CEE 370 Fall 2015

Laboratory #5 Drinking water treatment

Objective

To determine if the Robert's Meadow Reservoir meets the current water quality standards established by the US EPA for water supply.

Introduction

The most common and economical treatment for drinking water is "conventional treatment". Conventional treatment consists of the following processes: coagulation, flocculation, sedimentation (clarification) and filtration (USEPA, 2015, Figure 1) and is often followed by disinfection prior to a holding tank for achieving CT and then sent into the distribution system (Figure 2). Conventional treatment may also incorporate the use of filter media (such as granular activated carbon (GAC) or powdered activated carbon (PAC). This level of treatment will result in water that either meets or fails in meeting federal standards for pathogen control and for chlorinated disinfection byproducts (DBPs). In order to determine this, water quality testing is done.

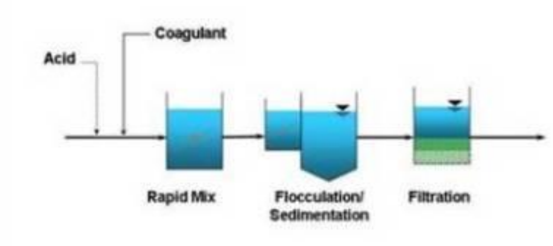

Figure 1. Schematic of conventional water treatment process (USEPA, 2015)

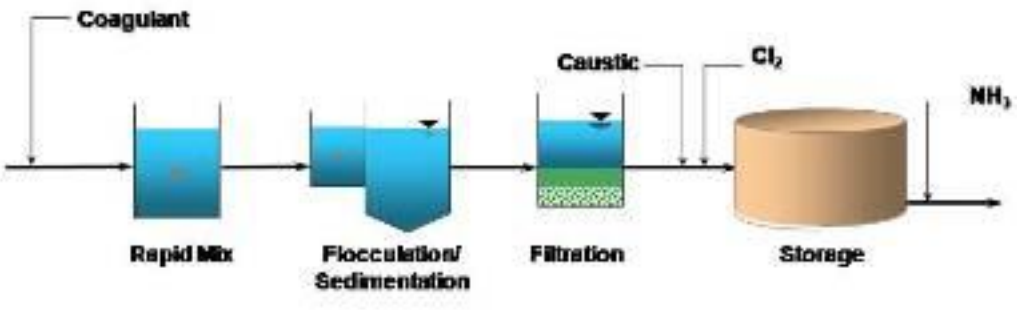

Figure 2. Schematic of conventional water treatment process with chlorine addition in the treatment process

Current Drinking Water Standards in the US

Surface Water Treatment Rule (USEPA, 1989) requires **0.5 log removal of *Giardia*** and **2.0 log removal of *viruses*** by disinfection when followed by conventional treatment with coagulation and filtration. To achieve this level of removal, water suppliers are required to provide a certain "**CT**" (i.e., the product of disinfectant concentration C and contact time T; Table 1). The values of CT depend on the disinfectant, the temperature and the pH. To account for short- circuiting in chlorine contact tanks, the USEPA requires that the $\mathbf{t_{10}}$

be used to calculate the “effective” retention time rather than the calculated hydraulic retention time (HRT) where:

$$HRT = V/Q \tag{Eq. 1}$$

such that V is the volume of the tank (m^3) and Q is the volumetric flow rate (m^3/s).

This $\mathbf{t_{10}}$ is essentially **the time it takes for the fastest 10% of the influent water to exit the tank**. It is determined by a tracer study on the full-scale tank, and it is usually represented as a percentage of the HRT. A well-baffled tank can reach t_{10} levels up to 50% of the HRT or more.

The Stage 2 Disinfectants/Disinfection Byproduct Rule (D/DBPR) (USEPA, 2006) requires that DBPs be kept below 80 µg/L for trihalomethanes (THMs) and 60 µg/L for haloacetic acids (HAAs). This means that the amount of precursor organic matter in the water after coagulation and filtration must be low enough so these DBPs do not exceed these limits even when the water has reacted with the chlorine for many days (the typical maximum value for distribution system residence times).

