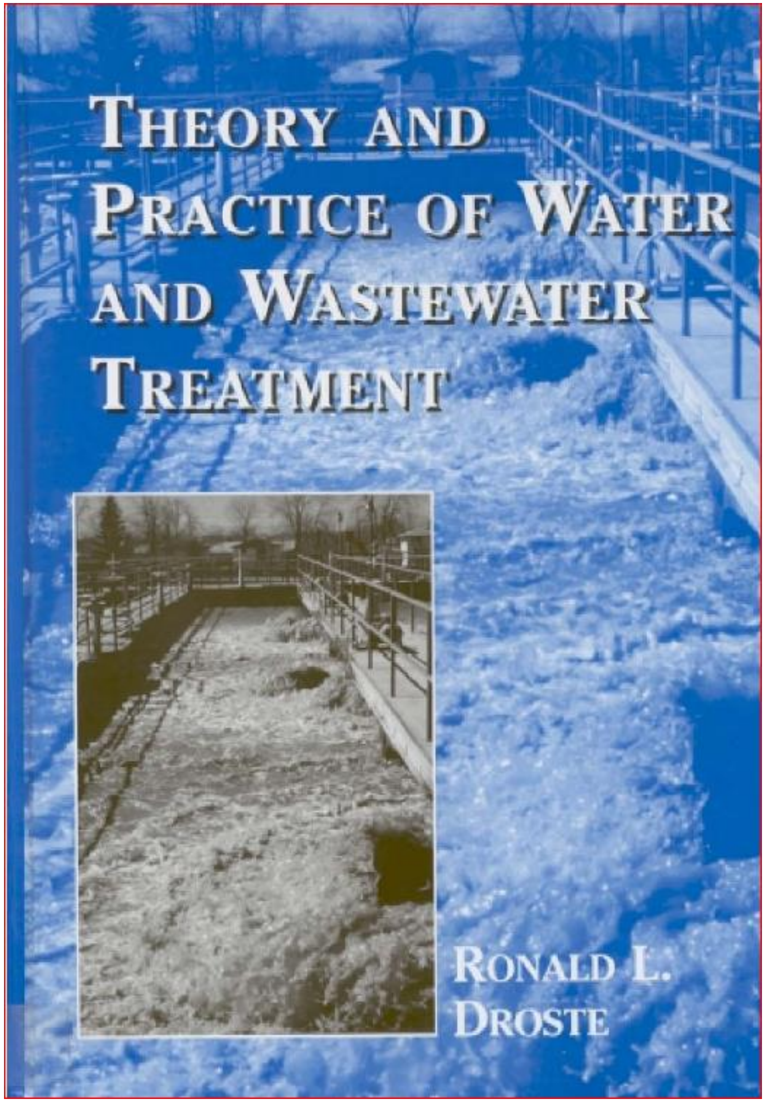
Introduction

Who is the lecturer

Why wastewater treatment

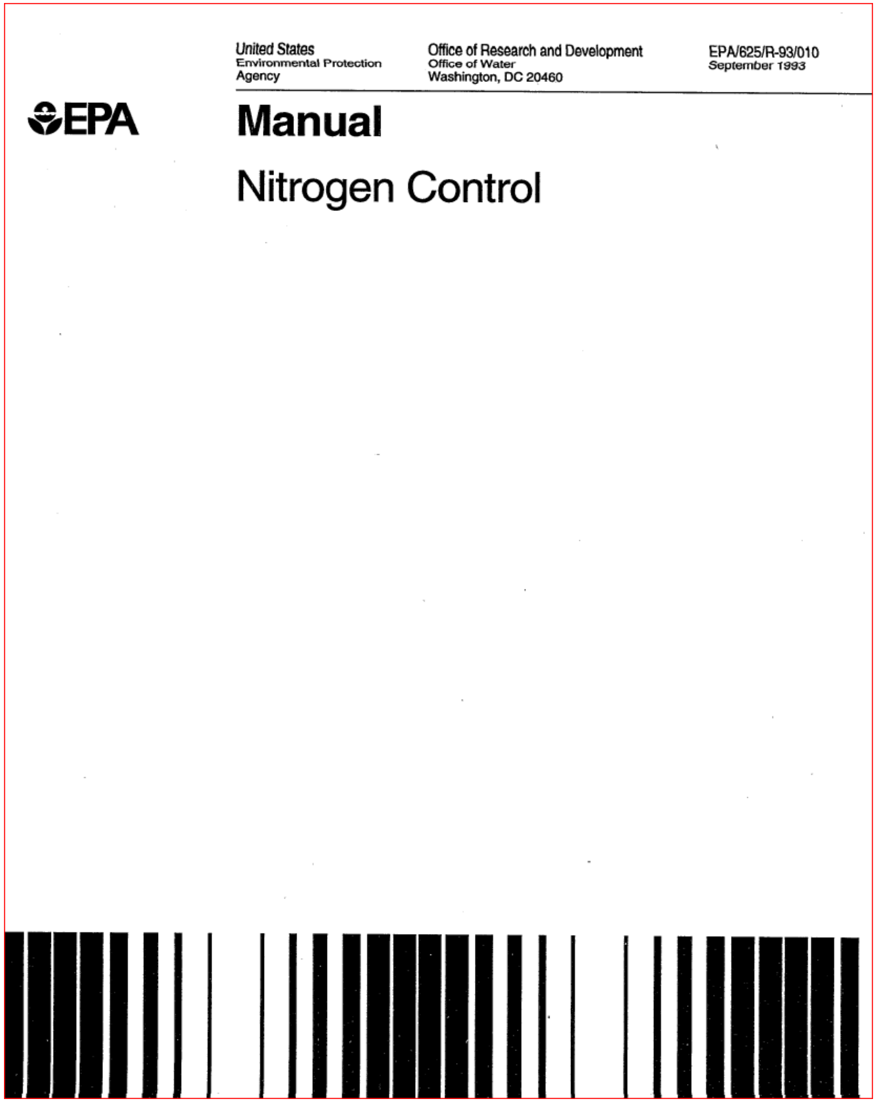
Composition of wastewater

Literature



THEORY AND PRACTICE OF WATER AND WASTEWATER TREATMENT

RONALD L. DROSTE



United States
Environmental Protection
Agency

Office of Research and Development
Office of Water
Washington, DC 20460

