

SIMULATION OF ACTIVATED SLUDGE PROCESSES WITH NITROGEN REMOVAL

Computer laboratory work in Wastewater Treatment –
W4

Preparation exercises:

1. Read the lab instruction carefully
2. Page 17-18 Exercise 4.3 a-b

Name	Comments by supervisor
Program Year entering the program	
Date	
Lab passed Sign	

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1 Introduction

Modeling and simulation studies become more and more common also in the wastewater treatment area. Since, a wastewater treatment plant is a very dynamic process, static rules of thumb may not be sufficient in the design and operation of the plant.

In all simulation studies it is of fundamental importance to be aware of model approximations and the validity of the model. Note that different needs often lead to different requirements of the accuracy of the underlying model.

In this laboratory work, a simulator based on the Activated Sludge Model No 1 (ASM1), will be used to simulate an activated sludge process. The simulator is denoted *JASS* (a Java based Activated Sludge process Simulator). The *JASS* simulator is written in *Java* and was made as a master thesis work by Pär Samuelsson in 1999. It has been updated by Mats Ekman in 2001 and by Gustav Grussel (Master thesis work in 2002). You will run the simulator using an ordinary web browser (for example Netscape Communicator) with Java Plugin 1.3.1. The purpose of the laboratory work is to study different aspects of nutrient removal in the activated sludge process. Two different alternatives for nitrogen removal in an activated sludge process will be considered:

- Pre denitrifying process
- Post denitrifying process

2 Simulation of an activated sludge process using the ASM1 and a graphical process simulator

2.1 Process layout

In the default version of the simulator program, an activated sludge process with pre denitrification and with the possibility to add an external carbon source in compartment 1 is used. It is also possible to choose the setup for simulating a post denitrifying process, see Section 4. A schematic layout of the process is shown in Figure 1 (lower half).

2.1.1 Volumes, flows and composition of the wastewater

The simulated process consists of a basin divided in 10 completely mixed compartments and a sedimentation unit (settler) The (default) configuration of the compartments is given in Table 1.

Compartment No.	Volume (m ³)	Operation
1	235	Anoxic
2	235	Anoxic
3	235	Anoxic
4	235	Anoxic
5	235	Anoxic
6	235	Aerobic
7	235	Aerobic
8	235	Aerobic
9	235	Aerobic
10	235	Aerobic

Table 1: The basin consists of 10 compartments, compartments 1 to 5 are non-aerobic (anoxic) and compartments 6-10 are aerobic.

The nominal flow rates used in the simulator are given in Table 2.

Flow	Rate [m ³ /h]
Influent	250
Excess sludge	4
Return sludge	250
Internal recirculation	0
External carbon flow rate	0

Table 2: Nominal values of the flow rates in the the simulation model.

Each compartment is modeled with the ASM1. The values of the parameters and concentrations in the model can be changed. The default concentrations of different compounds in the influent wastewater are given in Table 3.

Standard abbrev.	Abbrev. in simulator	Variable	Conc. (mg/l)
$X_{B,H}$	Xbh	Heterotrophic biomass	0
$X_{B,A}$	Xba	Autotrophic biomass	0
X_S	Xs	Slowly biodegradable substrate	82
X_I and X_P	Xi	Part. inert org. matter	43
$X_{N,D}$	Xnd	Part. biodegradable org. nitrogen	5.8
$S_{N,H}$	Snh	NH_4-NH_3 nitrogen	23.5
$S_{N,D}$	Snd	Soluble biodegradable org. nitrogen	2.1
$S_{N,O}$	Sno	Nitrate and nitrite nitrogen	1
S_I	Si	Soluble inert org. matter	37
S_O	So	Oxygen	0.1
S_S	Ss	Readily biodegradable substrate	80

Table 3: Influent wastewater composition. The values approximately correspond to the composition of pre sedimented wastewater at the main municipal plant in Uppsala.

2.1.2 The sedimentation unit

The sedimentation unit is modeled as a traditional one-dimensional layer model with 10 vertical layers. The equations describing the sedimentation model is given in Appendix 2.

The excess sludge is removed at the bottom of the sedimentation basin. The sludge age is calculated as

$$\theta_s = \frac{V * X}{Q_w * X_{rec} + Q_{eff} * X_{eff}} \quad [days] \quad (1)$$

where V is the volume of the aerobic compartments, X is the mean sludge concentration in the aeration basin, Q_w is the excess sludge flow rate (expressed in m^3/day), X_{rec} is the concentration of the sedimented sludge, Q_{eff} is the effluent biomass flow rate (expressed in m^3/day) and X_{eff} is the concentration of the effluent biomass. The sludge age presented in the simulator is calculated using (1).

