Delft University of Technology
Faculty of Civil Engineering and Geosciences
Subfaculty Civil Engineering
Section Sanitary Engineering

CT4471 Drinking water I - Technology

Date : 1 November 2006
Time : 9.00-12.00 h

There are 8 times 4 statements of equal weight. It not only necessary to answer the questions, but you should also **EXPLAIN** how you come to the answer. In all statements it is important to show insight in the influence of process parameters on the treatment step in consideration, in order to be able to optimise design and operation.

During the examination an A4 with own notes may **NOT** be used.

If there are uncertainties about the question, do not hesitate to ask the supervisor.

Motivate your answer and check if the answer is complete and practical.

Overview of questions

1. Introduction
2. Aeration
3. Filtration
4. Coagulation/flocculation
5. Softening
6. Adsorption
7. Sedimentation
8. Membrane filtration

General data

Table 1 – Atom mass of important elements in water chemistry.

Element	Atom mass	Element	Atom mass
H	1	S	32
C	12	Cl	35,5
N	14	K	39
O	16	Ca	40
F	19	Mn	55
Na	23	Fe	56
Mg	24	As	75
Al	27	Pb	207
P	31		

Table 2 - Dynamic and kinematic viscosity as function of temperature.

Temperature [°C]	Dynamic viscosity [10^{-3} Pa·s]	Kinematic viscosity [10^{-6} m^2/s]
0	1,79	1,79
5	1,52	1,52
10	1,31	1,31
15	1,15	1,15
20	1,01	1,01
25	0,90	0,90
30	0,80	0,80

Relevant formulas in water chemistry

bij T = 10°C

$CO_2 + 2H_2O \longleftrightarrow H_3O^+ + HCO_3^-$ $K_1 = 3{,}44 \cdot 10^{-7}$ $pK_1 = 6{,}46$

$HCO_3^- + H_2O \longleftrightarrow H_3O^+ + CO_3^{2-}$ $K_2 = 3{,}25 \cdot 10^{-11}$ $pK_2 = 10{,}48$

$CaCO_3 + CO_2 + H_2O \longleftrightarrow Ca^{2+} + 2HCO_3^-$ $K_a = 4{,}11 \cdot 10^{-5}$

$NH_3 + H_2O \longleftrightarrow NH_4^+ + OH^-$

$NH_4^+ + 2O_2 + H_2O \longleftrightarrow NO_3^- + 2H_3O^+$

$CH_2O + O_2 \longleftrightarrow CO_2 + H_2O$

$H_3O^+ + CaCO_3 \longleftrightarrow Ca^{2+} + HCO_3^- + H_2O$

$5CH_2O + 4NO_3^- \longleftrightarrow 2N_2 + 4HCO_3^- + CO_2 + 3H_2O$

$FeS \longleftrightarrow Fe^{2+} + S^{2-}$

$SO_4^{2-} + 2CH_2O \longleftrightarrow H_2S + 2HCO_3^-$

$S^{2-} + 2H_3O^+ \longleftrightarrow H_2S + 2H_2O$

$2CH_2O \longleftrightarrow CH_4 + CO_2$

$NaOH + Ca^{2+} + HCO_3^- \longleftrightarrow CaCO_3 + Na^+ + H_2O$

$Ca(OH)_2 + Ca^{2+} + 2HCO_3^- \longleftrightarrow 2CaCO_3 + 2H_2O$

$4Fe^{2+} + O_2 + 2H_2O + 8OH^- \longleftrightarrow 4Fe^{3+} + 12OH^-$

$Fe^{3+} + 3OH^- \longleftrightarrow Fe(OH)_3$

$2Mn^{2+} + O_2 + 4OH^- \longleftrightarrow 2MnO_2 + 2H_2O$

Table 3 - k_D-values for different gasses as function of temperature.

k_D	0°C	10°C	20°C
Nitrogen	0,023	0,019	0,016
Oxygen	0,049	0,039	0,033
Methane	0,055	0,043	0,034
Carbon dioxide	1,710	1,230	0,942
Hydrogen sulfide	4,690	3,650	2,870
Tetrachloroethene	-	3,380	1,880
Trichloroethene	-	4,100	2,390
Chloroform	-	9,620	5,070

