TU Delft Delft University of Technology

Examination CT3420 – Sanitary engineering

Date	:	1 July 2010
Time	:	9.00 - 12.00

This exam consists of 3 parts. Each part contains questions with a total of 100 points.
The end score is between 1 and 10, proportional to the total number of points. A minimum of 159 points (53%) is required to pass the exam.

With every question you have to show that you able to determine the influence of process parameters so you can optimize the design and the operation of the treatment processes.

If there is something unclear in the questions please inform the supervisor.

An A4 with own remarks is not allowed. Added to this exam are the most important equations.

Always give a motivation to your answer and ask yourself if the answer is complete and if the treatment process can be constructed in field practice.

Use a separate answer page for every part. Write your name and study number clearly on every answer page.

Students are allowed to give their answers in the Dutch laguage.

Formula sheet CT3420 - Drinking water

Table 1 – Atomic mass of the most important elements in water chemistry.

Element	Atomic mass	Element	Atomic 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 a 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

Equilibrium reactions calcium carbonate :

$CO_2 + 2H_2O$	<-->	$H_3O^+ + HCO_3^-$	$K_1 = 3.44\cdot10^{-7}$	$pK_1 = 6.46$
$HCO_3^- + H_2O$	<-->	$H_3O^+ + CO_3^{2-}$	$K_2 = 3.25\cdot10^{-11}$	$pK_2 = 10.49$
$CaCO_3$	<-->	$Ca^{2+} + CO_3^{2-}$	$K_s = 4.37\cdot10^{-9}$	$pK_s = 8.36$
$CaCO_3 + CO_2 + H_2O$	<-->	$Ca^{2+} + 2HCO_3^-$	$K_a = 4.68\cdot10^{-5}$	$pK_a = 4.33$

(K values at T = 10°C)

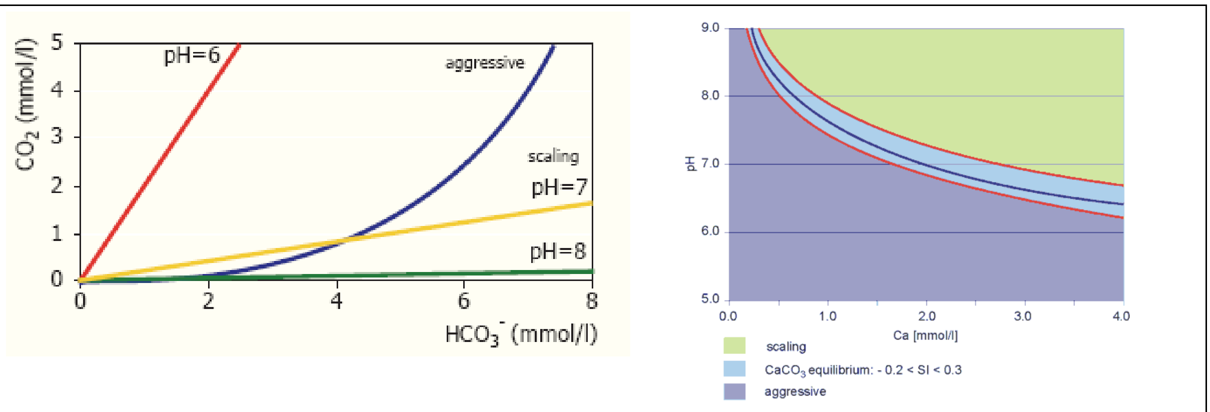


Figure 1. Tillmans-curves (on the left the relation CO_2-HCO_3^-, on the right the relation Ca-pH)

Gases in water:	
Gas exchange:	$\frac{dc}{dt} = k_2 \cdot (c_s - c)$, $\frac{c_s - c}{c_s - c_0} = e^{-k_2 \cdot t}$
General gas law:	$c_g = p_a/(RT)$ R=8,3143 J mol^{-1} K^{-1}
Henry's law:	$c_s = k_d . c_g$ (mol/m^3)

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

k_D	0°C	10°C	20°C
Nitrogen	0.023	0.019	0.016
Oxygen	0.049	0.041	0.033
Methane	0.055	0.043	0.034
Carbon dioxide	1.710	1.230	0.942
Hydrogen sulphide	4.690	3.650	2.870
Tetrachloroethene	-	3.380	1.880
Trichloroethene	-	4.100	2.390
Chloroform	-	9.620	5.070

Table 4 – Composition of air in volume% at 10 °C and under atmospheric pressure (101325 Pa).