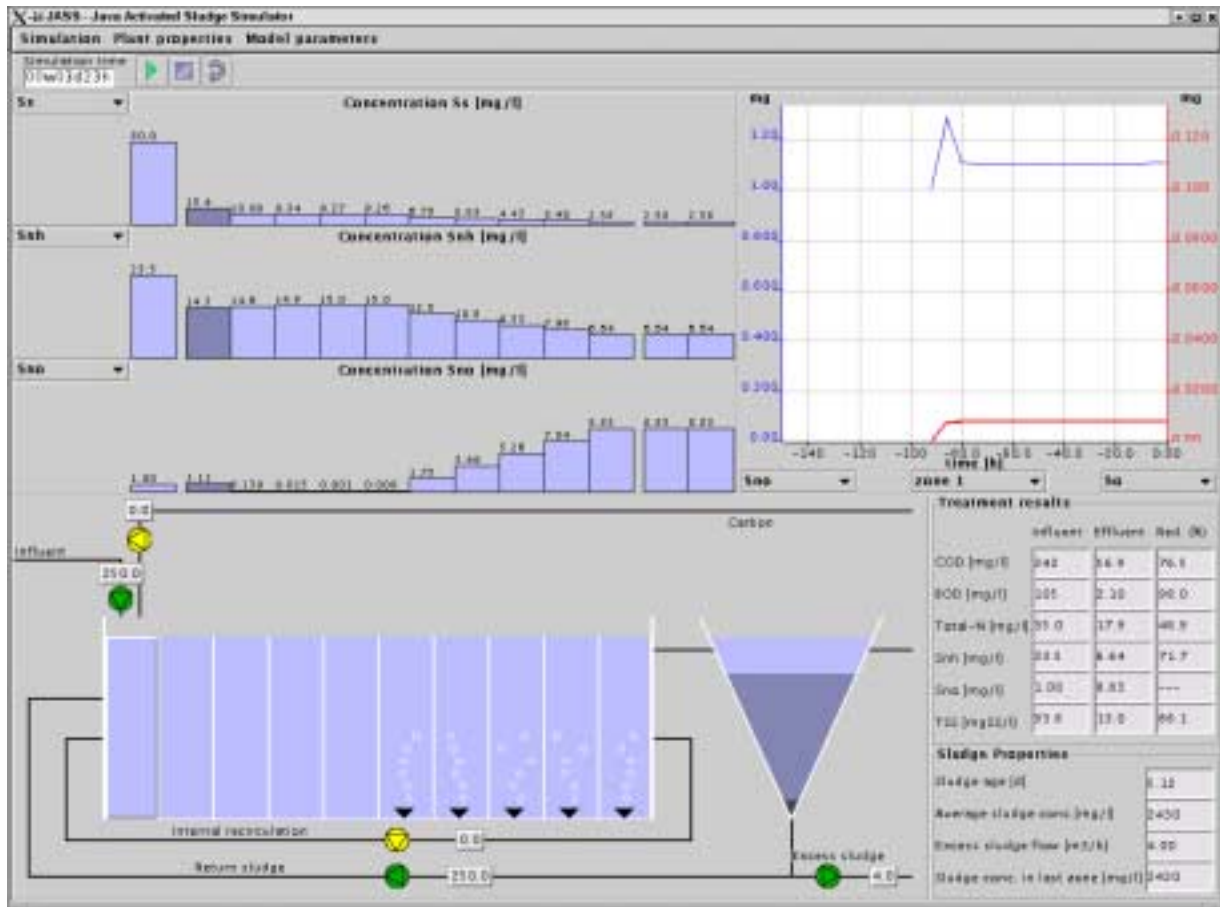
2.2 The graphical user interface (GUI)

The simulator is operated with a GUI where also the status of the plant is shown in real time. As seen from Figure 1, the plant is schematically drawn in the GUI. The simulated flow rates of the pumps are changed by clicking of the appropriate pump symbol in the process image, or selecting the corresponding item in the *Flow rates* sub-menu, located in the *Plant properties* menu. This displays a dialog box where the flow rate can be changed.

In the upper left corner of the GUI, the simulation time is presented during the simulation. Note, that some changes may take hours or days before they are fully observable.

Important process parameters are also shown in the GUI. For example, in the lower right of the GUI, the sludge age, the sludge concentration and the excess sludge flow


rate are displayed. The sludge concentration is here defined as the average concentration of particulate compounds in the aerobic compartments. To further improve the presentation of the status of the plant, three bar diagrams are used. Each diagram shows the concentration of a selectable compound in incoming water, all compartments, return sludge and the effluent water. In these diagrams, the numerical values of the concentrations are also shown. In the GUI an ordinary graph is also used. Here, the concentrations of two compounds in a specific compartment are plotted versus time.



2.3 Running the simulator

To start the simulator (wait until you have started reading Section 3 before you actually do this), do the following:

2.3.1 Starting the simulator

1. Start a web browser which has Java Plugin 1.3.1 installed. In the lab room, *Netscape Communicator* is recommended..
2. Load the actual URL, see Section 3 for details.
3. Select the plant to be simulated in the *Load plant setup* sub menu, located in the *Simulation* menu (upper left corner).
4. Click on the *Start* button () , located just below the menu bar in the GUI.