Table 1. CT Values for inactivation of Giardia Cysts by Free Chlorine at 20°C (USEPA, 1991)

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	6	12	18	24	30	36	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62
0.6	6	13	19	25	32	38	8	15	23	30	38	45	9	18	27	36	45	54	11	21	32	43	53	64
0.8	7	13	20	26	33	39	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66
1	7	13	20	26	33	39	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67
1.2	7	13	20	27	33	40	8	16	24	32	40	48	10	19	29	38	48	57	12	23	35	46	58	69
1.4	7	14	21	27	34	41	8	16	25	33	41	49	10	19	29	39	48	58	12	23	35	47	58	70
1.6	7	14	21	28	35	42	8	17	25	33	42	50	10	20	30	39	49	59	12	24	36	48	60	72
1.8	7	14	22	29	36	43	9	17	26	34	43	51	10	20	31	41	51	61	12	25	37	49	62	74
2	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62	13	25	38	50	63	75
2.2	7	15	22	29	37	44	9	18	27	35	44	53	11	21	32	42	53	63	13	26	39	51	64	77
2.4	8	15	23	30	38	45	9	18	27	36	45	54	11	22	33	43	54	65	13	26	39	52	65	78
2.6	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66	13	27	40	53	67	80
2.8	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67	14	27	41	54	68	81
3	9	16	24	31	39	47	10	19	29	38	48	57	11	23	34	45	57	68	14	28	42	55	69	83

CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	12	25	37	49	62	74	15	30	45	59	74	89	19	35	53	70	88	105
0.6	13	26	39	51	64	77	15	31	46	61	77	92	18	36	55	73	91	109
0.8	13	26	40	53	66	79	16	32	48	63	79	95	19	38	57	75	94	113
1	14	27	41	54	68	81	16	33	49	65	82	98	20	39	59	78	98	117
1.2	14	28	42	55	69	83	17	33	50	67	83	100	20	40	60	80	100	120
1.4	14	28	43	57	71	85	17	34	52	69	86	103	21	41	62	82	103	123
1.6	15	29	44	58	73	87	18	35	53	70	88	105	21	42	63	84	105	126
1.8	15	30	45	59	74	89	18	36	54	72	90	108	22	43	65	86	108	129
2	15	30	46	61	76	91	18	37	55	73	92	110	22	44	66	88	110	132
2.2	16	31	47	62	78	93	19	38	57	75	94	113	23	45	68	90	113	135
2.4	16	32	48	63	79	95	19	38	58	77	96	115	23	46	69	92	115	139
2.6	16	32	49	65	81	97	20	39	59	78	98	117	24	47	71	94	117	141
2.8	17	33	50	66	83	99	20	40	60	79	99	119	24	48	72	95	119	143
3	17	34	51	67	84	101	20	41	61	81	102	122	24	49	73	97	122	146

Background/Problem Description

The Robert's Meadow Reservoir (also referred as Hoxie Reservoir or the Leeds Reservoir) in the Leeds section of Northampton served for 34 years as the principal water supply for the town, and later as a supplemental supply. Following two large fires in Northampton in 1870, it was decided (February 1871) that the community should look to Roberts' Meadow Brook as a reliable water supply for its first municipal system. Construction of the reservoir began in May 1871 and by September of that year it was filled with about 4 million gallons of water. By 1873 there were 517 families that had been supplied with piped water, not to mention a large number of businesses and 107 fire hydrants. Eventually two more dams would be constructed in Roberts' Meadow system.

Recognizing the need for more water than could be supplied by Roberts' Meadow, the city began planning for two new supplies in Whately and Williamsburg, the West Whately Reservoir and the Mountain Street reservoir, respectively. Construction proceeded in the first few years of the 20th century. On March 30, 1905 the city started using the new upland sources exclusively. The Whately system would later be improved with the construction of the much larger Francis P. Ryan Reservoir immediately adjacent to the West Whately Reservoir.

Table 2 summarizes the drainage area, safe yield and reservoir storage of the four surface water sources in Northampton.

Table 2. Northampton's Surface Water Supplies (Northampton Watershed Resource Protection Plan, PVPC, June 1994)

Source reservoir	Drainage Area (acres)	Safe Yield (MGD)	Reservoir Storage (MG)
Roberts Meadow	6,900	2.00	85
West Whately	1,182	3.79	750
Ryan	2,762		
Mountain Street	541	1.17	375

Low water levels in the Mountain Street Reservoir forced the city to begin using Roberts Meadow again in October 1932. The state department of health found high bacterial counts from the Roberts Meadow supply, so the city installed a chlorination system for that supply that went into service on Nov 9, 1932. At this time it was also recognized that the water had high levels of organic matter (color) and algae (Gazette, May 4, 1932). The general water degradation was probably exacerbated by runoff from upstream farms. From this point on, the Roberts Meadow system was used only when the levels in Mt. Street Reservoir were low and the overall supply needed a supplement. In late 1950, two wells were constructed in the Florence section of Northampton to help provide some additional water. Roberts Meadow Reservoir was finally taken out of service in 1978- 1979, after 108 years of use. After this point it was still listed as a back-up source for emergencies, but it was apparently never used again.