Universal gas constant R = 8,3142 J/(K.mol)

Table 4 – Composition of air in atmosphere (T = 10°C, p = $1\cdot10^5$ Pa)

Gas	Volume percentage [%]
Nitrogen	78,1
Oxygen	20,95
Carbon dioxide	0,003
Argon	0,93
Rest gasses	0,0002

Relevant formulae

$$c = \frac{p}{R \cdot T} \cdot MW$$

$$\frac{dc}{dt} = k_2 \cdot (c_s - c)$$

$$RQ = \frac{Q_l}{Q_w}$$

$$K = \frac{c_e - c_0}{c_s - c_0}$$

$$K_1 = 1 - \exp(-k_2 \cdot t)$$

$$K_2 = \frac{1}{1 + \frac{1}{k_2 \cdot t}}$$

$$K_3 = \frac{1 - \exp\left(-k_2 \cdot t \cdot \left(1 + \frac{k_D}{RQ}\right)\right)}{1 + \frac{k_D}{RQ}}$$

$$K_4 = \frac{1 - \exp\left(-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right)}{1 - \frac{k_D}{RQ} \cdot \exp\left(-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right)}$$

$$K_5 = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}}$$

$$K = 1-(1-k)^n$$

$$I_0 = \frac{H_0}{L} = 180 \cdot \frac{\nu}{g} \cdot \frac{(1 - p_0)^2}{p_0^3} \cdot \frac{v}{d^2}$$

$$H = 130 \cdot \frac{\nu^{0.8}}{g} \cdot \frac{(1 - p_e)^{1.8}}{p_e^3} \cdot \frac{v^{1.2}}{d^{1.8}} \cdot L_e$$

$$H_{max} = (1 - p) \cdot L \cdot \frac{\rho_f - \rho_w}{\rho_w}$$

$$q_{max} = \frac{x}{m} = K \cdot c_s^n$$

$$\frac{c_0}{c_e} = 1 + \exp\left(k_2 \cdot EBCT \cdot \left(1 - \frac{BV \cdot c_0}{q \cdot \rho}\right)\right)$$

$$BV = \frac{Q \cdot T}{V} = \frac{T}{EBCT}$$

$$J = \frac{Q}{A_{mem}} = \frac{K_w \cdot (TMD - \Delta\pi)}{\nu}$$

$$TMD = \frac{P_f + P_c}{2} - P_p = P_f - \frac{\Delta P_{hydr}}{2} - P_p$$

$$\pi = \sum \frac{R \cdot T \cdot c_i \cdot z_i}{MW_i}$$

$$\gamma = \frac{Q_p}{Q_f}$$

$$Ret = 1 - \frac{c_p}{c_f}$$

$$\beta = \exp\left(\frac{J \cdot \delta}{D_i}\right)$$

$$G = \sqrt{\frac{P}{\mu \cdot V}}$$

$$P = \rho \cdot g \cdot Q \cdot \Delta H$$

$$s_0 = \frac{Q}{B \cdot L}$$

$$r = (1 - p_0) + \frac{1}{s_0} \cdot \int_0^{p_0} s\,dp$$

$$Re = \frac{v_0 \cdot R}{\nu}$$

$$Fr = \frac{v_0^2}{g \cdot R}$$

$$R = \frac{B \cdot H}{B + 2 \cdot H}$$

$$\tau = \frac{\lambda}{8} \cdot \rho_w \cdot v_s^2$$

1. Introduction

1.1. The dune water in the treatment plant of DZH used to be collected in an open channel. A year ago the catchment of the water coming from the dunes was closed. This is because (more answers can be possible):

a. The suspended solids concentration was increased after the open catchment because of small sand fractions blown in from the dunes
b. To prevent contamination with pollution of the industry in the neighbourhood of the water plant
c. To increase the disinfection capacity for pathogens of the total plant
d. To prevent birds swimming in the water contaminating the water
e. To prevent algal growth because of sunlight
f. In order to prevent a terrorist attack
g. In order to prevent contamination in case of nuclear fallout
h. It is a better view for the visitors