2.3.2 Reseting the simulator

5. The simulation can be reseted in two different ways, which gives different results:
 - By reloading the current plant setup from the *Load plant setup* sub-menu in the *Simulation menu*. In this case, everything is reseted to initial values, even model parameters.
 - By pressing the *Reset* button. This resets the internal states of the compartments and the sedimentation unit to their initial values. Nothing else is changed, so any changes made to compartment volumes, controllers etc remains.

2.3.3 Plotting and presenting data

6. To choose a certain component to plot in the bar diagrams, use the combo box to the left of a bar diagram. For instance, to plot the concentration of dissolved oxygen, choose S_O . The oxygen concentrations in influent water, all compartments, return sludge and effluent water are then displayed.
7. In the scrolling graph it is possible to plot the concentrations of two components at the same time. Three combo boxes are located under the graph. In the middle combo box it can be chosen whether to plot concentrations from influent water, any of the compartments, return sludge or the effluent water. Two components may then be selected from the combo boxes to the left and to the right.
8. The simulated time is presented in the top-left corner of the GUI, below the menu bar, in the field labeled *Simulation time*.
9. The sludge age, the excess sludge flow and the sludge concentration in the plant are displayed in the lower left of the GUI, in the area labeled *Sludge properties*.

10. The state of the sedimentation unit is shown in the process image. Here the concentration profile of particulate matter in the sedimentation unit is shown. The darkness of the color of each layer is proportional to the sludge concentration. When a sludge overflow occurs, a warning message appears above the sedimentation unit.
11. In the section labeled *Treatment results*, located in the lower left of the GUI, the concentrations of COD, BOD, total N, ammonium (S_{nh}), nitrate (S_{no}) and Total Suspended Solids (TSS) in influent and effluent of the plant are displayed. The reduction percentage is also shown, see further Appendix 3.

2.3.4 Changing the process

12. Changes in the process are performed in a number of different dialog boxes. It is important to note that no changes take effect until the *Apply* or the *OK* button is pressed. The *OK* button also closes the dialog box. The *Cancel* button closes the dialog box without applying any changes.
13. To change a flow rate, click on the appropriate pump symbol or select the appropriate item in the *Flow rates* sub-menu, located in the *Plant properties* menu. Sometimes it may happen that a click on the pump symbol is not detected, then use the sub-menu *Flow rates* instead. Note also that the dialog box may hide under the main GUI window.

In the dialog box that is displayed, enter the new flow rate (Flow average). It is also possible to add a sinusoidal variation with a given magnitude and period time.

An active pump will be colored green, and an inactive yellow. A pump that is currently being controlled by a controller will be colored gray. External carbon (ethanol) can be added manually by clicking on the pump on the pipe labeled *Carbon*.

14. To change ASM1 process parameters, select *ASM1-parameters* in the *Model parameters* menu. A dialog box where the new parameters may be entered is shown. Here, it is also possible to choose the simulated temperature of the water. The *ASM1-parameters* dialog box is depicted in Figure 2.
15. To change the concentrations of the components in the influent water, select *Influents* in the *Plant properties* menu. A dialog box appears, where new values for the influent concentrations can be entered.
16. By Selecting *Zone volumes* in the *Plant properties* menu, a dialog box appears where the volumes of all compartments can be changed.
17. By selecting *Settler properties* in the *Plant properties* menu, a dialog box appears. In the dialog box it is possible to change the settler properties such as settler area, settler height and the settler feed height.

2.3.5 Controlling the process

18. During simulation, it is possible to choose between running the simulator with a fixed excess sludge flow rate or with a fixed sludge age. In the default setup, the

Temperature dependent ASM1-parameters		
	at current temp.	at 20°C
myh	0.25	0.25
Bh	0.026	0.026
Ba	0.0083	0.0083
Kh	0.125	0.125
Kx	0.03	0.03
Ka	0.0033	0.0033
mya	0.033	0.033

Temperature independent ASM1-parameters	
Yh	0.67
Ya	0.24
fp	0.08
lxb	0.086
lxp	0.06
Ks	20
Koh	0.2
Kno	0.5
etah	0.4
etag	0.8
Knh	1
Koa	0.4

Figure 2: The dialog box for changing the ASM1 process parameters.

simulator is running with a fixed excess sludge flow rate. By selecting *Excess sludge controller* in the *Controllers* sub-menu, located in the *Plant properties* menu, a dialog box is displayed where the controller for the excess sludge flow can be enabled. This is done by checking the *Sludgeage control* checkbox and then entering the desired fixed sludge age. The simulator will then run with a fixed sludge age. By checking the *Manual flowcontrol* checkbox the excess sludge flow rate will be fixed instead.