With the near failure of the Whittenton Pond Dam in Taunton in 2005, the Commonwealth of Massachusetts began an aggressive campaign to inspect major public dams. At this time they decided that the Upper Roberts Meadow Dam was at risk and needed to either be repaired or removed. Following careful analysis by the city's consultant, the decision was made to remove it based largely on economic considerations. Most recently (Hampshire Daily Gazette; October 29, 2010), the Northampton Board of Public Works voted to have it removed. However, experience will tell you that in politics as with sports, "it is never over until it is over". There may still be appeals and possibly legal challenges to this decision. Nevertheless, the major portion of the Roberts Meadow supply is impounded by the Middle Roberts Meadow Dam which will remain regardless of the fate of the Upper Dam.

Purpose

The purpose of this laboratory study is **to determine if the Roberts Meadow supply could be treated using conventional (i.e., low cost) technology and meet existing standards for disinfection and disinfection byproducts**. Specifically, it would need to be of high enough quality so that after coagulation with alum and filtration, the remaining dissolved organic matter (DOM) is below a key threshold. That threshold is not defined by a simple UV_{254} absorbance nor is it fully defined by a total organic carbon level (TOC). Instead it is defined as a level that will not produce excessive THMs and HAAs in the distribution system when chlorine is added at sufficient dose and contact time to meet "CT" regulations for disinfection.

The US EPA requires that conventional treatment plants meet a certain percent removal of TOC. For the Roberts Meadow Supply, it would probably be 35% when the raw water TOC is below 4 mg/L and *45% when it is above this value).

In the laboratory, the conventional treatment process can be simulated with the classic Jar Test Procedure outlined below, followed by filtration on a glass fiber filter and then by the addition of chlorine. It must be done in this order to accurately reproduce what would occur in a full-scale water treatment plant. The chlorinated sample is then held for a period of time to simulate the residence time in the clear well (CT tank) and the distribution system.

Analysis

Measurement of Natural Organic Matter

We will use a Genesys 10s Ultraviolet-Visible (UV-Vis) Spectrophotometer for monitoring the concentration of natural organic matter in the coagulated water. In our case, we are using **absorbance as a "surrogate" measure of the amount of dissolved natural organic matter** (NOM) remaining in a treated samples. Thus the sample must be filtered prior to analysis. While we could pick almost any wavelength as our "surrogate" parameter, we normally use 254 nm by virtue of an arbitrary convention.

This instrument must be turned on and warmed up well before use. The first step in its use is to set the wavelength using the panel controls. It is then "calibrated", or more accurately, "zero-ed" by placing a cuvette with distilled water into the cell changer and pressing the button corresponding to 'measure blank' on the screen. Make sure you've selected the "Absorbance" readout. Then place your sample in a separate cuvette and press the button on the cell changer indicating the position of the sample. You will see a read out in absorbance units per centimeter. Also on the screen will be a reminder of the wavelength that this instrument is tuned to. The concentration of any absorbing compound is linearly related to its absorbance in accordance with Beer's Law (Eq. 2):

$$Abs = A \times C \times x \qquad \text{(Eq. 2)}$$

Where Abs is the measured absorbance, A is the absorptivity ($M^{-1}cm^{-1}$) in which case it is called the molar absorptivity), C is the concentration and x is the light path length of the sample cell (usually 1 cm, which is what we'll be using).

Measurement of Chlorine Residual by DPD Titration

The amount of chlorine added to water is called the "chlorine dose". The amount that persists or can be measured after addition is called the "chlorine residual". After addition of aqueous chlorine to water for treatment purposes, it is important to measure how much is left at any given time. This is because chlorine can become rapidly dissipated and its effectiveness is directly linked to its concentration and exposure time. In this treatment study you will be adding a range of chlorine doses (1-5 mg/L), but the residual chlorine will be a bit lower, sometimes a lot lower. At the end of each of the tests, you will be measuring the final chlorine residual using the DPD titration method as follows:

1. Add 5 mL of DPD buffer from auto pipet bottle to a separate Erlenmeyer flask without the diluted sample. Add 5 mL of DPD indicator solution from the other auto pipet bottle to the flask
2. Add 100 mL of a diluted sample to the Erlenmeyer flask. The solution would turn pink indicating the presence of chlorine.
3. Record the initial level of the titrant (ferrous ammonium sulfate, FAS) in the burette. Titrate with FAS until the pink color just disappears and record the final level in the burette. (The sample you're titrating must have a chlorine residual near or below 4 mg/L as Cl_2 (0.056 mM); add more if there is less than 4.5 mL remaining.)
4. The chlorine residual in mg/L as Cl_2 in your sample is equal to the number of mLs of titrant used: 1 mL of FAS = 0.1 mg/L of residual Chlorine as Cl_2.