Gas	Composition [volume percentage]
Nitrogen	78.084
Oxygen	20.948
Argon	0.934
Carbon dioxide	0.034
Methane	0.0001

Pipelines:	
Friction losses (Darcy-Weisbach):	$\Delta H_w = \lambda \cdot \frac{L}{D} \cdot \frac{v^2}{2 \cdot g}$ $\lambda = 0.02$
Total local losses:	$\Delta H_v = \sum \xi \cdot \left(\frac{v^2}{2 \cdot g} \right)$
Total cost pipelines:	$K_{total} = 19.2 \cdot 16.7 \cdot Q^3 \cdot D^{-5} \cdot L + 500 \cdot D \cdot L$ (*50 years*)

Relevant formulas aeration / degassing:

$$K_1 = 1 - e^{(-k_2 \cdot t)} \qquad K_2 = \frac{1}{1 + \frac{1}{k_2 \cdot t}}$$

$$K_3 = \frac{1 - e^{(-k_2 \cdot t(1 + \frac{k_d}{RQ}))}}{1 + \frac{k_d}{RQ}}$$

$$K_4 = \frac{1 - e^{(-k_2 \cdot t(1 - \frac{k_d}{RQ}))}}{1 - \frac{k_d}{RQ} \cdot e^{(-k_2 \cdot t(1 - \frac{k_d}{RQ}))}}$$

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

Relevant formulas filtration:

$$I_0 = \frac{H_0}{L} = 180 \cdot \frac{\nu}{g} \cdot \frac{(1 - p_0)^2}{p_0^{\,3}} \cdot \frac{v}{d_0^{\,2}}$$

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

Relevant formules sedimentation:

$$v_s = \frac{1}{18} \cdot \frac{g}{\nu} \cdot \frac{\rho_s - \rho_w}{\rho_w} \cdot d^2$$

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

$$c_p = \frac{v_o^{\,2}}{g \cdot R}$$

Formule sheet CT3420 - Urban drainage

Weir formula:

$$Q = mBH^{\frac{3}{2}}$$

Where:

Q	discharge in m^3/s
m	weir coefficient in $m^{0,5}/s$
B	width of the weir in m
H	energy level above weir in m

Local losses:

$$\Delta H = \xi \frac{Q|Q|}{2gA^2}$$

Where:

ΔH	energy loss in m
ξ	loss coefficient (dimensionless)
Q	discharge in m^3/s
A	wet cross-section in m^2
g	gravitation in m/s^2

Friction losses in a conduit:

$$\Delta H = \frac{Q|Q|L}{C^2 R_h A^2}$$

Where:

ΔH	energy loss in m
C	Chezy coefficient in $m^{0,5}/s$
Q	discharge in m^3/s
L	length of conduit in m
R_h	hydraulic radius in m
A	wet cross-section in m^2

The hydraulic radius R_h is defined as:

$$R_h = \frac{A}{P}$$

where:

A	wet cross-section in m^2
P	wetted perimeter in m

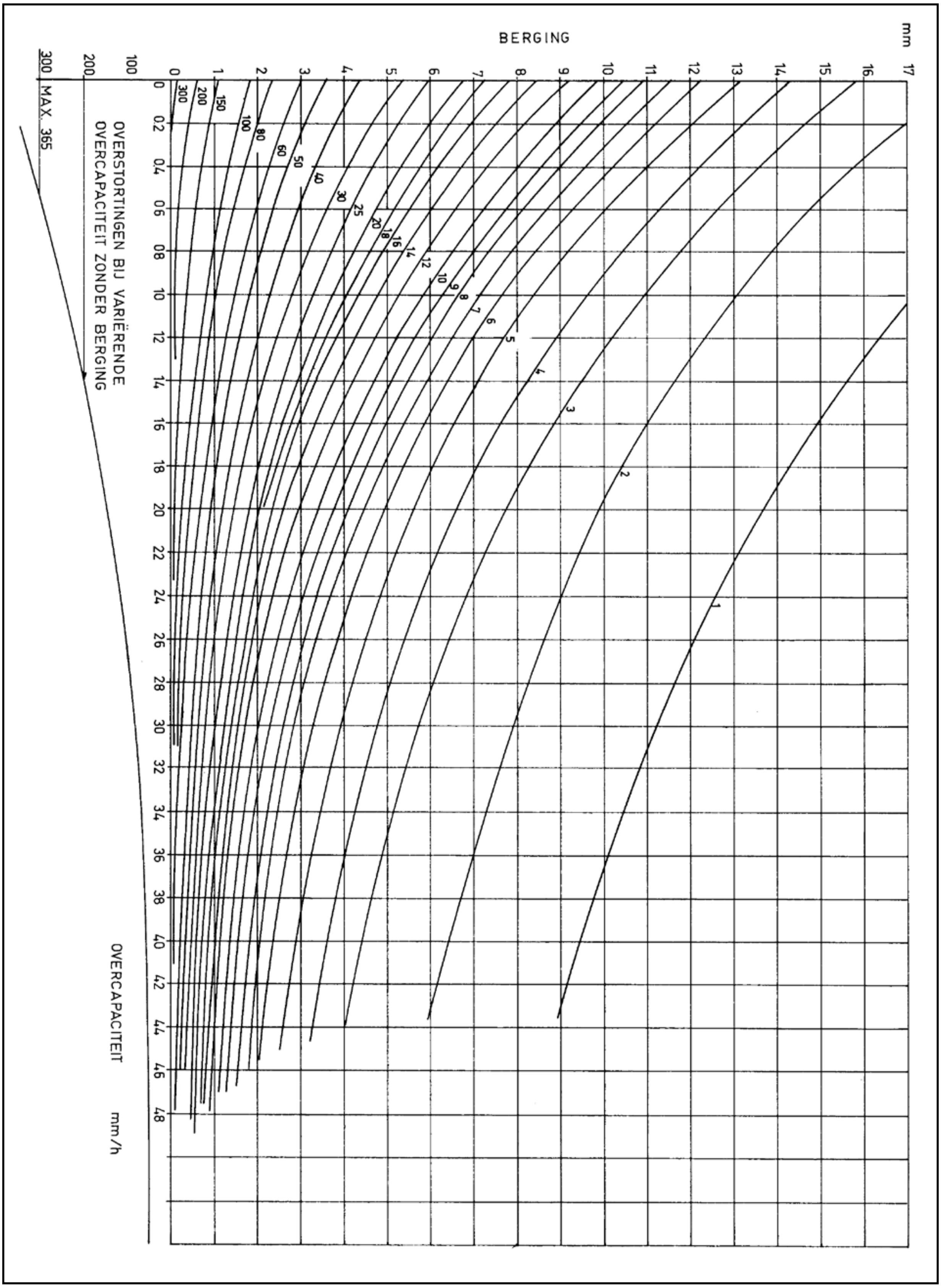
The Chezy coefficient is defined as:

$$C = 18^{10}\log\left[\frac{12R_h}{k_n}\right]$$

where:

C	Chezy coefficient in $m^{0,5}/s$
R_h	hydraulic radius in m
k_n	wall roughness in m

Veldkamp graph:



Berging = Storage (0 – 17 mm)
Overcapaciteit = Available pumping capacity for stormwater (0.0 – 4.8 mm/h)
Overstortingen... = Overflows at different available pumping capacities for stormwater, without storage

Part 1 - Drinking water

This examination all questions will be about the River-Dune water supply system of Waternet (the water cycle company for Amsterdam). The set-up of this system is presented in the attached brochure. Read the brochure carefully, as you will need to use the information in the brochure to answer the questions of this examination. The questions will follow the water flow, i.e. from the raw water intake until the transport and distribution of the drinking water.
The average annual production of this system is 70 million m^3.
The average raw water quality is:
Ca^{2+} 80 mg/L, Mg^{2+} 11.5 mg/L, HCO_3^- 244 mg/L, pH 8.3 and TSS (total suspended solids) 30 mg/L.

1 Raw water intake
Why don't they have a raw water reservoir?
Describe the 4 theoretical goals/functions of a raw water reservoir and explain how Waternet reaches those goals/functions in the River-Dune water system.

2 Coagulation/sedimentation
Calculate the average surface load of the settlement basins. Does it comply to the general design criterion?
Calculate the pH after the dosing of $FeCl_3$ (3 mg/L).

3 Rapid sand filtration (RSF)
What is the most important design criterion for the RSF and check whether it is met?
Which measures do you propose in case the run time of the filters becomes too short?
Differentiate between short term and long term measures.

