ENV 4417: WATER QUALITY AND TREATMENT

Fall 2015 | University of South Florida
Final exam | Civil & Environmental Eng.
Thursday, December 10 | Prof. J.A. Cunningham

Instructions:

1. You may read these instructions, but do not turn the page or begin working until instructed.
2. This exam contains two sections and a total of seven questions. In section 1, answer question 1, plus *any two of questions 2, 3, and 4*. In section 2, answer all questions (5, 6, and 7).
3. Some questions have multiple parts. In those cases, the point value of each part is indicated. The total number of points possible is 120 (one point per minute).
4. Unit conversion factors and other potentially useful information are provided on page 2.
5. Provide your own paper. Write your name on each sheet. Staple your pages together and turn them in at the end of the exam. If you attempted all 7 problems, only submit the 6 you want me to grade.
6. Show your work and state any important assumptions you make. I cannot award partial credit if I can't follow what you did.
7. Report a reasonable number of significant digits in your answers.
8. Include units in your answers. An answer without proper units is not correct!
9. The exam is closed-book, but you are allowed two personal note sheets of standard 8.5-by-11 or A4 paper. You may write anything you want on them, both front and back, but they must be hand-written.
10. A hand-held calculator is recommended. Other electronic devices are not permitted. Calculators may not be pre-programmed with formulae from the class.
11. Time limit: 120 minutes. 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.
12. Don't cheat. Cheating will result in appropriate disciplinary action according to university policy. More importantly, cheating indicates a lack of personal integrity.
13. You may keep this exam if you wish. If you do not want to save it, then please either recycle it, or turn it back in to me and I will recycle it.
14. 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.

Potentially useful constants:

Ideal gas constant, *R*:	8.314 Pa•m^3•mol^{-1}•K^{-1} = 82.06×10^{-6} atm•m^3•mol^{-1}•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 g/mL = 997.0 kg/m^3
Viscosity of water at 25 °C:	0.890×10^{-3} Pa•sec
Density of water at 15 °C:	0.9991 g/mL = 999.1 kg/m^3
Viscosity of water at 15 °C:	1.136×10^{-3} Pa•sec

Potentially useful conversion factors:

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

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$	pKa = 6.35
$HOCl \leftrightarrow H^+ + OCl^-$	pKa = 7.54
$NH_4^+ \leftrightarrow H^+ + NH_3$	pKa = 9.2
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$	pKa = 10.33

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PART 1: DRINKING WATER TREATMENT (60 POINTS)

Consider a fictional city in west-central Florida that provides potable drinking water to its residents at a rate of 6.0 million gallons per day (950 m^3/hr). This fictional city operates a very simple water-treatment operation. The city pumps water out of the ground, disinfects it with chlorine, adds some corrosion inhibitor to protect the plumbing, adds fluoride for dental health, and then pumps the water into the distribution system. Let's call this fictional city, hmm, Grant City.

The pH of untreated groundwater in Grant City is 7.6, and the temperature is 15 °C. Also, an analysis of the untreated groundwater in Grant City showed the following composition (all in mg/L).

Calcium, Ca^{2+}	76.
Magnesium, Mg^{2+}	34.
Sodium, Na^{+}	6.9
Bicarbonate, HCO_3^{-}	366.
Chloride, Cl^{-}	14.
Sulfate, SO_4^{2-}	24.

<u>All students should answer question 1.</u>

1. (20 pts)
   a. (10 pts) Calculate the concentrations of the six major ions in units of mmol/L and meq/L. Is the charge balance acceptable? Optional: draw a bar graph of the meq/L concentrations.
   b. (4 pts) Estimate/calculate the hardness of the untreated groundwater, in units of mg/L as $CaCO_3$.
   c. (6 pts) Estimate/calculate the osmotic pressure of the untreated groundwater. Report your answer in units of Pa and bar. Assume that the osmotic coefficient $\phi = 0.95$.

<u>Now pick any two of the following three questions.</u>

2. (20 pts) The groundwater in Grant City is usually free from pathogens. However, the federal Safe Drinking Water Act requires that the treatment process be able to achieve 99.99% inactivation of viruses, just in case the source water becomes contaminated. To ensure that their chlorination system can meet this standard, Grant City ran some batch tests in the lab. With a chlorine residual of 4.0 mg/L and a contact time of 5 min, the lab observed 99% inactivation of viruses. With a chlorine residual of 3.0 mg/L and a contact time of 10 min, the lab observed 99.9% inactivation of viruses. In practice, the plant operates a plug-flow disinfection process with a contact time of 15 min. What concentration of chlorine residual ("mojo") is required to ensure 99.99% inactivation of viruses? Hint: assume the Chick-Watson law is valid, and use a *Ct* approach.