Relationship between Chlorine Residual and DBP Concentration

Actual measurement of disinfection byproduct (DBP) concentrations is beyond the scope of the CEE 370 lab. However, it is possible to use chlorine residual measurements to estimate DBP formation from coagulated and filtered waters.

First, we need to define an important water quality parameter know as chlorine demand (Eq. 3):

$$Cl_2 \text{ Demand (mg/L)} = \text{Chlorine Dose (mg/L)} - \text{Chlorine Residual (mg/L)} \qquad \text{(Eq. 3)}$$

From this we can estimate DBP formation. The reason is that waters with almost entirely “organic” chlorine demand, such as this one, will result in a certain percent conversion of reacted chlorine to organic chlorine by-products. The correlation we will use comes from research studies conducted at UMass. Equations 4 and 5 give estimates of the THM and HAA formation under the same conditions that were used for chlorine demand test (i.e., same pH, time, and temperature).

$$THM = 1.919(Cl_2demand)^{0.47}(pH)^{1.245}(time)^{0.053}(temp)^{0.204} \qquad \text{(Eq. 4)}$$
$$HAA = 35.24(Cl_2demand)^{0.178}(pH)^{.0.314}(time)^{0.141}(temp)^{0.125} \qquad \text{(Eq. 5)}$$

where both THM and HAA are in units of μg/L, chlorine demand is in mg/L, time is in hours, and temperature is in °C.

Procedure

Table 3 summarizes the responsibilities for every set number, in addition to the amount of bicarbonate and alum dose to be added.

Table 3. Summary of Test Conditions for Each Lab Period

Set #	Bicarbonate addition (mL of 78 g/L $NaHCO_3$)	Alum Dose (mg/L)
1	0	0, 5, 10, 15, 30, 60
2	2 mL	0, 5, 10, 15, 30, 60
3	0	0, 10, 20, 45, 60, 100
4	2 mL	0, 10, 20, 45, 60, 100

Part A1. Jar Testing

1. Receive testing assignment (Set #) from TA
2. Measure out 1-L (or 700 mL if smaller beakers are used) volumes of the raw water by pouring from a carboy to a plastic 1-L graduated cylinder and dispense to the each of the six beakers
3. Add Bicarbonate solution ($NaHCO_3$) as needed (for sets #2 and #4) to each beaker
4. Measure out an additional volume (e.g, 250 mL) of raw water into a separate 500-mL beaker and add the same dose ratio of ($NaHCO_3$) to this, accounting for the smaller volume. Use this sample for measurement of raw water pH, temperature and UV-Vis scan. While you’re taking the scan, record the raw water UV absorbance at 254 nm. You may wish to do this while the 6 beakers are in their slow mix (#8) or settling phase (#10).
5. Place beakers under the 6-paddle stirrer (jar test machine) and stir at high speed (~100 rpm).
6. One-by-one add the requisite volume of alum stock to achieve the desired doses for your set# (rapid mix phase)
7. Once the last beaker has been dosed, wait 60 seconds and reduce the mixer speed to 20 rpm. Maintain this slow mix phase for 20 minutes (flocculation). During this time you may wish to make the measurements on the small sample in the 500 mL

beaker (e.g., raw water pH, temperature, UV_{254} and the UV-Vis scan).

8. Remove the six beakers from the 6-paddle stirrer. Gently measure **coagulated pH** of each coagulated sample and the raw water from step 5.
9. Allow all 6 beakers to sit quiescently (settling phase) for 30 minutes.
10. One-by-one, carefully decant (pour, without disturbing settled solids) ~500-700 mL into a graduated cylinder. Stop pouring once the settled solids (if any) begin to flow out of the beaker

Part A2. Analysis of Settled and Filtered Water

11. Pour about a small volume from the graduate cylinder into a turbidimeter cell and measure turbidity (**settled turbidity)**.
12. Place a new Glass Fiber filter (GF/C) into the Millipore filtration apparatus. Re-assemble the apparatus and turn on the vacuum pump. Then pour the full remaining decanted sample volume from the large graduated cylinder into the reservoir.
13. Once filtration is complete, withdraw a few mL with a pasteur pipet and use this to measure absorbance on the filtered sample (**filtered UV_{254} absorbance**).
14. Pour the filtered sample from the vacuum flask back into the graduated cylinder and record the exact volume. Then pour this into a 500-mL amber bottle. If the volume of water equal or exceeds 500 mL, pour about 490 mL, leaving a few mL of headspace in the bottle. In either event, it is important that you know exactly what the volume of sample is in the bottle. Label it, and set aside for chlorine demand testing.
15. Repeat Steps 12-15 for each settled sample

