PART A

Written examination in Drinking Water Engineering 20 March 2019, at 08:30-13:30

Course BOM075, Chalmers

Teacher: Thomas Pettersson, ext. 2127

The written examination consists of totally 50 credits (25 credits on Part A and 25 credits on Part B)

To pass the examination a minimum of 10 credits per part is required.

Part A consists of 5 theory questions, *no aid allowed* *(Suggested time spent on Part A is ~60-90 min)*

Part B consists of 3 problems, where optional (pocket) calculator ("valfri miniräknare") and course literature (see list) are allowed, but not solved problems ("lösta exempel")

Short and precise answers recommended!

1. Water stress is an important international issue that can limit drinking water supply. Define the term water stress, and what negative raw water quality effects may water stress situations cause to drinking water supply? (5p)

2. In your project assignment, you assessed the health risk for the drinking water consumers using MBA and QMRA methods. Describe how the risk assessment results varied for your specific system from the two different methods. What does the difference (if any) mean? What is the general difference between the two methods regarding the health risk principle? (5p)

3. At the waterworks of Anneboda, better barrier function against microorganisms is desired. At Anneboda, surface water is treated with chemical coagulation and flocculation using alum ($Al_2(SO_4)_3$) followed by sedimentation; rapid granular media filtration through granular activated carbon; and disinfection with free chlorine. Two options are considered for the upgrade; ozonation and UV.

   Compare ozonation and UV in terms of:
   - principal mechanisms of action
   - needs for additional pre-/post-treatment and monitoring for successful application (6p)

4. Turbidity and pH are two parameters that are measured on-line in drinking water production. At a waterworks, the treatment train for drinking water production from surface water consists of:
   - chemical coagulation and flocculation using alum ($Al_2(SO_4)_3$)
   - sedimentation in horizontal flow clarifiers
   - rapid granular media filtration using sand
   - disinfection using free chlorine

   Select two positions at the waterworks for on-line measurements of turbidity and pH. Explain your choices. (4p)

5. Name three microbial risks in the distribution network and rate their priority for health according to literature. Describe how hydraulic and physical breaches for one of these risks can lead to contamination of the drinking water. (5p)

PART B

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***where* optional (pocket) calculator ("valfri miniräknare") and the course literature (see list) are allowed to use for Part B, but not solved problems ("lösta exempel")**

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1. The Larsberg drinking water treatment plant (DWTP) supplies the local town with 18600 cubic meters of water each day. The water treatment chain is quite simple with only coagulation and sedimentation followed by UV disinfection (40 mJ/cm^2) and chlorination (1.0 mg/l chlorine).

   Currently, Larsberg DWTP is using iron chloride ($FeCl_3$) as a coagulant. However, $FeCl_3$ is reactive and difficult to work with and due to safety concerns, they have decided to switch coagulants and use aluminium sulphate (Alum) in the future. Results of jar tests comparing the two coagulants are shown in Fig. 1.

   Refer to Table 1 and Fig. 1 to answer the following questions. Use pKa_1=6.52 in your calculations.

   (1) What is the minimum cost per day of treating the town's drinking water with (a) $FeCl_3$, and (b) Alum? Consider only coagulant costs and ignore other chemicals.

   (2) During coagulation with Alum it is planned to use lime, $Ca(OH)_2$, to increase hardness to 20 mg Ca^{2+}/l. Calculate how much to lime to add and predict what will be the final pH.

   (3) Assume that after dosing alum and lime in the plant, the pH is measured and found to be 7.05. Is it necessary to add any more chemicals to ensure an appropriate water quality before distribution? If so, suggest which specific chemicals should be added.

   (4) Assume that the plant will make no other change in its operations other than what you recommended in parts (1)-(3) above. Discuss how the subsequent disinfection steps at the DWTP are likely to be affected by the change in coagulant.