4 Infiltration system
Describe the 3 most important water quality goals of an infiltration system.
Which goal will not be used in this system?
What are the consequences for the post-treatment?

5 Aeration
What is the main function of the cascades?
There are 3 steps in the cascade. The total efficiency for the removal of CO_2 is 58%.
Calculate the RQ of the cascades (assume that the kinetics are not limiting).

6 Ozonation
What are the functions of the ozonation?
What is the main design criterion and check whether it is met?

7 Softening
Assume that the water quality is the same as the raw water.
Calculate the required dose of NaOH to soften the water to 1.5 mmol/L and calculate the composition of the clear water. Is it possible to use split-treatment in this case?

8 Activated carbon filtration (ACF)
Why do they dose HCl in front of the ACF and NaOH after the ACF?
Why do they dose oxygen after the carbon filters in summer?
Why don't they use cascades for this?

9 Slow sand filtration (SSF)
What is the most important design criterion for SSF and check whether it is met?
Why are the SSF-units much bigger than the RSF-units?

10 Storage, transport and distribution
What is the most important design criterion for clear water storage and check whether it is met? What is the maximum peak factor that the drinking water pumps can supply?
Give your comment on the design of the storage and pumping station?

(*each question 10 points*)

Part 2 - Urban drainage / Sewerage

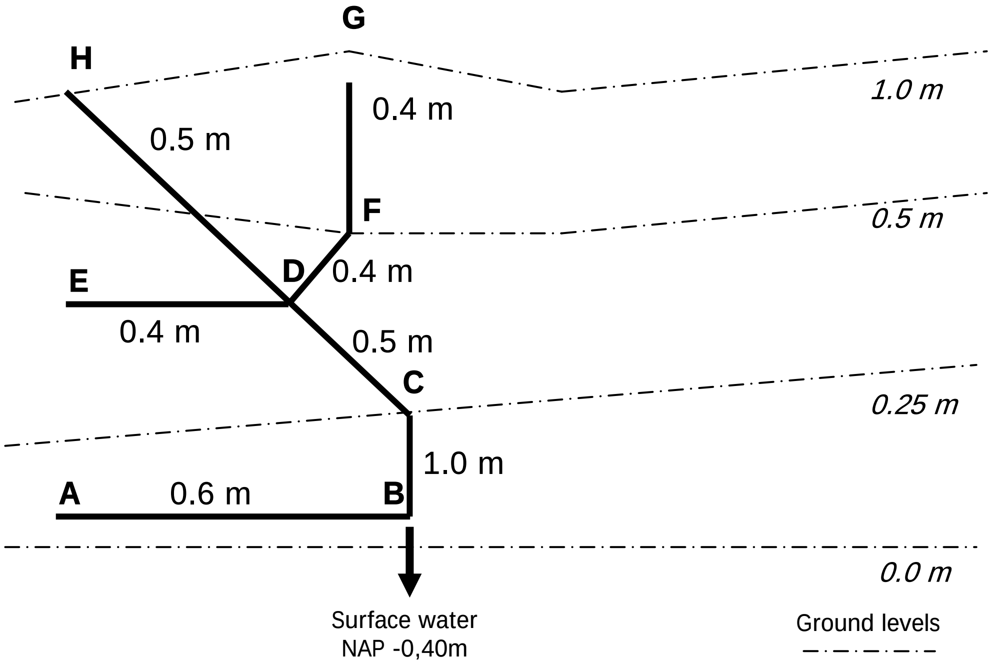
1 Stormwater run-off can be calculated based on rainfall and a run-off coefficient.

a. Explain what the run-off depends on. (*10 points*)

b. Give a range for the value of the run-off coefficient for impervious and for pervious surfaces. Explain the difference. (*10 points*)

c. Do you expect the value of the run-off coefficient to be higher in summer and in winter? Explain why. (*10 points*)

2 The following system is to be constructed for a new urban area: water from the area is discharged through the network and flows to surface water over a combined sewer overflow in point B.