EPA/625/R-93/010
September 1993

EPA

Manual

Nitrogen Control

Literature

European Commission

JRC SCIENCE FOR POLICY REPORT

Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector

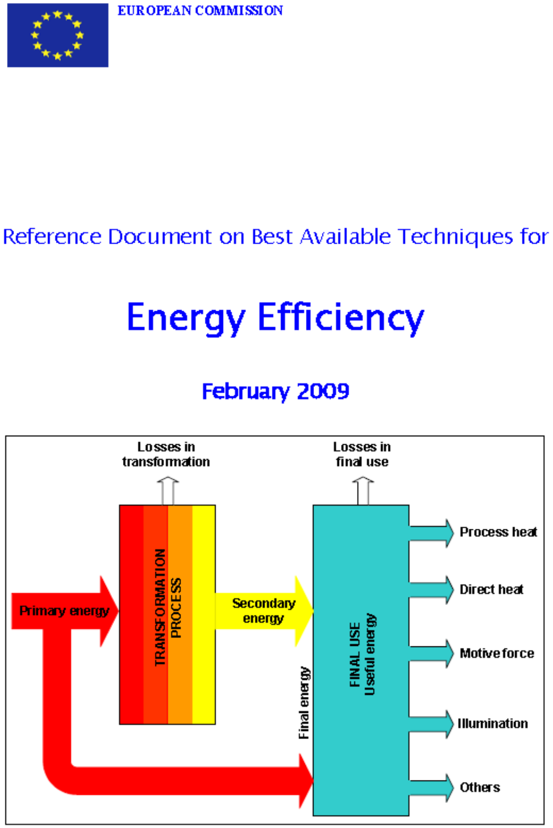
Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)

Thomas Brinkmann, Germán Giner Santonja,
Hande Yükseler, Serge Roudier,
Luis Delgado Sancho