(8p)

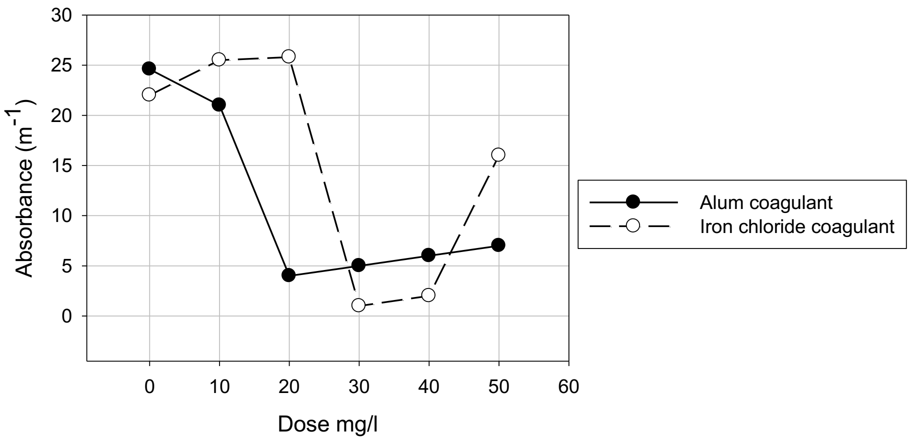


Figure 1: Results of coagulation tests in Larsberg DWTP at 5 °C.

Equilibrium equations

1. $H_2CO_3 + H_2O$	$\rightleftharpoons$ $HCO_3^- + H_3O^+$	$pK_{a1} = 6.52$
2. $HCO_3^- + H_2O$	$\rightleftharpoons$ $CO_3^{2-} + H_3O^+$	$pK_{a2} = 10.4$
3. $2H_2O$	$\rightleftharpoons$ $OH^- + H_3O^+$	$pK_w = 14$
4. $Al_2(SO_4)_3{\cdot}18H_2O$	$\rightleftharpoons 2Al^{3+} + 3SO_4^{2-} + 18H_2O$	K is very large
5. $Al^{3+} + 3HCO_3^- + 3H_2O$	$\rightleftharpoons Al(OH)_3 + 3H_2CO_3$	K is very large
6. $H_2SO_4 + 2HCO_3^-$	$\rightleftharpoons 2H_2CO_3 + SO_4^{2-}$	K is very large
7. $Na_2CO_3 + H_2CO_3$	$\rightleftharpoons 2Na^+ + 2HCO_3^-$	K is very large
8. $NaOH + H_2CO_3$	$\rightleftharpoons Na^+ + HCO_3^- + H_2O$	K is very large
9. $Ca(OH)_2 + 2H_2CO_3$	$\rightleftharpoons Ca^{2+} + 2HCO_3^- + 2H_2O$	K is very large

Table 1: Chemical data

Raw water quality: • Temperature: 5ºC • Alkalinity: 10 mg/l in HCO_3^- • Ca^{2+} : 14 mg/l • pH: 6.5	Aluminium sulphate (Alum): • Formula: $Al_2(SO_4)_3 \cdot 18H_2O$ • Molecular weight: 666 g/mol • Price per kg in US dollars: \$0.55
Iron chloride ($FeCl_3$): • Formula: $FeCl_3$ • Molecular weight: 162 g/mol • Price per kg in US dollars: \$0.24	Other molecular weights • Ca: 40 g/mol • O: 16 g/mol • C: 12 g/mol • H: 1 g/mol • Cl: 35.5 g/mol

2. A town of 10 000 inhabitants wants to construct a reservoir in order to be able to handle daily variations of demand and be prepared for a 2 hour fire. The fire flow needed is 20 l/s. The town has an average consumption of 160 liters per person per day and the population is considered to be uniform. The pump is able to provide 22.5 l/s at a constant rate. Due to pressure head requirements from the network, the maximum height of the tank is 6 m.

   The consumption varies throughout the day according to the following pattern:

Time	% daily consumption/3h
00-03	2
03-06	8
06-09	22
09-12	12
12-15	11
15-18	25
18-21	15
21-24	5

   Determine what volume, area and diameter for the tank is needed to handle normal daily variation in addition to having 2h emergency storage for firefighting.