19. The dissolved oxygen (denoted S_o in the simulator) is controlled by a PID controller:

$$u(t) = K(e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de(t)}{dt})$$

where u is the control signal (air flow rate), e is the control error ($S_{o_{ref}} - S_o$). If $T_i = 0$ is selected, the integration is not used and a pure PD controller is obtained. For the oxygen control, no derivative action is needed (T_d should be 0)

To change the reference values¹ for dissolved oxygen, select *DO PID controllers* in the *Controllers* menu. A dialog box is displayed with 10 tabs labeled *zone1*, *zone2*, ..., *zone10*. In each of the tabs, parameters for the DO PID controller for the zone is displayed. Enter the new DO reference value in the field labeled

¹In the description we will use reference value and set point interchangeable.

Reference value. Note that this dialog box works a little different than the others. Pressing the *Apply* button applies any changes done in the current tab, while pressing the *Reset* button resets the current tab to the latest applied values. The *Cancel* button closes the dialog box. This makes it necessary to press *Apply* in each panel where changes has been done. Also note that the air bubbles in the compartment will disappear when $DO_{ref} = 0$ is chosen.

20. It is also possible to use a supervisory controller for the DO controllers. Then the oxygen controller above is used but also a master controller for controlling the set point of dissolved oxygen. The goal for the supervisory controller is to control the dissolved oxygen levels so that the ammonium level in a desired compartment (typically the last aerated compartment) is kept at a desired set point. The controller is given by

$$S_{o_{ref}}(t) = K(e_A(t) + \frac{1}{T_i} \int e_A(t)dt + T_d \frac{de_A(t)}{dt})$$

where the control error is given by $e_A = S_{nh} - S_{nh_{ref}}$.

In order to run the supervisory DO controller, select *DO setpoint controller* in the *Controllers* menu. In the *Reference value* field, the reference value for ammonium concentration can be entered. In the *Reference zone* combo box it is also possible to select in which zone the ammonium concentration should be controlled. The user may also set the PID-parameters of the controller. To use the DO setpoint controller, the *Controller enabled* radio button **must** be selected.

21. It is possible to automatically control the flow rate of external carbon by the following PID controller:

$$u_{kol}(t) = K(e_{kol}(t) + \frac{1}{T_i} \int e_{kol}(t)dt + T_d \frac{de_{kol}(t)}{dt})$$

where u_{kol} is the control signal (flow rate of carbon), e_{kol} is the control error ($S_{no} - S_{no_{ref}}$). The output S_{no} is the nitrate level in a selected compartment (by default the last anoxic compartment)

The carbon controller is activated by selecting *Ext. carbon controller* in the *Controllers* menu. In the dialog box that is displayed, select the *controller enabled* to enable the controller. The controller uses the value given in the *Reference value* field as reference value for the nitrate concentration in the zone selected in the *Reference zone* checkbox. It is also possible to set the zone where the carbon is added, the PID-parameters and the min and max flow rate. Note that the minimum and maximum values are in m^3/h , while in the rest of the GUI carbon flow rate is presented in l/h .

3 Exercises - Pre denitrification process

You will here study the effect on the process when changing different process parameters. Some supporting calculations will also be done.

Exercise 3.1, Getting used to the simulator

First, start Netscape and go to the following URL: <http://www.syscon.uu.se/JASS>. Select the link *JASSeng* in the table. Load the predenitrification plant by selecting *pre-denit-10* in the *Load plant setup* sub menu, located in the *Simulation* menu (upper left corner).

Push the *Start* () button to start the simulations.

Familiarise yourselves with the simulator! Go briefly through the items presented in Section 2.2. Reload the simulator if you have made any changes. Check that you have the predenitrification plant loaded!

Check that:

- The flow of the incoming water=250 m³/h, the internal recirculation=0 m³/h, the excess sludge flow=4 m³/h and the return sludge flow = 250 m³/h.
- The three bar diagrams to the left show readily biodegradable substrate (*S_s*), ammonium (*S_{nh}*) and nitrate (*S_{no}*)
- The oxygen concentrations should be around 2 mg/l in the last five compartments and zero in the first five. This is checked by choosing *S_o* in one of the bar diagrams.

Note that in the lower right of the GUI, in the area labeled *Treatment results*, you can see some important information about influent and effluent concentrations and the percentage reduction of different compounds.

Let the simulator reach steady state values (this may take 5-10 days) and check:

- Effluent ammonium (*S_{nh}*) = mg/l
- Effluent nitrate (*S_{no}*)= mg/l
- Nitrate (*S_{no}*) in last anoxic compartment = mg/l

Exercise 3.2, Effect of internal recirculation rate

An increase of the internal recirculation rate reduces the effluent nitrate concentration if the denitrification is complete or almost complete.

Assume that the influent flow is *Q*, internal recirculation is *rQ*, return sludge is *sQ*. Assume further that

- No other reactions than denitrification and nitrification are affecting the nitrogen mass balance.
- Nitrification only occurs in aerated compartments and denitrification only occurs in non aerated compartments. No reactions occur in the settler.
- The denitrification is complete (*S_{NO}* = 0 in the last anoxic compartment).