Information for questions 3 and 4:

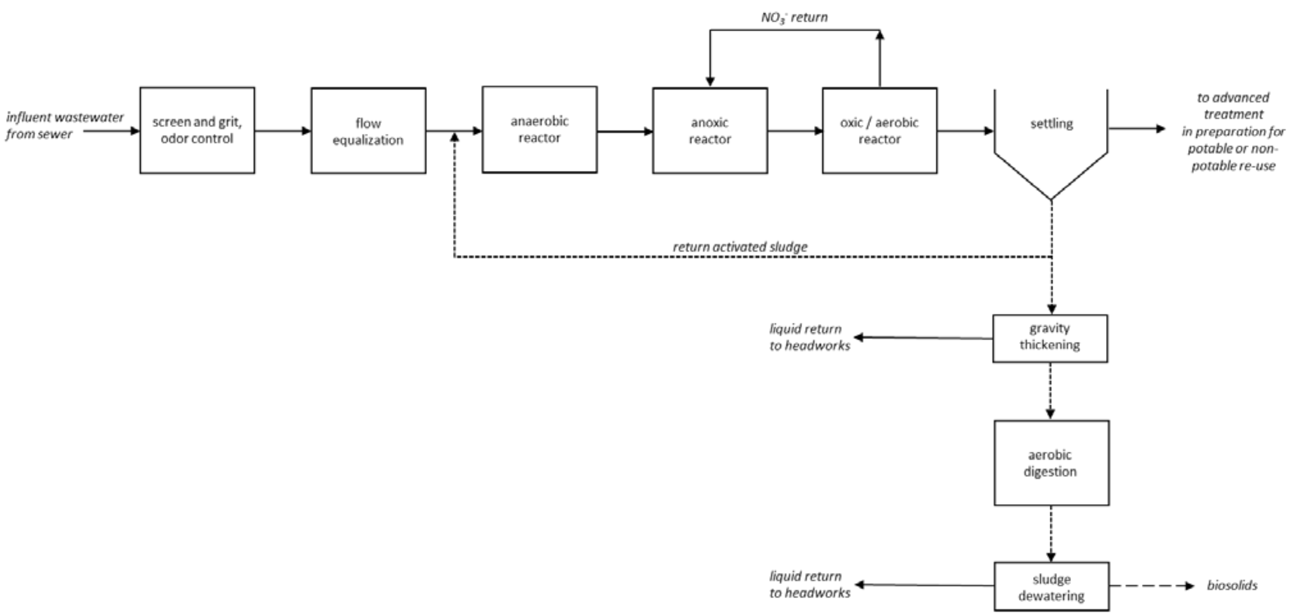
The residents of Grant City have long complained about how hard the water is. When the mayor and the city manager both had to purchase new Keurig coffee brewers, they finally decided it was time to expand the water-treatment plant to treat the water further. Imagine that you are a consultant that has been hired to perform some initial analysis of what treatment processes might be viable for the city. You are not yet performing a full-scale design; you are just performing a preliminary assessment of some different options that have been suggested.

3. (20 pts) One option under consideration is a lime-softening plant. The city will add lime in the form of CaO, which converts to $Ca(OH)_2$ when it is dissolved in water. If necessary, they will also add soda ash, Na_2CO_3. Suppose the city wants to soften its water to reduce the total hardness to 50 mg/L as $CaCO_3$. This level should make the coffee machines last much longer.
   a. (8 pts) Is it necessary to add soda ash to achieve the goal? Back up your answer with appropriate calculations – no credit for a lucky guess.
   b. (12 pts) Estimate/calculate the rate at which CaO and, if necessary, Na_2CO_3 would be added to the water. Report your answer(s) in kg/d.

4. (20 pts) Another option under consideration is reverse osmosis (RO). This is under consideration because it is considered a robust process: if the source water quality deteriorates over time, the plant can just increase the pressure to maintain desired water quality in the product water. The city is considering a two-stage RO process, with a goal of 60% recovery in each stage. For each stage, a number of pressure vessels would be operated in parallel. Each pressure vessel holds 7 membrane elements in series. It is possible to show that if the recovery of each membrane element is 12%, then the recovery of each pressure vessel will achieve the desired 60%. (You can take my word for it.)
   a. (5 pts) Based on a two-stage configuration with 60% recovery in each stage, what would be the overall recovery of the plant?
   b. (5 pts) Based on the overall recovery from part (a), at what rate must groundwater be supplied to the plant, to produce the necessary 950 m^3/hr? If the first stage contains 30 pressure vessels, at what rate must groundwater be fed to each pressure vessel?
   c. (10 pts) Assuming that each membrane element has an area of 35 m^2, and assuming that the feed pressure on the first stage is 40 bar = 4×10^6 Pa, estimate/calculate the mass transfer coefficient k_w required to give 12% recovery in each membrane element. Report your answer in units of L/(m^2•bar•s).