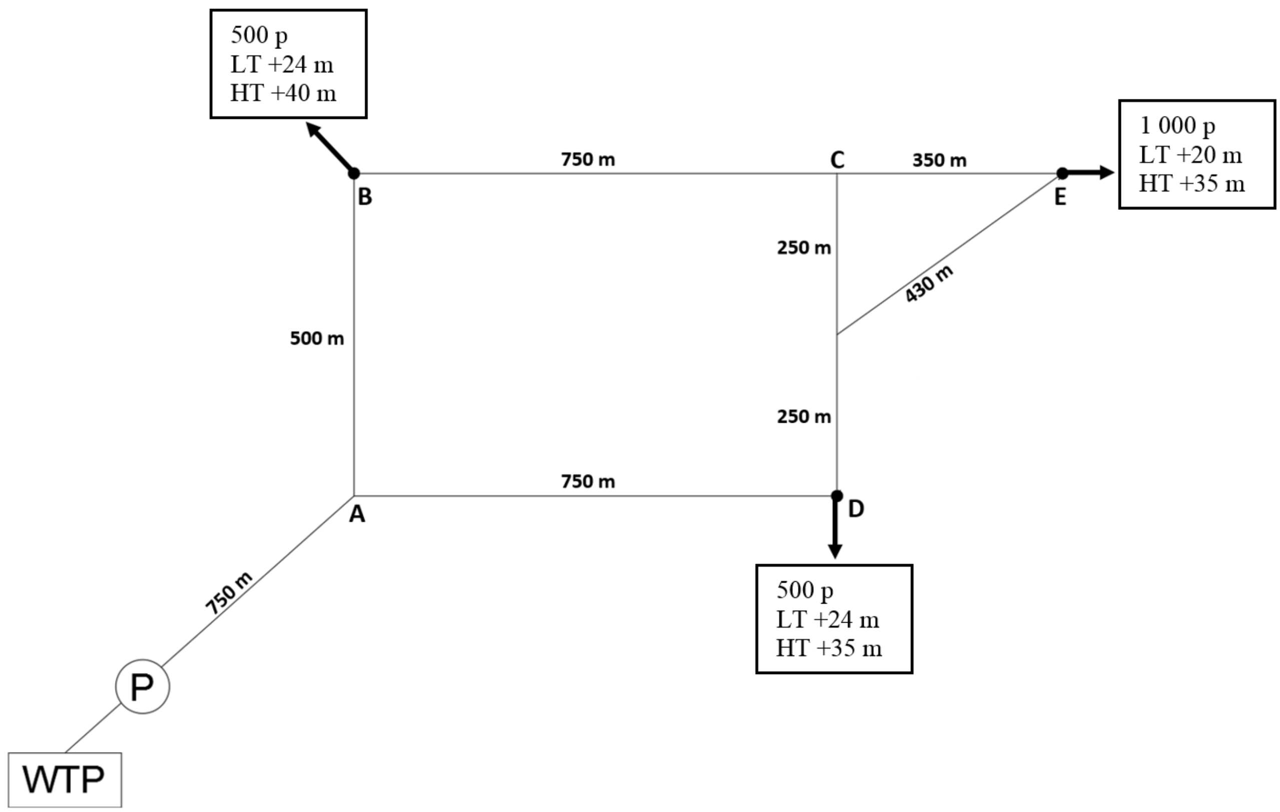
   (6p)

3. In a small and hilly town drinking water is supplied to the 2000 consumers, living in apartments, from a local drinking water treatment plant (WTP). A grid network is planned to be used to transport the water to the consumers.

   Your task is to design all the pipes in the distribution network, including the pipe from the pump (P-A). The system should provide a minimum velocity of 0.6 m/s (at design flow) and adequate pressures at the taps. Acceptable error for the grid is 0.1 l/s. You should also design the pump at the WTP (P, located +10 m).

   The network to design (including information on low and high taps, population in the areas) is presented in the figure below.