The following mass balance then holds:

$$Q S_{NH,in} = (Q + rQ + sQ)S_{NO,eff} + Q S_{NH,eff} \quad (2)$$

which can be written as

$$S_{NO,eff} = \frac{1}{1 + r + s}(S_{NH,in} - S_{NH,eff}) \quad (3)$$

a) Use (3) to calculate r so that $S_{NO,eff} = 6$ mg/l. Assume that $S_{NH,eff}$ is not affected by the recirculation rate r and hence is the same as in Exercise 3.1. The influent ammonium level is $S_{NH,in} = 23.5$ mg/l.

ANSWER:

b) Increase the internal recirculation rate in the simulator according to Exercises 3.2. Fill in the values below.

- Internal recirculation rate = m³/h
- Effluent ammonium = mg/l
- Effluent nitrate = mg/l
- Nitrate in last anoxic compartment = mg/l

Does the effluent nitrate roughly ($\pm 10\%$) became as expected?

ANSWER:

c) Next, increase the internal recirculation rate to 1000 m³/h. Fill in the values below.

- Effluent ammonium = mg/l
- Effluent nitrate = mg/l
- Nitrate in last anoxic compartment = mg/l

Is expression 3 still valid? If not, try to explain what assumption presented in Exercise 3.2 that is not valid.

ANSWER:

Exercise 3.3, Effect of incoming biodegradable substrate

a) Now, set the internal recirculation back to zero and change the concentration of readily biodegradable substrate S_S in the influent water to 25 mg/l (Go to *Plant properties/influent* in the menu). Wait for the process to reach steady state.

Note the effluent levels of ammonium and nitrate.

- Effluent ammonium = mg/l
- Effluent nitrate = mg/l

What can you say about the ammonium and nitrate levels compared to the case in Exercise 3.1?

ANSWER:

b) Which biological process is most sensitive to lack of readily biodegradable substrate in the influent water?

ANSWER:

c) Now, increase the internal recirculation to the same value as used in Exercise 3.2b

- Effluent nitrate = mg/l
- Nitrate in last anoxic compartment = mg/l

Compare the result with Exercise 3.2 b. Is the effluent nitrate level decreased significantly? Does it seem feasible to increase the recirculation rate in this case?

ANSWER:

Exercise 3.4, Adding an external carbon source

In this exercise you should continue with the same internal recirculation as above.

A common way of getting a higher denitrification rate when there is a lack of easily degradable organic matter in the anoxic compartments is to add external carbon (ethanol in our case) in the first anoxic compartment.

A carbon source is added by clicking on the carbon pump and enter a ethanol flow rate (l/h) in the dialog box that appears. In the dialog box it is also possible to select to which zone the carbon is added. By default the first anoxic compartment, zone 1, is selected, so leave the zone selection unchanged.

Try to add a carbon flow rate so that the effluent nitrate is (approx) 6 mg/l. Fill in the table below.

- External carbon flow rate = l/h
- Effluent ammonium = mg/l
- Effluent nitrate = mg/l
- Nitrate in last anoxic compartment = mg/l

Comment on your results! Compare your results with Exercise 3.3.

ANSWER:

Exercise 3.5, Changing the DO levels

a) First of all, turn off the external carbon flow and set the concentration of S_s back to 80 mg/l. Let the internal recirculation flow rate be 250 m³. Wait for the simulations to reach steady state. Write down values of air flow rates, ammonium and nitrate concentrations.

- Air flow rates in compartment 6....., 7....., 8....., 9....., 10.....
- Effluent ammonium = mg/l

- Effluent nitrate = mg/l

b) The dissolved oxygen concentration has a large impact on the activated sludge process. By default, it is set to 2 mg/l in all the five aerobic compartments. Change the DO set-point (the reference value of dissolved oxygen) to 1.5 mg/l in compartments 6 to 10. In order to do this, go to *Plant properties/Controller/DO PID Controllers* and select set the reference value to 1.5 for zone 6 to 10. See Section 2.3

Verify in the bar diagram that all aerobic compartments have DO=1.5 mg/l. Write down the values of: air flow rates, nitrate concentrations and effluent ammonium after you have changed DO set-point.

- Air flow rates in compartment 6....., 7....., 8....., 9....., 10.....
- Effluent ammonium = mg/l
- Effluent nitrate = mg/l

Compare the results with 3.5a and comment.

ANSWER:

Exercise 3.6, Increase of influent ammonium - Optional task.

First, change all five (compartment 6-10) oxygen reference values back to 2.0 mg/l. Let the simulator reach steady state values (this may take 5-10 days). Choose S_o and S_{nh} in compartment 10 in the time graph. Increase the ammonium concentration by 4.5 mg/l (to 28 mg/l) and study the effect in ammonium, nitrate concentrations, and air flow rates. Explain what happens with the air consumption and the ammonium levels in the effluent. Why do the nitrate concentrations increase? (Compare the results to Exercise 3.5).