2016

Joint Research Centre

EUR 28112 EN



EUROPEAN COMMISSION

Reference Document on Best Available Techniques for

Energy Efficiency

February 2009

Links to documents of all branches (for free) under

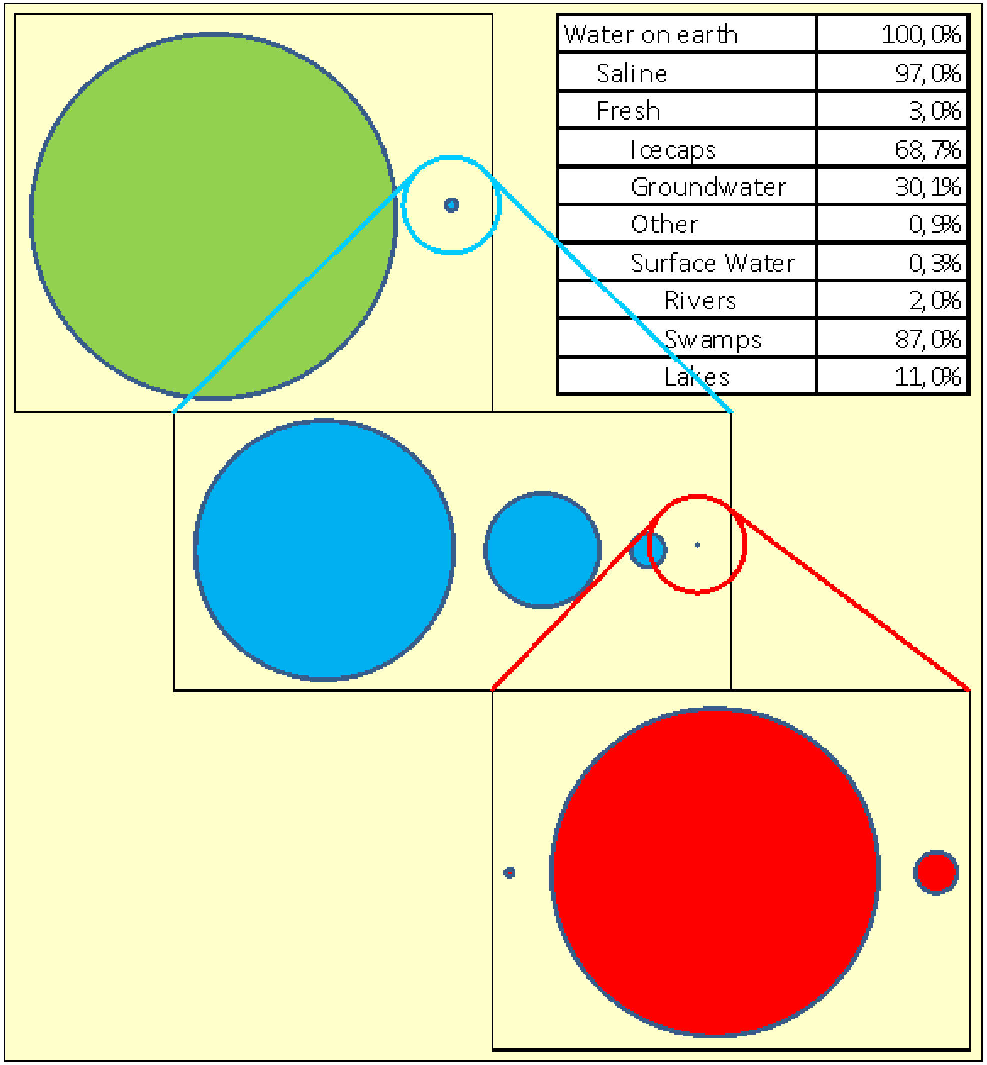
http://eippcb.jrc.ec.europa.eu/reference/

Grading

Activities	Percentages
Final Exam	50%
Midterm Exam	30%
Quizzes-Seminars	15%
Assignments	5%

Further details will be reported as soon as possible.