   (11p)


500 p
LT +24 m
HT +40 m
750 m
C
350 m
1 000 p
LT +20 m
HT +35 m
B
E
250 m
430 m
500 m
250 m
750 m
A
D
750 m
500 p
LT +24 m
HT +35 m
P
WTP

Problem 1

The Larsberg drinking water treatment plant (DWTP) supplies the local town with 18600 cubic meters of water each day. The water treatment chain is quite simple with only coagulation and sedimentation followed by UV disinfection (40 mJ/cm^2) and chlorination (1.0 mg/l chlorine).

Currently, Larsberg DWTP is using iron chloride ($FeCl_3$) as a coagulant. However, $FeCl_3$ is reactive and difficult to work with and due to safety concerns, they have decided to switch coagulants and use aluminium sulphate (Alum) in the future. Results of jar tests comparing the two coagulants are shown in Fig. 1.

Refer to Table 1 and Fig. 1 to answer the following questions. Use pKa_1=6.52 in your calculations.

(1) What is the minimum cost per day of treating the town's drinking water with (a) $FeCl_3$, and (b) Alum? Consider only coagulant costs and ignore other chemicals.

a) Alum – 20 mg/L * 18600 000 L * 1e-6 kg/mg * 0.55 $/kg = $205 (1p)
b) $FeCl_3$ – 30 mg/L * 18600 000 L * 1e-6 kg/mg * 0.24 $/kg = $134

(2) During coagulation with Alum it is planned to use lime, $Ca(OH)_2$, to increase hardness to 20 mg Ca^{2+}/l. Calculate how much to lime to add and predict what will be the final pH.

Added [Ca] = 20-14 = 6 mg/l = 6/40 = 0.15 mmol/l
Added [$Ca(OH)_2$] = added [Ca] = 0.15 mmol/l
Added [$Ca(OH)_2$] = 0.15 mmol/l x 74 g/mol = 11.1 mg/l (1p)

From Fig 1: Added [Al^{3+}] = 2 x [Alum] = 40 mg/l = 40/666 = $6 \cdot 10^{-2}$ mmol/l

From Table 1: [HCO_3^-]= 10/61 =0.164 mmol/l

Calculate initial carbonic acid:

$$[H^+] = 10^{-6.5} = 10^{-6.52} \left\{\frac{[H_2CO_3]}{[HCO_3^-]}\right\} \; so \; [H_2CO_3] = 0.1717 \; mmol/L \quad (1p)$$

Calculated pH following addition of coagulant and lime:

$$\left[H^+\right] = K_{a1} \frac{\left[H_2CO_3\right] + 3\left[Me^{3+}\right] - 2\left[Ca(OH)_2\right]}{\left[HCO_3^-\right] - 3\left[Me^{3+}\right] + 2\left[Ca(OH)_2\right]} \quad (0.5\ p)$$

$$[H^+] = 10^{-6.52} \left(\frac{[0.1717] + 3\left[2 * \frac{20}{666}\right] - 2[0.15]}{[0.164] - 3\left[2 * \frac{20}{666}\right] + 2[0.15]} \right) \frac{10^{-3}}{10^{-3}}$$

$$[H^+] = 5.52 \cdot 10^{-8} \; and \; pH = 7.26 \quad (1.5p)$$

(3) Assume that after dosing alum and lime in the plant, the pH is measured and found to be 7.05. Is it necessary to add any more chemicals to ensure an appropriate water quality before distribution? If so, suggest which specific chemicals should be added.

pH needs to be raised above 7.5. Add a base that contains carbonates (e.g. Na_2CO_3 because alkalinity is low (only 20 mg/L) and carbonates contribute most to alkalinity . (1p)

(4) Assume that the plant will make no other change in its operations other than what you recommended in parts (1)-(3) above. Discuss how the subsequent disinfection steps at the DWTP are likely to be affected by the change in coagulant.

The new coagulant has slightly worse performance for removing organic matter than the old coagulant. Also, the optimum pH for the two coagulants will be different so there may be a different pH prior to disinfection. You should discuss the degree to which these two factors will affect each of the disinfection steps at the DWTP.

(2p)

Problem 2

The pump is able to provide 22.5 l/s or 81 m^3/h or 243 m^3/3h.