- Air flow rates in compartment 6....., 7....., 8....., 9....., 10.....
- Effluent ammonium = mg/l
- Effluent nitrate = mg/l

ANSWER:

Exercise 3.7, Increase of excess sludge flow

The amount of biomass in the bioreactor affects the whole process. The most critical process to maintain is usually the nitrification process, why? Change the excess sludge flow rate to 40 m³/h and study the ammonium concentration, nitrate concentration and air flow rates. Explain what you see.

ANSWER:

Now you have made a wash-out! Be thankful it was only done in a simulator.

Exercise 3.8, Decrease of the temperature - optional task

Reload and restart the simulator. Set the internal recirculation flow rate to 250m³/h, and wait for the process to reach steady state. The activated sludge process is affected by the temperature, some processes more than others. Change the simulated temperature to 10 °C. This is done by selecting *ASM1-parameters* in the *Model parameters* menu and enter the value in the *Process temperature* field in the displayed dialog box. Note how this affects the process parameters. What seem to happen when the temperature is decreased? What process is most affected? Motivate this by checking the process parameters!

ANSWER:

As you can see the temperature decrease leads to high ammonium levels in the effluent water. A way of dealing with this problem is to aerate more compartments. When more compartments are aerated you may not have complete denitrification in the last anoxic compartment anymore, and the nitrate removal may therefore be increased by adding external carbon to the first compartment. Your task is now to make the nitrogen removal of the plant to work as good as possible. The internal recirculation may *not* be increased to more than 300 m³/h. For instance, aerate compartment 4 and compartment 5 (i.e set the oxygen reference values in these compartments to about 2.0 mg/l) and wait for simulations to reach steady state (note that this takes quite a while). When you add carbon to the first compartment, try not to add more than is needed to get an almost complete denitrification in your last anoxic compartment (a reasonable initial guess may be in the order 1-10 l/h). You can also try to use the supervisory DO controller. Describe and explain your results below.

ANSWER:

4 Exercises - Post denitrification process

Load the post-denitrification plant by selecting *post-denit-10* in the *Load plant setup* sub menu, located in the *Simulation* menu (upper left corner).

Start the simulations in the same way as before. The simulator has the same influent concentrations, process constants, and volumes as the previous one.

Exercise 4.1, Set-point (supervisory) control of the DO

Make the following changes:

- In the bar diagram select S_o , S_{nh} and S_{no} .
- Select the sludge age to 10 days (Go to *Plant properties/controllers/Excess sludge controller*).
- Turn on the set-point DO controller as described in Point 20 in Section 2.3.5. This controller controls the ammonium level in the last aerated compartment (zone 5). The controller adjust the set-point of the DO controllers in the aerated compartments so that the ammonia level in the last aerated zone is equal to the reference value (set point). The

Try some different ammonium reference values (for example 0.5, 1, 2 and 4 mg/l) and explain what happens to

- DO concentrations and air flow rates.
- The total nitrogen reduction (The total nitrogen reduction can be studied in the area labeled *Treatment results*).

ANSWER:

Decrease the sludge age for a given ammonia-set point. Why do the DO concentrations changes?

ANSWER:

Exercise 4.2, Preparations for external carbon dosing

Reload the plant setup (See Sec. 2.3.2) and then start it and let it reach steady state values (this may take 5-10 days) and check:

- Effluent ammonium = mg/l
- Effluent nitrate = mg/l

What can you say about the levels of nitrate in the effluent water compared to Exercise 3.1. What can you do to improve the nitrate removal?

ANSWER:

Exercise 4.3, Calculation of external carbon dosage

In many cases, it is of value to calculate the (approximate) amount of external carbon needed. A simplified approach is to be carried out below.

a) Consider a completely mixed reactor which is described by the ASM1 using the following assumptions:

- The dissolved oxygen $S_o = 0$. (completely anoxic)
- The hydrolysis process is ignored.
- The decay rate is zero.
- Only heterotrophic biomass $X_{B,H}$ is considered
- An (adapted) external carbon flow rate with COD value S_c and flow rate u is added.
- The dilution rate is $D = Q/V$.

The model then becomes (make sure you can derive this model from the ASM1 matrix and basic bioreactor modeling):

$$\frac{dX_{B,H}}{dt} = \mu(\theta)X_{B,H} + D(X_{B,H,in} - X_{B,H}) \quad (4)$$

$$\frac{dS_S}{dt} = -\frac{1}{Y_H}\mu(\theta)X_{B,H} + D(S_{S,in} - S_S) + \frac{S_C}{V}u \quad (5)$$

$$\frac{dS_{NO}}{dt} = -\frac{1 - Y_H}{2.86Y_H}\mu(\theta)X_{B,H} + D(S_{NO,in} - S_{NO}) \quad (6)$$

where $\mu(\theta)$ is the specific growth rate which depends on several variables (denoted θ).