Characteristics of conduits:

Section	*Discharge* m^3/s	*Diameter* *m*	*Length* *m*
AB	0.5	0.6	100
CB	0.4	1.0	40
DC	0.4	0.5	60
ED	0.1	0.4	60
FD	0.1	0.4	20
GF	0.1	0.4	60
HD	0.2	0.5	80

a. The total area connected to the system is 150 ha. The capacity of the pumping station for stormwater is sufficient to empty the system in 10 hours. Calculate the storage, the available pumping capacity for stormwater ("pompovercapaciteit") and determine the expected overflow frequency. (*23 points*)

b. The width of the overflow weir at point B is 1.0 m, weir coefficient m=0.9, wall roughness k_n=2mm. Calculate the energy head in point B and in point G, draw the energy gradient from point B through C, D, F to G. (*23 points*)

c. The results of b. show that flooding is expected to occur in several locations (energy level above ground level). What recommendations would you make with respect to the dimensions of the weir and the conduits to improve the design and why? (*24 points*)

Part 3 - Treatment of wastewater

Primary sedimentation

1. The average wastewater flow to a WWTP is 40,000 m^3/day. The maximum flow rate of the wastewater is 5,000 m^3/h. Following bar screens and grit removal the wastewater is treated in two rectangular primary sedimentation tanks (W = 13 m, L = 50 m).
   For primary sedimentation the following constants can be used:
   - hydraulic surface loading rate : $v_0 = 2 – 4$ $m^3/(m^2.h)$
   - minimum retention time : $t_{min} \approx 1$ h
   - critical scouring velocity : $v_s = 0.30$ m/s (sand)
     : $v_s = 0.03$ m/s (primary sludge)
     : $v_s = 0.02$ m/s (activated sludge)

   a. Are the primary sedimentation tanks overloaded or not? (*3 points*)
   b. Calculate the average depth of the primary sedimentation tanks. (*4 points*)
   c. Check retention time at average flow. (*3 points*)
   d. Explain how the primary sludge is removed from the sedimentation tanks. (tip: give also a sketch) (*4 points*)

Biological treatment

2 A conventional activated sludge plant, consisting of an aeration tank and secondary settler receives domestic sewage from a Dutch town "Y" with an average dry weather flow (adwf) of 15,000 m^3/d and an average BOD of 250 mg/L. The volume of the aeration tank is 3500 m^3 and the concentration of mixed liquor suspended solids in the aeration tank is 4 g/L.

   a. What would be the approximate number of inhabitants in town "Y"? Explain your guess. (*4 points*)
   b. Calculate the organic sludge loading rate in the activated sludge plant of town "Y". (*6 points*)
   c. Would the town "Y" sewage treatment plant be a nitrifying activated sludge plant? Explain. (*4 points*)

3 Define sludge age using a formula and explain, in words, how sludge age is related to organic loading rate. (*14 points*)

4 Bulking sludge is sludge with extremely bad settling characteristics and is often characterized by the presence of abundant filamentous micro-organisms. The growth of this sludge can be suppressed by the application of high loading rates, for example in a so called selector. Explain the function of such a selector, and use a graph to illustrate the mechanism. (*14 points*)

5 In contrast to heterotrophic micro-organisms that oxidize carbonaceous matter, nitrifying micro-organisms are able to oxidize ammonia. Make a list to compare at least six different characteristics of heterotrophic and nitrifying micro-organisms and their specific process conditions. (*14 points*)

6 Biological nitrogen and phosphorus removal takes place in an activated sludge system that consists of three compartments and a secondary settling tank.

   a. Draw the process scheme for this system, including the reactor compartments and flows. (*3 points*)
   b. Describe for each compartment the required process conditions. (*5 points*)
   c. Describe the reactions that take place in these compartments and describe how the nitrogen and phosphorus are removed. (*5 points*)
   d. Explain the main difference in terms of fate of nitrogen and phosphorus in the biological removal process. (*3 points*)

Sludge treatment

7 A flow of 1,000 m^3/day of waste sludge (1% SS of which is 70% organic matter) is pumped to a gravity thickener in which the sludge is thickened to a SS-concentration of 50 gSS/L. The solids concentration of the effluent is 250 mg/L.
The maximum solids loading rate is 40 kgSS/(m^2.day).
The sludge residence time should be around 1 day.

a. Give the dimensions (D and H) of the thickener. (*7 points*)

b. What is the height of the sludge layer? (*7 points*)

ANSWERS

Part 1 - Drinking water

1 They don't have a raw water reservoir because the function are included in other parts of the system. The 4 functions are: analysis (they use upstream monitoring systems for this), self-purification (they use the dunes for this and the multi-barrier system), mixing/levelling of peaks (they use the dunes for this) and storage (they use the dunes for this in combination with local ground water abstraction).