The max daily factor for uniform population and 10 000 inhabitants is 1.92

Total volume of water needed throughout the day is
Vday= 160 * 10000 * 1.92 / 1000 = 3072 m^3

This means the pump can provide 243/3072 = 7.91% /3h

Time	% daily consumption/3h	Pump flow (%/3h)	Tank needs to cover (Pump – demand)
00-03	2	7.91	5.91
06-mar	8	7.91	**-0.09**
09-jun	22	7.91	**-14.09**
12-sep	12	7.91	**-4.09**
15-dec	11	7.91	**-3.09**
15-18	25	7.91	**-17.09**
18-21	15	7.91	**-7.09**
21-24	5	7.91	2.91 ∑negatives = 45.54%

The tank needs to supply 45.54% of the total daily volume to compensate for the pump.
$V_{deficiency}$ = 3072 * 45.54% = 1399 m^3

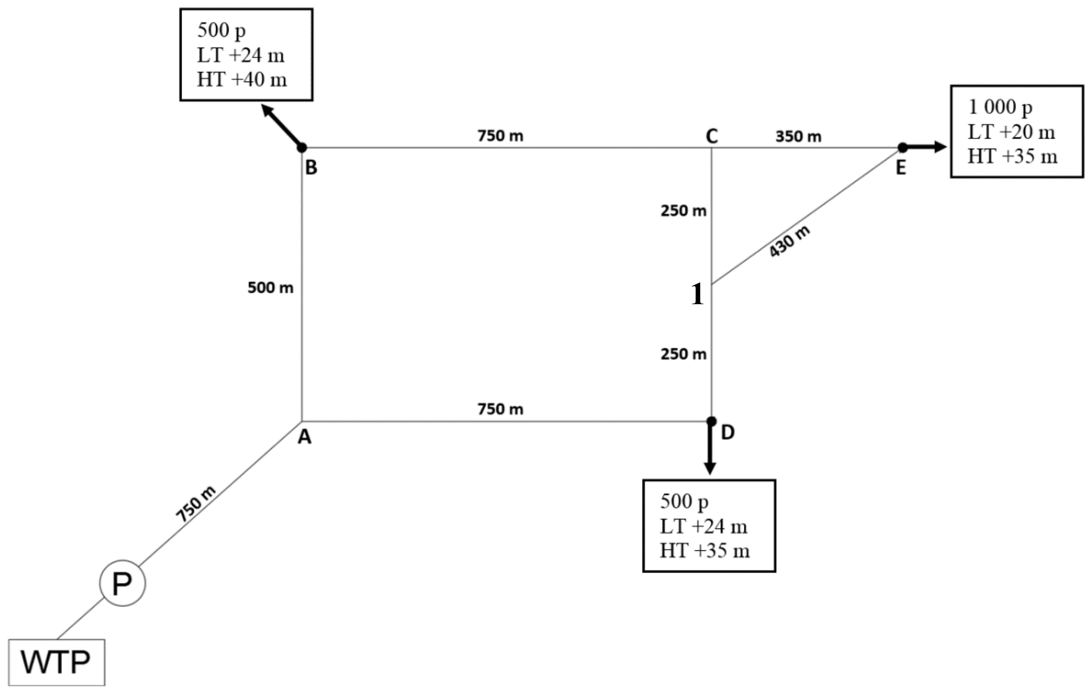
The tank also needs to provide fireflow for 2 hours
V_{fire} = 20*2*3600 = 144 m^3

