required to achieve the removal you found in part (a)). Estimate/calculate how much FeCl_3 the plant will need, in units of kg/d.



Requires 1 mole FeCl_3 per mole P ... but need 50% excess.

$$\begin{aligned} & \left(450 \frac{\text{m}^3}{\text{hr}} \text{ flow}\right) \left(\frac{24 \text{ hr}}{\text{d}}\right) \left(\frac{3.0 \text{ mg P removed}}{1 \text{ L}}\right) \left(\frac{1000 \text{ L}}{1 \text{ m}^3}\right) \left(\frac{1 \text{ mmol P}}{30.97 \text{ mg P}}\right) \left(\frac{1.5 \text{ mmol FeCl}_3}{1 \text{ mmol P}}\right) \left(\frac{162.2 \text{ mg FeCl}_3}{1 \text{ mmol FeCl}_3}\right) \left(\frac{1 \text{ kg}}{10^6 \text{ mg}}\right) \\ & = \underline{\underline{250 \text{ kg/d FeCl}_3 \text{ required}}} \end{aligned}$$

That's not terrible. Well, it is a lot, nearly 100 tons per year, but relatively speaking, less than one ton per day of coagulant is not so bad.

6. ANAEROBIC DIGESTION (20 pts)

Assuming that 40% of the applied VSS is removed in the anaerobic digester, estimate the volume of methane gas that the digester will produce, in units of m^3/d . Hint: use your answers from 2(b) and 3(d) to estimate the rate at which volatile suspended solids enter the anaerobic digester.

From 2(b), 135 kg/hr solids removed, assume $100 \text{ kg/hr VSS} \Rightarrow 2400 \frac{\text{kg}}{\text{d}}$ VSS

From 3(d), 410 kg/d VSS in secondary sludge

Interesting, we get much more from primary than we do from secondary, I would not have expected that... I would have expected about even. But OK.

$$(2810 \text{ kg/d VSS to anaerobic digestion})(0.40 \text{ removed}) = 1124 \text{ kg/d VSS removed}$$

We know we get $\sim 0.49 \text{ m}^3 \text{ CH}_4$ per kg VSS removed

$$\Rightarrow \underline{\underline{550 \text{ m}^3/\text{d} \text{ CH}_4 \text{ produced}}}$$

If we get additional sludge from the nitrogen removal system, then we might get more methane, but the nitrogen removal system has not yet been designed, so we will not include that for now.

END OF EXAM