1.2 The ozone in Weesperkarspel is in front of the pellet softener. This is because (multiple choice)

a. to create some extra contact time in the softeners
b. it was handy because of the lay out of the plant and it does not influence the softening process
c. a) and b) are correct
d. a) and b) are both not correct

1.3 Give an estimation of the recoveries of the following treatment process

Rapid sand filtration	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
Slow sand filtration	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
Nanofiltration	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
Sea water desalination	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
UV-desinfection	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
Pellet softening	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
Activated carbon filtration	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]
Ultrafiltration	[50%] [60%] [70%] [80%] [90%] [98%] [99,999%] [100%]

1.4 Anaerobic groundwater is free of pathogens (true or false)

2. Aeration and gas transfer

2.1. Aeration is normally placed before softening because (more answers can be possible):

a. Methane will react with calcium

b. Oxygen is necessary for the formation of calciumcarbonate

c. Carbondioxide will react with the chemicals needed for softening

d. Hydrogensulfide will accumulate in the softening reactor

2.2. For the removal of carbon dioxide by cascades it is theoretically more advantageous to have many different small steps than a few large steps (true or false)

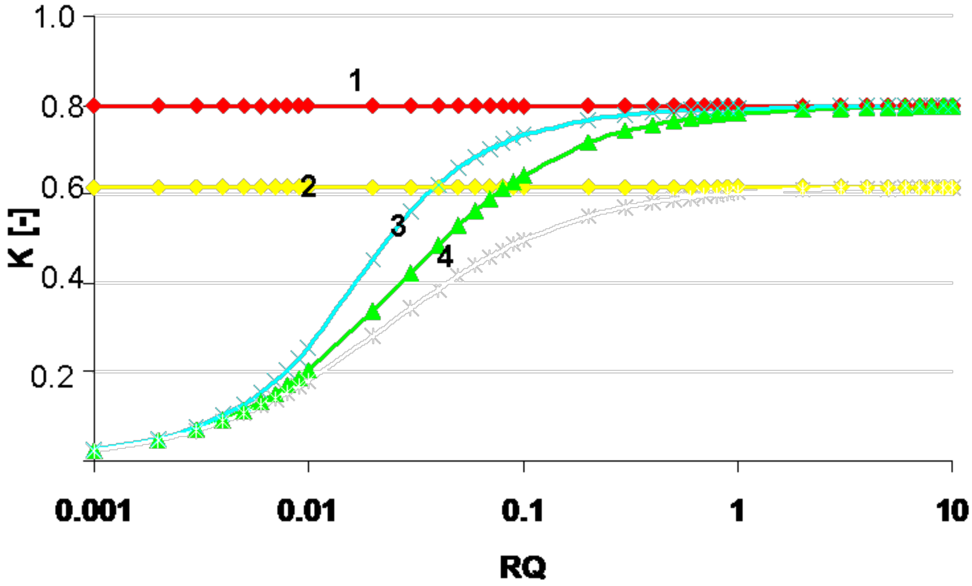
2.3. Indicate which of the lines of the figure (about efficiency for oxygen removal) belongs to:

a. Co-current flow of gas and water

b. Counter current flow of gas and water

c. Mixed flow with constant gas concentration

d. plug flow with constant gas concentration



2.4 Assuming anaerobic water with a temperature of 10^{o}C under atmospheric conditions then the oxygen concentration after 4 cascades steps is …. (fill in the blank and assume an efficiency per step of 25%.