Total volume of the tank is
V_{tank} = 1399+144 = 1543 m^3

Area is 1543/6 = 257.16 m^2

Diameter of the tank is
$D_{tank} = \sqrt{257.16*4/\pi} = 18.1$ m

Problem 3



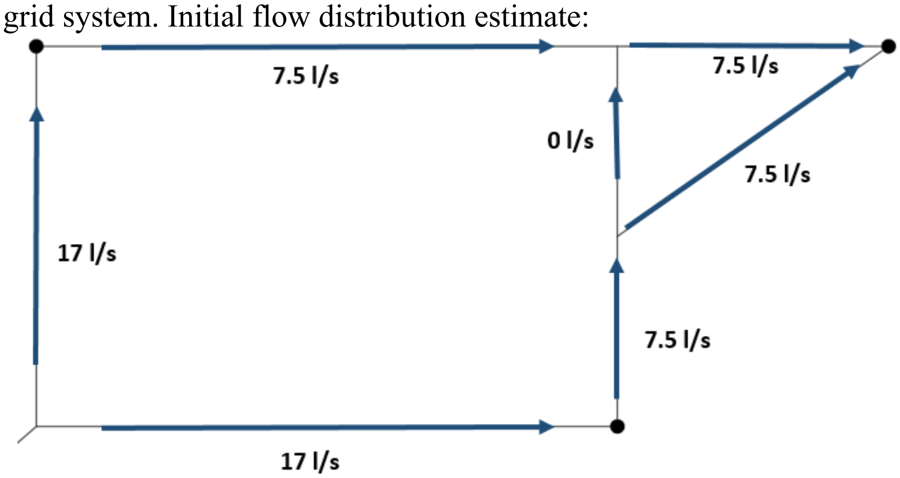
Designing P-A. Total consumers is 2000 p. From table Q = 24 l/s.

Section	Demand	Diameter	m	L	m*L	q [m³/s]	hf [m]
P-A	24.00	200	5.9	750	4 425.00	0.024	2.5488

Demands for other areas:

Area	Consumers	HT	LT	Demand (l/s)
B	500	40	24	9.5
D	500	35	24	9.5
E	1000	35	20	15

Designing the grid system. Initial flow distribution estimate:



Iteration 1										
Loop 1	Q	D	m	L	m*L	q [m³/s]	hf [m]	hf/q		
A-B	17.00	150	27	500	13 500.00	0.017	3.9015	229.5	Δq1 =	-0.98271
A-D	-17.00	150	27	750	20 250.00	-0.017	-5.85225	344.25		
B-C	7.50	100	230	750	172 500.00	0.0075	9.703125	1293.75		
C-1	0.00	100	230	250	57 500.00	0	0	0		
1-D	-7.50	100	230	250	57 500.00	-0.0075	-3.23438	431.25		
							4.518	2298.75		
Loop 2										
C-E	7.50	100	230	350	80 500.00	0.0075	4.528125	603.75	Δq2 =	0.384615
1-E	-7.50	100	230	430	98 900.00	-0.0075	-5.56313	741.75		
C-1	0.00	100	230	250	57 500.00	0	0	0		
							-1.035	1345.5		