2 Average flow = 70 million m^3/a= 8000 m^3/h. Surface area =300*120=360000m^2. Surface load = 8000/36000= 0.22 m/h, way less than 1 m/h so OK.
$FeCl_3$-> $Fe(OH)_3$ + 3 H^+, so H^+-production is (3/56)*3=0.16 mmol/L. This will convert 0.16 mmol/L HCO_3- into CO_2, so the pH will become 6.4 + log (3-0.16)/0.16 = 7.7

3 The most important design criterion is the surface load or filtration velocity. Average flow is 8000 m^3/h. Surface area is 2368 m^2. Velocity is thus 8000/2368=3.37 m/h, way less then 5 m/h so OK.
Measures to improve run time: increase grain size (short term), increase bed height (long term), improve sedimentation (short term, flocculants), upflow filtration (long term), multi-media (long term).

4 Disinfection (not met here because of abstraction in open canals), strorage, water quality improvement (mixing, self purification).
Consequences are that disinfection is necessary in the post-treatment (ozonation).

5 Oxygen uptake.
Total effciency is 58 %, so per step this is 25%. So k_d/RQ= 1/0.25=4, so RQ=4*1.23=5

6 Disinfection and breakdown of NOM before the BACF. Design criterion is detention time. Average flow is 8000 m^3/h. Volume is 5 * 778 m^3= 3890 m^3.
Detention time is (3890/8000)*60= 29 min, way more than 15 min, so OK.

7 Total hardness is 2.5 mmol/L, so 1 mmol/L softening is required, so dose of NaOH is 1 mmol/L and drinking water quality is Ca 1 mmol/L, Mg 0.5 mmol/L, HCO_3= 3 mmol/L.
Split-treatment is possible, minimum hardness approx 1 mmol/L, so split treatment X*0.5+(1-X)*2=1, so X=0.66

8 HCl before the BACF to prevent scaling after the softening. NaOH after the BACF to increase the pH to equilibruim after the pH-decrease due to biological processes. Oxygen dose because of oxygen consumption due to biological processes. They don't use cascades because of hydraulic line.

9 Design criterion is velocity. Flow is 8000 m^3/h, area is 32000 m^2, so velocity =0.25 m/h, less than 0.5 m/h. Units are bigger because they don't need bachwashing.

10 Storage approx. 6 hours, 13400 m^3/8000=1.67 hours, not enough.
Peak factor = 34500/8000=4.3 so very high.
So they have not enough storage and too much pumps.

Part 2 - Urban drainage / Sewerage

1 a. Run-off coefficient depends on: land use and slope, soil and vegetation type, rainfall intensity and duration, antecedent conditions.

b. Values of C range from:
0.70-0.95 (impervious surfaces)
0.05-0.35 (pervious surfaces).

c. Run-off coefficient is lower in summer: higher evaporation, more interception by leaves, drier antecedent conditions leading to higher initial losses and infiltration.

2 a. Calculate the volumes of all sections: total storage is 110m^3. Pipes are below surface water level, because distance between water level and ground level at outflow point is only 0.7 m: total pipe volume is available for storage. Connected area is 150 ha; storage in mm is: 110/150*10=0.07mm. Pumping capacity: 0.07/10= 0.007mm/h. Read overflow frequency from graph: 300/year.

b. Overflow discharge at B: QAB + QCB = 0.9 m^3/s. Apply weir formula to calculate height of overflow jet: H = 1.0 m. Assume weir is 0.1 above surface water level: NAP-0.3 m. Energy level at point B: NAP-0.3+1 = NAP+0.7 m.
Energy losses in BC, CD, DF, FG according to formula for friction losses:

	Q	D	L	R	C	dH	Sum dH	Ground level
BC	0.4	1.0	40	0.25	57	0.012	0.71	0.25
CD	0.4	0.5	60	0.125	52	0.74	1.46	0.4
DF	0.1	0.4	20	0.1	50	0.05	1.51	0.5
FG	0.1	0.4	60	0.1	50	0.15	1.66	0.9

c. Improvements: increase width of weir to decrease the height of the overflow jet and increase diameter of conduit FG to reduce high energy loss in this conduit.
Weir: maximum H at overflow is 0.3 m: width must be at least 6 m.
Additionally, change diameter of section DC to decrease friction losses, for instance for D=0.6 m, dH=0.28 m instead of 0.74 m and all energy levels will be below ground level.