Water on earth…



Water on earth	100,0%
Saline	97,0%
Fresh	3,0%
Icecaps	68,7%
Groundwater	30,1%
Other	0,9%
Surface Water	0,3%
Rivers	2,0%
Swamps	87,0%
Lakes	11,0%

Total share of fresh water…	
Groundwater	0,9030%
Lakes	0,0010%
Rivers	0,0002%

…and vulnerability and rehabilitation time of the most important fresh water bodies (drastically simplified)

	Shielded?	**Rehabilitation time in case of pollution**
Groundwater	By soil	very long
Lakes	No	long
Rivers	No	short

Why wastewater treatment?

Many purposes for a body of water:

- water supply for drinking,
- water supply for industrial and commercial purposes,
- irrigation,
- fishing,
- swimming, recreation, etc.

All need good and clear water!

Discharge of untreated wastewater devalues water bodies.

Expenditure for water supply will raise sharply, diseases may occur and so on.

Otherwise, wastewater treatment eliminates pollutants before they can be discharged into the water. Thus, the **self-cleaning power** of the waters is secured at a high level.

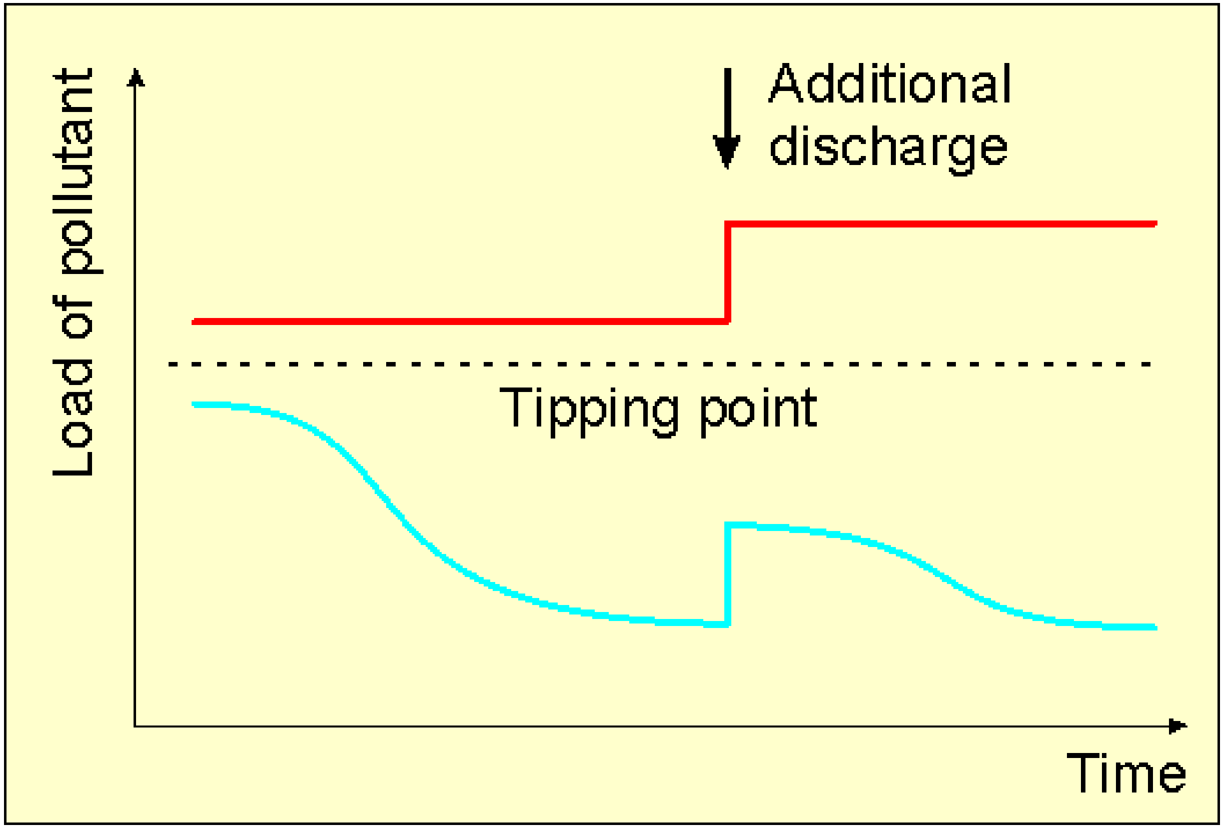
Why wastewater treatment?