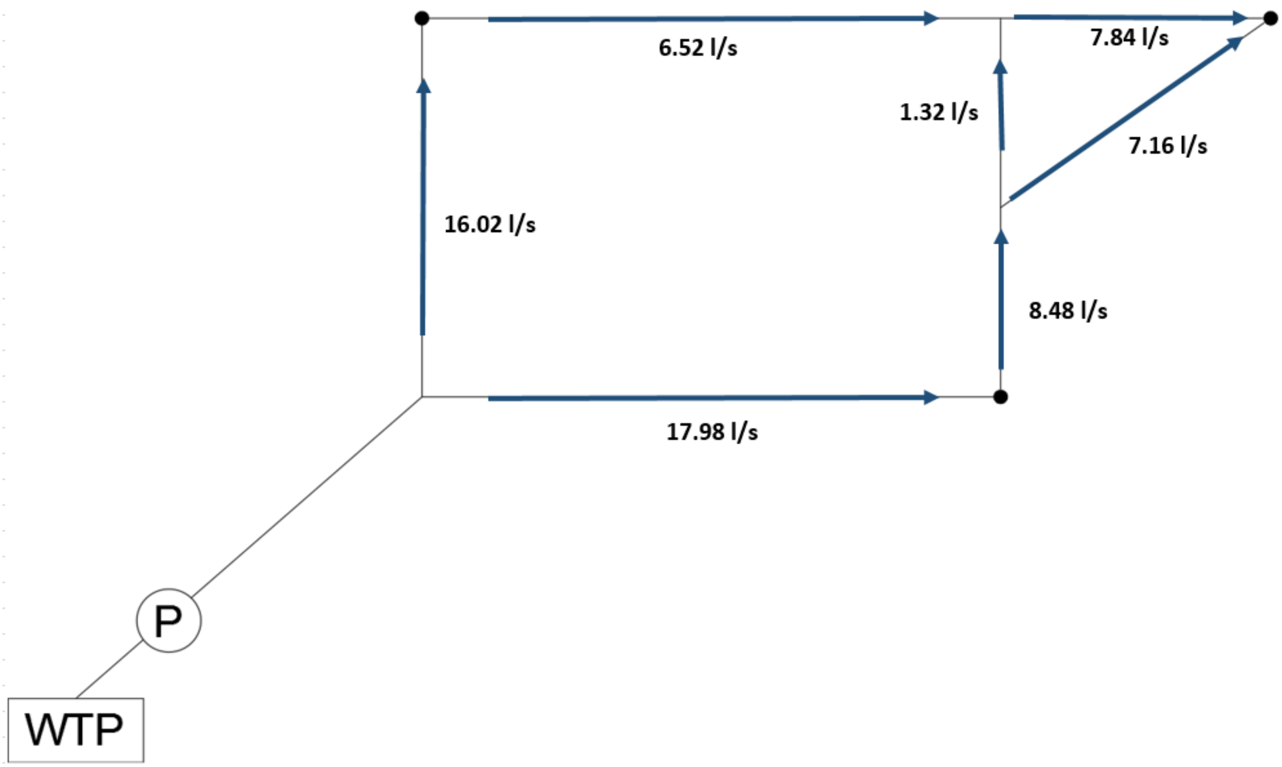
$\Delta q_i > 0.1$ l/s

Iteration 2										
Loop 1	Q	D	m	L	m*L	q [m³/s]	hf [m]	hf/q		
A-B	16.02	150	27	500	13 500.00	0.016017	3.463474	216.2334	Δq1 =	0.000675
A-D	-17.98	150	27	750	20 250.00	-0.01798	-6.5484	364.1498		
B-C	6.52	100	230	750	172 500.00	0.006517	7.326954	1124.233		
C-1	-1.37	100	230	250	57 500.00	-0.00137	-0.1075	0		
1-D	-8.48	100	230	250	57 500.00	-0.00848	-4.13749	487.7557		
							-0.00296	2192.372		
Loop 2										
C-E	7.88	100	230	350	80 500.00	0.007885	5.004456	634.7115	Δq2 =	-0.03914
1-E	-7.12	100	230	430	98 900.00	-0.00712	-5.00718	703.7115		
C-1	1.37	100	230	250	57 500.00	0.001367	0.1075	0		
							0.104779	1338.423		

$\Delta q_i < 0.1$ l/s

Final flow distribution and velocity check:

Loop 1	Q	D	hf	Velocity check
A-B	16.02	150	3.46	0.91
A-D	– 17.98	150	6.55	1.02
B-C	6.52	100	7.33	0.83
C-1	– 1.32	100	0.10	0.18
1-D	– 8.48	100	4.14	1.08
Loop 2				
C-E	7.84	100	4.95	1.00
1-E	– 7.16	100	5.06	0.91
C-1	1.32	100	0.10	0.18



Pressure checks

P-A-B	(40 – 10) + 2.55 + 3.46 + 20 =	56.01 m	
P-A-D	(35 – 10) + 2.55 + 6.55 + 20 =	54.10 m	
P-A-B-C-E	(35 – 10) + 2.55 + 3.46 + 7.33 + 4.95 + 20 =	**63.30 m**	Max pressure pump
P-A-D-1-E	(35 – 10) + 2.55 + 6.55 + 4.14 + 5.06 + 20 =	**63.30 m**	

Max pressure at lowest tap

P-E	63.30 – (20-10) =	53.30 m	< 70 m

Ans: Pump should provide a flow of 24 l/s and 63.30 m head. The pipes should be dimensioned according to the tables above. Pipe section C-1 has a lower velocity than 0.6 m/s, therefore additional measures will be needed (e.g., flushing).