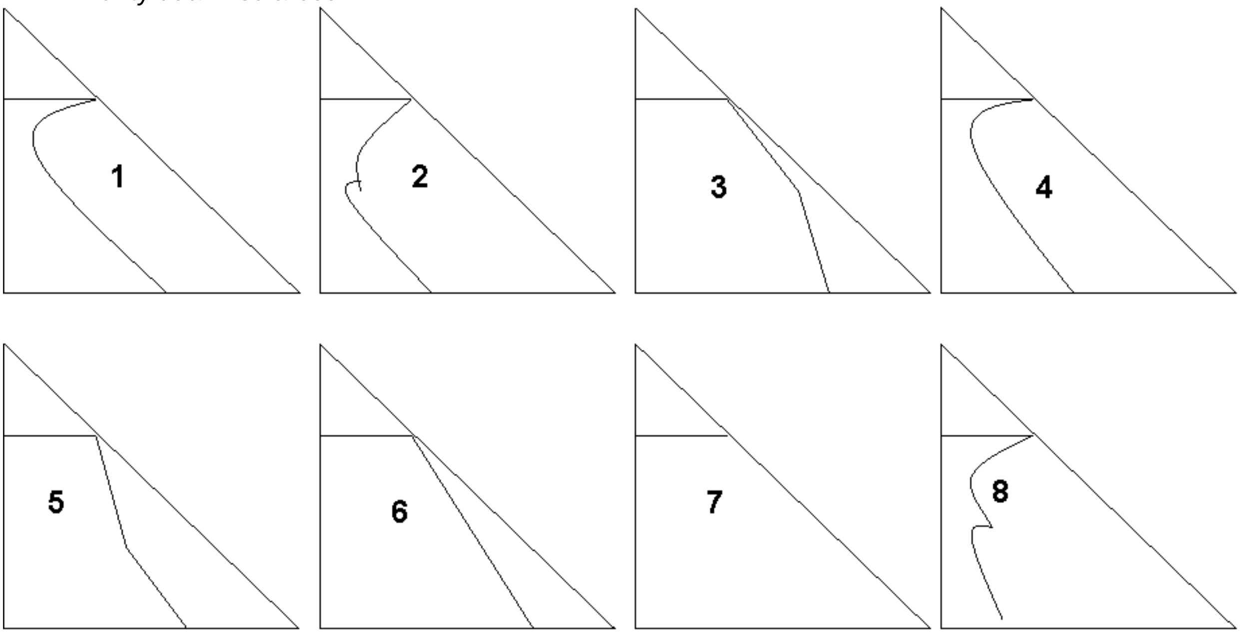
3. Filtration

3.1. Filtration of deep anaerobic groundwater is to remove (more answers are possible):

a. iron
b. manganese
c. magnesium
d. natriumchloride
e. calciumcarbonate
f. nitrate
g. ammonium

3.2. Match the following descriptions of a Lindquist diagram with one of the drawings:

A. clean single media bed
B. dirty single media bed
C. clean dual media bed
D. dirty dual media bed



3.3. The clean bed resistance of a filter bed consisting of sand with a grain size diameter of 1 mm, a bed height of 1.5 m and a porosity of 40%, treating water with a temperature of 10 ^oC and a superficial flow of 10 m/h is ……. (fill in the blank).

3.4. A filter bed consisting of sand with a grain size diameter of 1 mm, a bed height of 1.5 m and a initial porosity of 40%, treating water with a temperature of 10 ^oC needs a backwash velocity of …. m/h (fill in the blank) to reach an expansion of 30%.

4. Coagulation and flocculation

4.1. Coagulation is very important for (more answers can be possible):

a. removal of pesticides
b. removal of suspended solids
c. removal of bacteria
d. removal of salts
e. removal of colour
f. removal of viruses
g. removal of sand
h. removal of dissolved organic matter
i. removal of clay

4.2. Electrostatic coagulation is the main coagulation mechanism in drinking water practice (true or false)

4.3 The velocity gradient for the flocculation in a slow steering device is too low because of the low temperatures. The flocculation is not optimal and the flocks do not grow large enough. A solution for this can be (more answers are possible):

a. decrease the volume of the steering device
b. increase the temperature
c. decrease the viscosity by adding chemicals
d. increase the steering rate
e. decrease the steering rate
f. dose polymers (flocculant aid)
g. increase the flow rate in the steering device

4.4. The most important drawbacks of a sludge blanket clarifier are (more answers can be possible):

a. The blanket is sometimes discharged with the effluent
b. The flocculation is not tampered
c. There is no fast mixing
d. It is not robust
e. They have to be cleaned very often
f. The sedimentation is hindered by the up flow of the water
g. A lot of labour is needed to get the sludge out

5. Softening

5.1. In pellet softening calcium and magnesium ions (together named total hardness) are reduced using chemicals such as caustic soda and lime (true or false).