Proper wastewater treatment leads to a situation, where all uses of water can be realized without extensive pretreatment.

In addition, because it is much more simpler to remove pollutants in high than in lower concentration, the removal of pollutants before discharge into a body of water is always much more economical than the removal of pollutants from raw water, which was taken from a contaminated water body. For instance: Organic pollutants don't have been eliminated by a WWTP close to the source but were discharged into the water body. Than one needs a lot of treatment steps including granulated active coal in order to win potable water downstream.

Self-cleaning power and tipping points

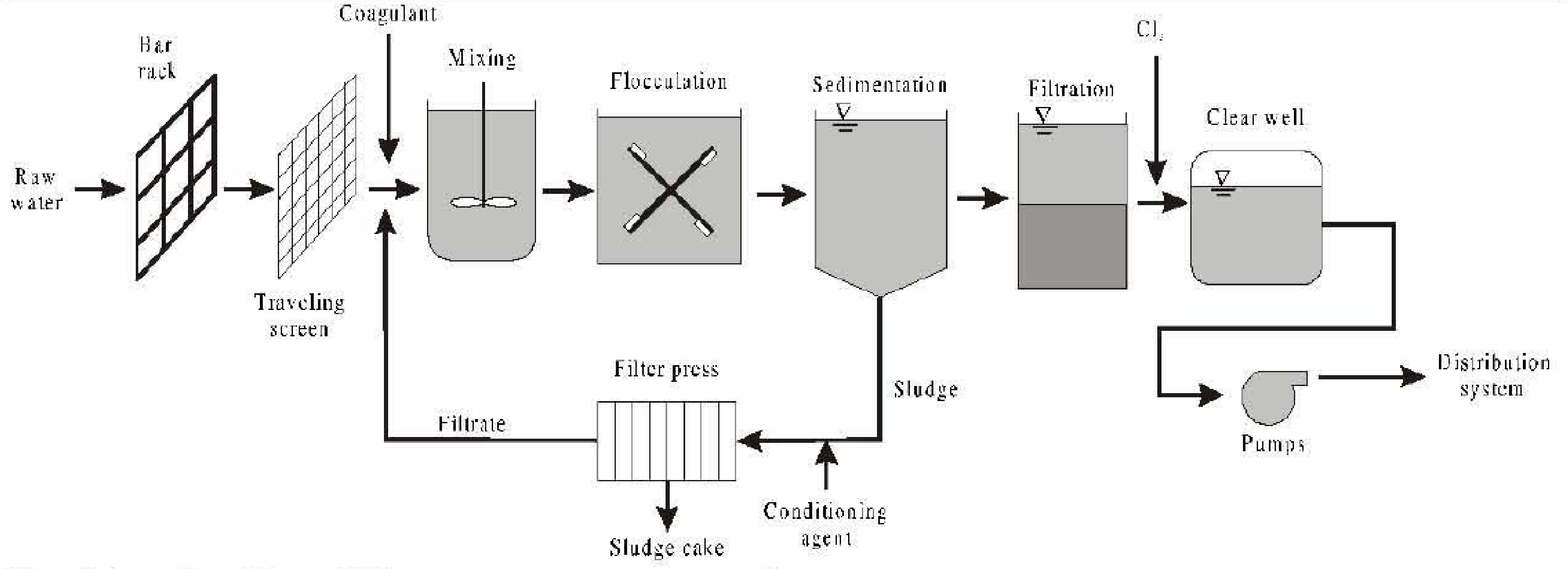
The self-cleaning power of the waters is a free service of nature. Unfortunately, it does not work if the tipping point of pollution has been exceeded.



Turning point of pollution exceeded, water quality deteriorates!