Part 3 - Treatment of wastewater

Primary sedimentation

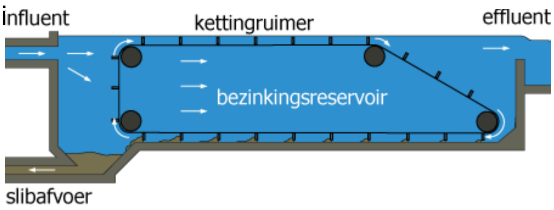
1. a. $v_0 = \dfrac{5{,}000}{2 \times 13 \times 50} = 3.8$ m³ /(m².h) $\rightarrow$ OK .

   b. based on scouring velocity: $\dfrac{5{,}000 \, \frac{1}{3{,}600}}{2 \times 13 \times H} \leq 0.03 \text{ m/s} \rightarrow H \geq \dfrac{5{,}000 \, \frac{1}{3{,}600}}{2 \times 13 \times 0.03} = 1.8 \text{ m}$.

   based on retention time: $\dfrac{2 \times 13 \times 50 \times H}{5{,}000} \geq 1 \text{ h} \rightarrow H \geq \dfrac{5{,}000}{2 \times 13 \times 50} = 3.8 \text{ m}$.

   → H = 3.8 m.

   c. $T = \dfrac{2 \times 13 \times 50 \times 3.8}{40{,}000} \times 24 = 3.0 \text{ h} \rightarrow \text{OK}$.

   d. 

Biological treatment

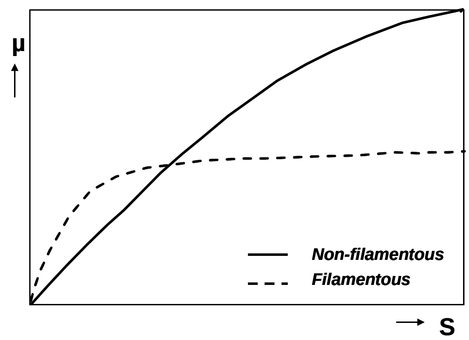
2 a. Average water consumption per inhabitant is about 125 L/d, and this is roughly the amount of sewage produced. An amount of 15,000 m^3/d would then be produced by 15,000/0.125=120,000 people. Not included is the contribution of water from industries (minor portion in case of domestic sewage) and precipitation (peak loads).

b. 15,000 [m^3/d]×0.250 [kgBOD/m^3]/(3500 m^3×4 kgMLSS/m^3])=0.27 kgBOD/kgMLSS.d.

c. Sludge loading rate B_X is 0.27 kgBOD/kgMLSS.d, and this is too high (i.e. >0.20) to allow growth and retention of nitrifying biomass. Hence it is likely a non-nitrifying plant.

3 Sludge age is the average residence time of suspended solids in the system: $\theta_X = V_{AT} \cdot X_{AT}/P_X$ or $\theta_X = V_{AT} \cdot X_{AT}/(Q_S \cdot X_S)$. Sludge production rate or sludge wastage rate is proportional to organic loading rate and hence sludge age is inversely proportional to organic loading rate.

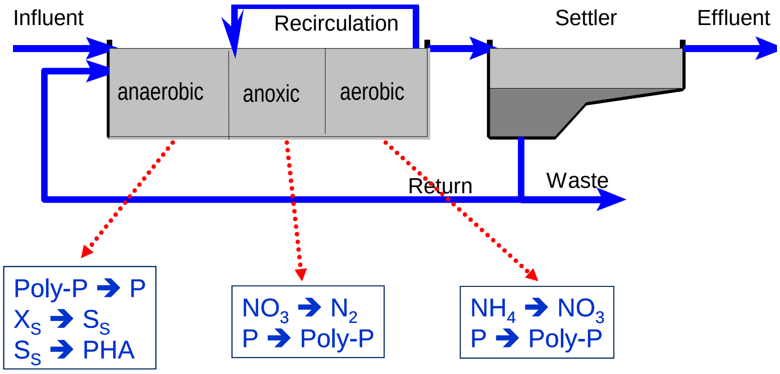
4 Selector has a relatively large load to volume ratio and hence the organic loading is relatively large. At high loading rates non-filamentous micro-organisms that tend to grow in flocs (low SVI) have a selective advantage over filamentous organisms in terms of achievable growth rate, and so they will dominate the microbial population. At low loading rates, for example if no selector is present, the reverse happens: filamentous organisms achieve higher growth rates because they have easier access to lower substrate concentrations. The head end part of a plug flow reactor has a similar function as a selector.