5.2. Assuming a total hardness of 2.25 mmol/l (2 mmol/l Ca and 0.25 mmol/l Mg), a temperature of 10^{o}C, a pH of 7 and a m-number of 3 mmol/l then …. mmol/l NaOH has to be dosed to reduce the total hardness towards 1.5 mmol/l (fill in the blank).

5.3. The fluidised pellet bed of a pellet reactor becomes higher when (true or false)

- the flow through the reactor is higher
- the temperature of the water becomes higher
- the pellet diameter in the bottom of the reactor becomes larger
- the caustic soda dosage increases.

5.4. The temperature of the water is 10 ^{0}C, the flow velocity through the pellet softening reactor is 70 m/h, the density of the pellets is 2700 kg/m^3 and the pressure drop over the bottom 50 cm of the filter is 40 cm, then the porosity of the fluidised pellet bed is … and the pellet diameter is .. mm (fill in the blanks).

.

6. Adsorption

6.1 Pseudo moving bed configuration of GAC-columns results in lower regeneration costs compared to parallel columns and also the investment costs are lower (true or false).

6.2. Powdered activated carbon is more efficient compared to granular activated carbon in removing high peaks of micro pollutants compared to granular activated carbon but the PAC can not be regenerated so the variable costs are higher (true or false)

6.3. For the removal of assimilible organic carbon (AOC) we can only use GAC and not PAC (true or false)

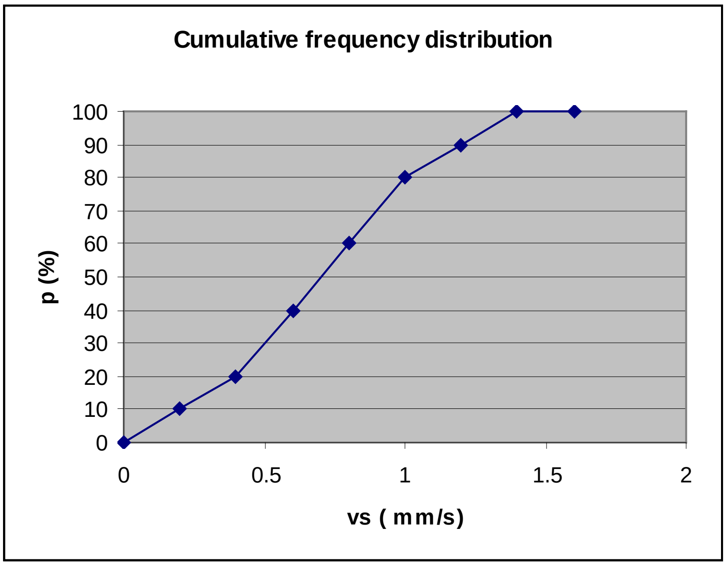
6.4. A GAC-filter of 25 m^2 and 3 m bed height is loaded with an influent concentration of 2 μg/l atrazin and a velocity of 10 m/h. The density of the carbon is 500 kg/m3. The maximum saturation of the carbon is determined by the following Freundlich constants: n=0.5 and K = 30 (g/kg)•(m3/g)^n. The breakthrough time of Atrazin stored in the effluent of the filter (assuming a steep adsorption front) is …….. (fill in the blank).

7. Sedimentation

7.1. During settling of surface water for drinking water treatment the following compounds can be (partly) removed (more answers can be possible):

a. suspended solids
b. colloidal solids
c. dissolved solids
d. phosphate
e. sulphate
f. chloride
g. natural organic matter
h. micro-organisms

7.2. Assuming water containing suspended solids with a cumulative frequency distribution of settling velocities given in the figure, then the discrete removal of solids in a vertical flow settling reactor is … % (fill in the blank) and in a horizontal flow settling reactor is … (fill in the blank). Assume a surface loading of 1 mm/s.