Load below turning point of pollution, additional loads can be absorbed because of self-cleaning without deterioration of water quality!

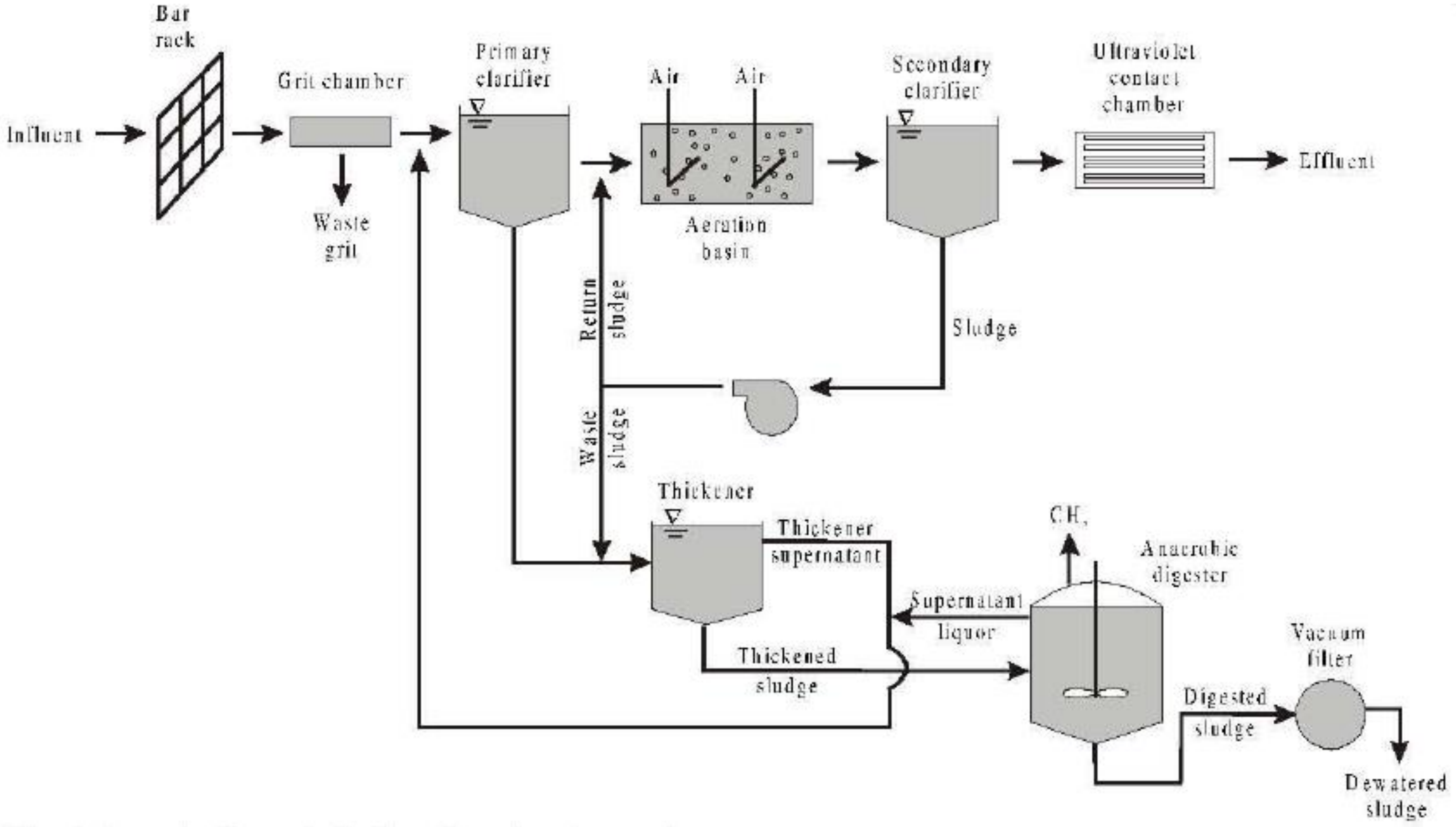
Water and wastewater treatment operations