5 Heterotrophic and nitrifying micro-organisms and their specific process conditions:

Heterotrophic	**Autotrophic**
Needs O_2	Needs a lot of O_2
Carbon source: organic C	Carbon source: CO_2
Energy source: organic C	Energy source: NH_4
Fast growth: ~6 /d	Slow growth: ~0.8/d
Required DO minimal 0.5 mg/l	Required DO minimal 2 mg/l
Max loading rate: 3 kg/kg.d	Max loading rate: 0.15 kg/kg.d
Sludge age: 1-2 d	Sludge age: >2 d
Moderate inhibition at low temperature	Strong inhibition at low temperature
Moderate sensitivity to toxicants	High sensitivity to toxicants

6 a.



b. The first compartment is anaerobic, that is: no inorganic electron acceptor (nitrate, nitrite), not oxygen is present. The second compartment is anoxic, that is: inorganic electron acceptor is present but no oxygen. The third compartment is oxic, that is: it is aerated and the dissolved oxygen concentration is greater that zero.

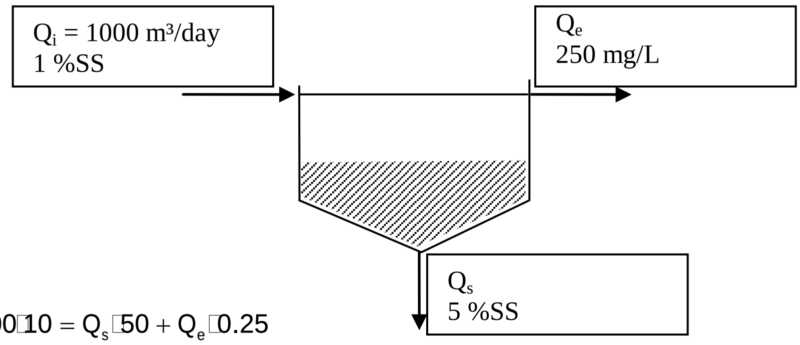
c. In the biological removal of phosphorus, the phosphorus is accumulated into the cell biomass of phosphorus accumulating micro-organisms (luxury uptake). In the anaerobic compartment readily biodegradable organic matter (partly introduced with the wastewater, and partly produced from the hydrolysis of slowly biodegradable particulate organic matter) is taken up by the bacterial cells and stored in the form of hydroxybutyrate. The energy required for this process is obtained from the hydrolysis of stored poly-phosphate. In the subsequent compartment nitrate (and possibly some nitrite) is used as final electron acceptor and converted to N_2 for the degradation of PHB (denitrification). This yields energy that is partly stored by converting phosphate into poly-phosphate. In the third compartment the oxygen is used as electron acceptor for the degradation of PHB, while part of the obtained energy is stored by the formation of poly phosphate. Simultaneously ammonium is oxidized to nitrite and (mainly) nitrate (nitrification). Part of the nitrate-rich liquid from this reactor is recycled to the anoxic reactor in order to provide nitrate for the denitrification process.

d. Nitrogen is ultimately removed by converting it to nitrogen gas that escapes into the air. Phosphorus is accumulated in the biomass and because there is a net growth of biomass the phosphorus leaves the system with the waste activated sludge. Some of both nutrients is also incorporated into newly grown cell mass.

Sludge treatment

7 a $v_s = \frac{Q_s \cdot c_s}{\frac{1}{4}\pi D^2} = 40 \text{ kgSS/(m}^2\text{.day)} \rightarrow D^2 = \frac{1000 \times 10}{\frac{1}{4}\pi \times 40} = 318.3 \text{ m}^2 \rightarrow D = 17.8 \text{ m}.$

b



$$1000 \cdot 10 = Q_s \cdot 50 + Q_e \cdot 0.25$$

$$Q_s + Q_e = 1000$$

$$\rightarrow Q_s = 196.0 \text{ m}^3/\text{day}$$

$$\text{sludge residence time} = 1 \text{ day} = \frac{\frac{1}{4}\pi \times 17.8^2 \times H_{sludge}}{196.0}$$

$$\rightarrow H_{sludge} = 0.78 \text{ m}$$