7.3. In a tank with a length x width x height of 50 x 5 x 3 m^3 , a water flow of 300 m^3/h is treated with a temperature of 10 ^oC. The flow in the tank is turbulent and stable (true or false)

7.4. In a tank with a length x width x height of 50 x 5 x 3 m^3, a water flow of 300 m^3/h is treated with a temperature of 10 ^oC. Then the oulet construction has to have a length of …. times the width of the tank (fill in the blank).

8. Membrane filtration

In a full scale nanofiltration plant the staging is 8-4 (8 pressure vessels first stage; 4 pressure vessels second stage) each pressure tube has 6 elements of 34 m2 membrane surface area each. The permeate flow is 50 m3/hour and the concentrate flow is 25 m3/hour. The feed pressure is 10 bar and the osmotic pressure of the feed is 2 bar. The osmotic pressure in the permeate can be neglected.

8.1. The recovery is ….. and the average flux is ….. l/(m^2.h) (fill in the blanks).

8.2. Due to fouling of the membrane surface the permeate flow is decreasing. What should the operator do to maintain the flows mentioned above? (multiple choice)

a) Increase the feed pressure and increase the concentrate pressure
b) Increase the feed pressure only
c) Increase the feed pressure and decrease the concentrate pressure
d) Increase the concentrate pressure only

8.3 The second stage contains less pressure vessels compared to the first stage. This is due to the problem of high osmotic pressure in the feed water of the second stage (true or false)

8.4 The cross flow velocity is decreased due to biofouling in the feed spacers. Because of this the concentration polarization in the first element is increased from 1.5 to 2.0. The needed feed pressure to maintain the original flux in the first element is …… bar (fill in the blank).

Answers CT4471 examination 1 nov 2006

1. Introduction
1.1. c,d
1.2. b, They do not need extra contact time; also the extra time is rather short
1.3. Rapid sand filtration [98%] backwash water
Slow sand filtration [99,999%] after scraping some water loss
Nanofiltration [80%] to prevent scaling
Sea water desalination [50%] to prevent too high osmotic pressure
UV-desinfection [100%] no water loss
Pellet softening [99,999%] small drain with the pellets
Activated carbon filtration [98%] backwashed
Ultrafiltration [90%] backwashed
1.4. True, all pathogens are aerobic and killed under anaerobic conditions. Viruses are retained by the subsurface

2. Aeration and gas transfer
2.1 c. Carbondioxide will react with the chemicals needed for softening and thus more chemicals are needed for softening, therefore it is better to remove carbon dioxide beforehand.
2.2. true, the removal efficiency of carbon dioxide is independent of fall height and therefore it is better to have many small steps.
2.3. 1d; 2c; 3b; 4a; the removal efficiency of plugflow is better than mixed flow and independent of gas flow. Counter-current flow is more efficient than co-current flow and only with higher RQ as efficient as plug flow reactor
2.4 saturation concentration is 11.3 mg/l; $K= 1-(1-0.25)^4 =0.68 = cwe/11.3 \Rightarrow cwe= 7.7$ mg/l.

3. Filtration
3.1. a,b,(e), g; iron is oxidized during aeration and ironhydoxide flocs will be removed; manganese is oxidized in the filter and ammonium is oxidized through bacteria into nitrite and nitrate. In case of softening some calcium carbonate will be present in the water in the form of carry over. This will also be removed by filtration
3.2. A6; B4; C3; D8; clean single media bed head loss is uniform over the bed, the line of the Lindquist diagram of the dirty single media bed is in the bottom of the bed not parallel to hydrostatic pressure, cleanbed dual media filter has large grains at the top (low clean bed resistance) and small grains in the bottom (high clean bed resistance) this is also true at the bottom of each layer in a dirty dual media bed
3.3. $H=180.\nu/g.(1-p0)^2/p0^3.v/d^2.L = 0.56$ m
3.4. $pe=(p0+E)/(1+E)=0.7/1.3=0.54$; $Le=1.3*L=1.95$; $H=130.\nu^{0.8} /g.(1-pe)^{1.8}/pe^3.v^{1.2}/d^{1.8}.Le =1.5m \Rightarrow v= 61$ m/h.