PART 2: WASTEWATER TREATMENT / WATER RECLAMATION (60 POINTS)

On the second exam this semester, we looked at a possible design for a new water reclamation facility in Sprawlville. A problem with the proposed design was that the nitrogen removal system had been designed inappropriately. Several students suggested that, to fix the nitrogen removal process, the entire plant should be re-designed. OK, you asked for it! The primary sedimentation, the secondary treatment, the nitrogen removal, and the phosphorus removal processes will all be taken out. The new design is based on an A^2O process, as shown.



As a reminder, the flow rate coming from the flow equalization tank is 900 m^3/hr, and the soluble BOD_5 concentration coming from the flow equalization tank is 80 mg/L. Also, the concentration of ammonium (NH_4^+) coming from the flow equalization tank is 28 mg/L as N.

5. (20 pts)
   a. (5 pts) How much removal of NH_4^+ would you expect to achieve in the anaerobic reactor and the anoxic reactor? Explain in terms of the relevant processes (or lack thereof). Hint: no calculations are required.
   b. (5 pts) Given your answer to part (a), calculate the loading of NH_4^+ that enters the oxic/aerobic reactor, in units of kg/d (as N).
   c. (10 pts) Let's use that information to determine the size of the oxic/aerobic reactor. If we assume that the MLVSS concentration in the oxic/aerobic reactor is 2,000 mg/L, and the temperature is 15 °C, then your text book says the ammonia loading should be no greater than 16 lb NH_3-N per 1000 ft^3 per d, which is 256 mg/(L•d), assuming that pH = 8.4. Use a pH correction factor of 0.8 and a peaking factor of 1.5. Based on those numbers, estimate/calculate the required hydraulic residence time in the reactor (in hr) and the required size of the reactor (in m^3).

Assume the concentration of soluble BOD_5 entering the oxic/aerobic reactor (from the anoxic reactor) is 20 mg/L. Also assume that the concentration of MLVSS in the oxic/aerobic reactor is 2,000 mg/L, and the following Monod kinetic parameters apply for BOD_5 removal.

- half-velocity coefficient K_S = 60 mg/L BOD_5
- bacterial death rate coefficient k_d = 0.14 d^{-1}
- maximum specific growth rate coefficient μ_{max} = 2.0 d^{-1}
- yield coefficient Y = 0.60 mg biomass produced per mg BOD_5 consumed

6. (20 pts)
   a. (5 pts) The estimated concentration of soluble BOD_5 entering the oxic/aerobic reactor (20 mg/L) is significantly lower than the concentration of soluble BOD_5 exiting the flow equalization tank (80 mg/L). Why? There are actually two reasons, one that is more obvious (to me) than the other. Try to identify both reasons if you can.
   b. (6 pts) Assume the allowable concentration of soluble BOD_5 exiting the oxic/aerobic reactor is 9 mg/L (from exam #2). Estimate/calculate the required solids retention time (also called sludge age or mean cell residence time). Hint: use the Monod kinetic parameters given above.
   c. (6 pts) Estimate/calculate the required aeration time (in hr) and the required volume of the aeration basin (in m^3) to achieve the required BOD_5 removal.
   d. (3 pts) Compare your answer from 5(c) to your answer from 6(c). Which controls the required size of the reactor – nitrification, or removal of carbonaceous BOD_5 removal? What size reactor do you recommend (in m^3)?

7. (20 pts)
   a. (5 pts) The concentration of solids in the waste activated sludge (WAS) is 12,000 mg/L, and the density of the WAS is 1006 g/L. Estimate/calculate the solids concentration in the WAS as % solids by mass.
   b. (15 pts) The gravity thickener thickens the sludge to 3% solids by mass. Also, 90% of the solids entering the thickener go to aerobic digestion, and 10% of the solids are returned in the liquid return stream. Based on these numbers, for every 100 L of WAS that goes to the thickener, how many L of sludge go to digestion, and how many L of sludge are returned to the head of the plant? The density of the thickened sludge is about 1017 g/L and the density of the liquid return stream is about 1000 g/L. Hint: do not panic. With a couple good material balances, this problem is not too difficult.

END OF EXAM