Consider (4) - (6) during *steady state*. Derive an expression for the necessary stationary flow rate of external carbon u using the following steps. First, assume $S_{S,in} = 0$ (i.e. no internal organic matter available for denitrification) and $S_S = 0$ (all external carbon is used). Solve for u in (5). You will note that u depends on $\frac{1}{Y_H}\mu(\theta)X_{B,H}$. An expression for this can be obtained from (6) and inserted into the expression for u . Finally, let $\Delta S_{NO} = S_{NO,in} - S_{NO}$ and you should end up with a neat expression for how much carbon flow rate that is needed in order to remove ΔS_{NO} mg/l nitrate.

ANSWER:

b) Calculate the desired flow rate of external carbon (transformed to l/h) for the case

$$Y_H = 0.67$$

$$Q = 250 + 250 = 500 \text{ m}^3/\text{h}$$

$$S_C = 1200000 \text{ mg/l}$$

$$\Delta S_{NO} = 2 \text{ mg/l}$$

ANSWER:

Exercise 4.4, Adding an external carbon source

Make the following changes:

- Set $Kh = 0$ (we assumed no hydrolysis), this parameter is found after opening the *ASM1-parameters* dialog box.
- Set the dissolved oxygen to zero in compartment no 5 (Go to the DO-controller and change the reference value to 0 for zone 5). The latter is done in order to reduce the oxygen inflow to zone 6.
- Select the sludge age to 8 days (Go to *Plant properties/controllers/Excess sludge controller*). This is done so that wash-out is not obtained when decreasing the aeration volume in the step above.

External carbon (ethanol) will be added in order to improve the denitrification and reduce the nitrate level in the anoxic compartments. The ethanol will be added in compartment 6 (first anoxic compartment). To add ethanol, just click on the pump

symbol above the compartment and enter a value of the flow rate (unit l/h).

Set the flow rate as calculated in Exercise 4.2b. Let the process reach steady state and check the nitrate removal² $\Delta S_{NO} = S_{NO}^{zone5} - S_{NO}^{zone10}$. Write down the nitrate removal.

ANSWER:

Exercise 4.5, Effect of hydrolysis

Set $Kh = 0.125$ and continue to add external carbon. Now, the nitrate removal should increase. Try to explain why.

ANSWER:

In the long run, manual control of the external carbon source is not a very cost efficient way of getting a good nitrate removal. In the next two tasks you will run an automatic carbon flow rate controller. The key idea of the control strategy³ is to adjust the flow rate so that the nitrate level in the last anoxic zone is kept at a selected set-point.

Exercise 4.6, Automatic control of the external carbon source

The purpose with this exercise is to illustrate a control strategy for controlling the ethanol flow rate.

First reload the plant setup (See Sec. 2.3.2) and start the simulation.

Select *Ext. carbon controller* in the *Controllers* menu. The controller is started by selecting the *Controller enabled* radio button and pressing *Apply*. The carbon controller is by default setup to control the nitrate concentration in zone 10 by adding external carbon (ethanol) to zone 6. Do not change this. A reference value for the nitrate concentration can be given in the *Reference value* field. Do not forget to press *apply* to make any changes take effect. The controller may be turned off by selecting

²Note that since we have a recycle of nitrate we can not state that the nitrate level in the effluent is decreased with 2 mg/l, what we may say is that the reduction in the anoxic compartments should be 2 mg/l.

³In the course "Modellering och styrning av miljötekniska processer", period 43 you will learn how to design and tune a carbon controller

the *Controller disabled* radio button (and pressing *Apply*), which allows for manual control of the carbon flow rate.

Try different reference values (set-points) for the nitrate level and study how the flow rate of external carbon is affected.

ANSWER:

Exercise 4.7, Control of the external carbon when influent ammonium concentration is changed

Set the nitrate level set-point in compartment 10 to 6.0 mg/l.

When the system has reached steady state, increase the concentration of influent ammonium to 40 mg/l. Study how the effluent nitrate is affected. Can you see any differences in the nitrate levels when the disturbance is applied?

Write down the steady state concentration of the effluent nitrate when the influent ammonium is 40 mg/l:

- Effluent nitrate = mg/l

Decrease the influent ammonium to 23 mg/l and wait for steady state. Switch the carbon controller to manual mode and then increase the influent ammonium to 40 mg/l. What happens?

- Effluent nitrate = mg/l

Summarize and comment on the result below.

ANSWER:

Exercise 4.8, Sludge overflow in the sedimentation unit

a) Reload the simulator. Before you push the start button, double both the influent flow rate and the return sludge flow rate to 500 m³/h each, also increase the influent concentration of X_i to 300 mg/l. This can be regarded as a storm with sewer flush-out simulation. Start the simulation and look at the state of the sedimentation unit in the process image. Note that the height of the sludge blanket is increasing (the layers with black color). How long time did it take until you reached sludge overflow (40 mg/l suspended solids concentration i effluent water)?

ANSWER:

b) According to the solid flux theory, what is the condition for a sludge escape in a settler?