4. Coagulation and flocculation
4.1. b,c,e,h,i.
4.2. False, No: the dissolved iron (or alum) concentration is too low for that. Adsorptive coagulation and sweep coagulation are the main mechanisms.
4.3. d,f,. decreasing the volume you also deacrease the flocculation time, decreasing the temperature is not practical, decreasing the viscosity by adding chemicals is not possible, decreasing the steering rate has opposite effects, dosing polymers might help, increasing the flow rate in the steering device gives a a shorter residence time
4.4. b, (c is also true, but this can be beforehand)

5. Softening

5.1. False, in pellet softening only calcium ions are removed (and magnesium ions pass the reactor)

5.2. when pH=7 and m-number is 3 mmol/l then CO2 concentration is 0.85 mmol/l (7=6.46-log([CO2]/[HCO3]); for removal of 0.75 mmol/l calcium 0.75 mmol/l NaOH has to be added. In total this means a dosage of 1.6 mmol/l NaOH.

5.3. true, false, true, false; a higher flow gives more expansion, a higher temperature gives lower viscosity and thus less expansion, when the pellet size increases more volume is taken by the pellets and thus more mass is in the reactor, an increase in caustic soda dose does not have influence on the pellet bed. It is even so that a higher caustic soda dose means more by-pass and thus a lower reactor flow.

5.4. H=(1-p).L.(rhof-rhow)/rhow =>pe=0.52; $H=130.\nu^{0.8}/g.(1-pe)^{1.8}/pe^{3}.v^{1.2}/d^{1.8}.Le=0.4$ m => d=1.75 mm

6. Adsorption

6.1. False: The regeneration costs are lower but the investment csts are higher (more pipes, valves, fittings, two steps)

6.2. False: PAC is less efficient in removing high peaks of micro pollutants because the effluent of a batch process is always the equilibrium concentration at a certain equilibrium loading. So we have to dose a lot in order to go to low equilibrium concentrations. In GAC the effluent is zero (at enough contact time) until breakthrough. In the ideal case the GAC-column is loaded to the influent concentration.

6.3. True, for the removal of AOC we need biomass which is growing in GAC-columns. PAC is dosed without bacteria and the bacteria are not growing fast enough to accumulate within 20 minutes of contact time in a PAC-process.

6.4. The amount of GAC in the column is: 25*3*500=37500 kg. 2 μg/l= 0.002 g/m3. The maximum adsorbed amount of atrazin is: q=K*cinfl^n=30*(0.002)^0.5=1,34 g/kg. so 1,34*37500=50312 g atrazin. This amount of atrazin is in 50312/0.002=25.000.000 m3 water, so the running time is: 25.000.000/250=100.000 hours is 11.4 years.

7. Sedimentation

7.1. a,b,d,g,h; During settling flocs are removed where (after coagulation) suspended solids, colloids (clay), pathogens (also colloids), ironphosphate and NOM is incorporated.

7.2. With a surface loading of 1 mm/s, a discrete settling tank will have 20% removal and a horizontal settling tank 62%. That can be read from the figure.

7.3. False, R=B*H/(B+2H)=15/11=1.37; v0=Q/BH=300/15=20 m/h; $Re=v0*R/\nu=5812>2000$ (turbulent); $Cp=v0^2/g*R=2.3e-6<1e-5$ (instable)

7.4. Q/nB<5.H.vs0; vs0=Q/A=0.33e-3 m/s; n=Q/(B*5e-3)=3.33

8. Membrane filtration

8.1. The recovery is 67% and the average flux is 20.4. l/(m2.h).

8.2. a

8.3. The answer can be either true or false:
True: Due to concentration polarisation the osmotic pressure can be increased at the membrane wall. A high cross flow velocity is used to decrease the concentration polarisation. Less pressure vessels in the second stage means higher cross flow in the second stage
False: This is not changing the ion concentration (in the bulk). Decreasing the number of vessels is used to increase the cross flow and decrease the concentration polarization

8.4. At first the osmotic pressure at the membrane wall is 1.5*2 is 3 bar. So the net driving pressure is: 10-3 bar=7 bar. If the CP=2 the osmotic pressure at the membrane wall is now 2*2 is 4 bar. So the total pressure needed is: 7+4=11 bar.