Part B. Chlorine Demand Testing

1. Add the requisite volume of chlorine stock to achieve the desired chlorine dose (See Table 4 below). Cap and mix by inverting several times.
2. Make sure the amber bottle is properly labelled (group name, jar#, conditions) and place it on the bench for room-temperature incubation (reaction).
3. At the end of each of the 5 chlorine contact times, locate your bottles, pour out 100 mL and measure **residual chlorine** for each of the five. After you are done, cap the bottles and return them to the bench to continue incubating. Except for the first recording time (@1 hr), you will have to return during a non-lab time to make the measurement. Please make arrangements for this with your lab partners. Only one person from each group need be present to make these measurements. Please contact the instructor or TA if the door is locked. Be aware that you can modify the reaction time for your convenience, but it is important you record the exact time of analysis. Also you should be aware that some bottles may run out of chlorine before the last scheduled reaction time. If you notice one that has dropped to zero residual, there is no need to continue measuring it.
4. Measure and record **final pH** in each sample after the last chlorine measurement.
5. When the last measurement is made, measure and record the **final water temperature** for at least one sample.

Table 4. Summary of test conditions for each lab period

	Chlorine Dose	Approximate Reaction Times
1	1.5 mg/L	1 hr, 14 hrs, 26 hrs , 2 days, 3 days
2	2.5 mg/L	1 hr, 14 hrs, 26 hrs , 2 days, 3 days
3	3.5 mg/L	1 hr, 38 hrs, 3 days, 5 days, 7 days
4	5 mg/L	1 hr, 38 hrs, 3 days, 5 days, 7 days

Steps for completing the lab write-up

Sharing of Data

a) Transfer your coagulation data to the excel spreadsheet template that you were sent by email.
b) Send the filled-in spreadsheet by email to the instructor and to lab TA. Do this within 24 hours of your lab period.
c) Continue to fill in the chlorine residual portion of the spreadsheet as you collect more data.
d) Send the completed spreadsheet (including chlorine residual data) to the instructor and TA by Tuesday, April 17th at noon.

Presentation of your own Data and Discussion

e) Graph the raw water absorbance spectrum and a spectrum of coagulated/filtered water (use the one with the highest dose). Graph both on the same set of axes with wavelength (200-400 nm) on the x-axis. Are they similar? What does this tell you about using 254 nm as an indicator of organic matter concentration?
f) Graph settled water turbidity and UV absorbance (254 nm) versus alum dose in mg/L. Alum dose is the independent variable, and therefore it should be identified with the x-axis.

Interpretation Regarding Current EPA Regulations

g) The instructor and Lab TAs will provide you with the entire class's data at some point during the second week of the lab. You should incorporate this dataset into your group's lab writeup.
h) Use the power function equations (#2 and #3) to estimate THM and HAA levels for the various treatment scenarios (alum dose, pH, chlorine dose) with special attention to the 3 day chlorine reaction time as this is the normal maximum water age in the Northampton system.
i) Comment on the feasibility of meeting both THM and HAA standards while still maintaining a measureable chlorine residual (i.e., >0.1 mg/L) for the 3-day reaction time.
j) Propose at least 2 scenarios (chlorine dose and soda ash addition) that will meet these requirements. If none do, propose at least 2 scenarios that come closest. Comment on the "optimal" alum dosage for this scenario.
k) Calculate a chlorine contact tank volume for the two scenarios needed to meet the "CT" requirement assuming a flow of 2 MGD at Roberts Meadow. Use 0.5°C as a conservative design condition (Table 1). Although the USEPA requires an additional 0.5 log Giardia removal by chlorination, assume the City wants to achieve a full 1 log removal credit to provide an additional margin of safety. You should also assume a t_{10} of 50% of

the hydraulic retention time of the tank.

References:

USEPA, 1989. Drinking Water, National Primary Drinking Water Regulations, Filtration, Disinfection, Turbidity, Giardia Lamblia, Viruses, Legionella, and Heterotrophic Bacteria, Vol 54 (124).
USEPA, 2015. Conventional Treatment. Retrieved on October 29, 2015 from: http://iaspub.epa.gov/tdb/pages/treatment/treatmentOverview.do?treatmentProcessId=1934681921

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USEPA, 1991. Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources. Retrieved from: http://water.epa.gov/lawsregs/rulesregs/sdwa/swtr/upload/guidsws.pdf