ANSWER:

A Appendix 1

Constants in model

```
deltaT = 0.0100
alfa = 5.000000
KCs = 8.6370000
```

--- *** ASM1 constants

--- stoichiometric constants :

```
Yh = 0.6700
Ya = 0.2400
fp = 0.0800
Ixb = 0.0860
Ixp = 0.0600
```

--- kinetic constants for heterotrophic bacteria:

```
mytH = 0.25
bh = 0.026
Ks = 20.000
Koh = 0.2000
Kno = 0.5000
etaG = 0.8000
```

--- kinetic constants for autotrophic bacteria:

```
mytA = 0.0330
ba = 0.0083
Knh = 1.0000
Koa = 0.4000
Ka = 0.00330
```

--- kinetic constants for hydrolysis:

```
Kh = 0.125
Kx = 0.0300
etaH = 0.4000
```

B Appendix 2

Secondary settler

- Geometry:
 - A: Area = 500 m²
 - $z_m = 1$ to 10: Height of layer m (all equal)
 - Height = 4 m
 - Settler volume = 2000 m³
- Solid flux due to gravity sedimentation J_s :

$$J_s = v_s(X)X$$

where X is the total sludge concentration

- Double-exponential settling velocity function:

$$\max \left[0, \min \left\{ v'_0, v_0 \left(e^{-r_h(X-X_{min})} - e^{-r_p(X-X_{min})} \right) \right\} \right]$$

$$X_{min} = f_{ns}X_f$$

Maximum settling velocity	v'_0	m/h	8.7
Maximum Vesilind settling velocity	v_0	m/h	18
Hindered zone settling parameter	r_h	m ³ /gSS	0.00057
Flocculant zone settling parameter	r_p	m ³ /gSS	0.00286
Maximum settling velocity	f_{ns}		0.00128

- Mass balances for the sludge:

– For the feed layer:

$$\frac{dX_m}{dt} = \frac{Q_f X_f + J_{clar,m+1} - (v_{up} + v_{dn})X_m - \min(J_{s,m}, J_{s,m-1})}{z_m}$$

where Q_f is the flowrate from the last bioreactor and X_f is the sludge concentration from the last bioreactor.

– For the intermediate layers below the feed layer:

$$\frac{dX_m}{dt} = \frac{v_{dn}(X_{m+1} - X_m) + \min(J_{s,m}, J_{s,m+1}) - \min(J_{s,m}, J_{s,m-1})}{z_m}$$

– For the bottom layer:

$$\frac{dX_1}{dt} = \frac{v_{dn}(X_2 - X_1) + \min(J_{s,2}, J_{s,1})}{z_1}$$

– For the intermediate clarification layers above the feed layer:

$$\frac{dX_m}{dt} = \frac{v_{up}(X_{m-1} - X_m) + J_{clar,m+1} - J_{clar,m}}{z_m}$$

where

$$J_{clar,j} = \begin{cases} \min(v_{s,j}X_j, v_{s,j-1}X_{j-1}) \\ v_{s,j}X_j \text{ if } X_{j-1} \leq X_t \end{cases}$$

– For the top layer:

$$\frac{dX_{10}}{dt} = \frac{v_{up}(X_9 - X_{10}) - (J_{clar,10})}{z_1}$$

with

$$J_{clar,10} = \begin{cases} \min(v_{s,10}X_{10}, v_{s,9}X_9) \\ v_{s,10}X_{10} \text{ if } X_9 \leq X_t \end{cases}$$

The threshold concentration X_t is equal to 3000 mg/l

• For the soluble components:

– For the feed layer:

$$\frac{dZ_m}{dt} = \frac{\frac{Q_f Z_f}{A} - (v_{up} + v_{dn})Z_m}{z_m}$$

– For the intermediate layers below the feed layer:

$$\frac{dZ_m}{dt} = \frac{v_{dn}(Z_{m+1} - Z_m)}{z_m}$$

– For the feed layer and the layers above the feed layer:

$$\frac{dZ_m}{dt} = \frac{v_{up}(Z_{m-1} - Z_m)}{z_m}$$

where

$$v_{dn} = \frac{Q_r + Q_w}{A}$$

$$v_{up} = \frac{Q_{eff}}{A}$$

C Appendix 3

Quality parameters in effluent

The total suspended solids is calculated as

$$TSS = 0.75(Xs_{eff} + Xi_{eff} + Xp_{eff} + Xbh_{eff} + Xba_{eff}).$$

The total nitrogen concentration is calculated as

$$totalN = Sno_{eff} + S_{NKj,eff}$$

where

$$S_{NKj,eff} = Snh_{eff} + Snd_{eff} + Xnd_{eff} + Ixb(Xbh_{eff} + Xba_{eff}) + Ixp(Xi_{eff} + Xp_{eff}).$$

Biochemical oxygen demand is calculated as

$$BOD = 0.25(Ss_{eff} + Xs_{eff} + (1 - fp)((Xbh_{eff} + Xba_{eff}))$$

and chemical oxygen demand as

$$COD = Ss_{eff} + Si_{eff} + Xs_{eff} + Xi_{eff} + Xp_{eff} + Xbh_{eff} + Xba_{eff}.$$