Rapid sand filtration water treatment plant

from DROSTE, 1997, p. 215

Water and wastewater treatment operations



Activated sludge plant for domestic wastewater treatment

from DROSTE, 1997, p. 222

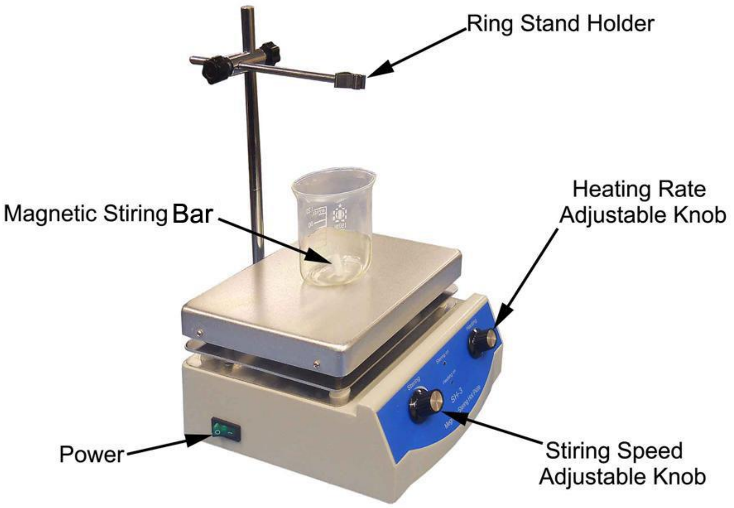
Polluting substances in communal wastewater

In order to design the unit operations for wastewater treatment properly we have to know what kind of pollutants we face.

- Leftovers (meat, fish, edible fat, cooking oil, vegetables and so on),
- feces (excrements), urine,
- bacteria, viruses,
- protein, sugar, salt,
- sand, gravel, silt, clay,
- pieces of wood,
- plastics, paper,
- cosmetics,
- drug ingredients and so on

Lab analysis of communal wastewater

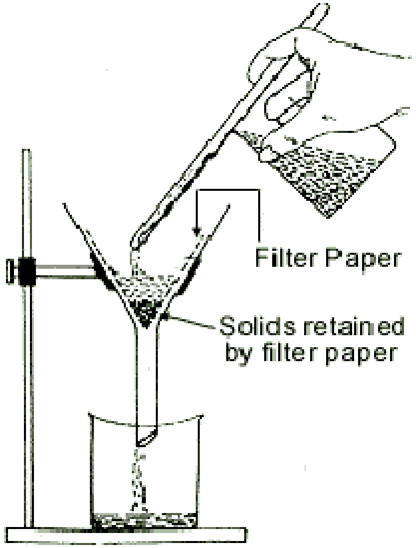
1. Step: Examination of the homogenized sample



The sample with all substances in it will be mixed.
Even swimming substances like oil or solids like pieces of meat or wood are homogenized.
The homogenized sample will be examined for BOD, COD, and so on.

Lab analysis of communal wastewater

2. Step: Separation of suspended solids



Filtrate

International convention between all water and wastewater specialists: Suspended Solids are, what is retained by filter paper with pores of 45 µm.

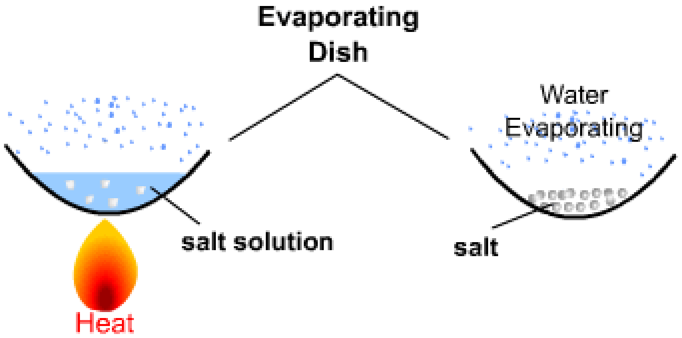
Lab analysis of communal wastewater

3. Step: Further investigation of the filtrate (liquid phase)

The liquid phase of the sample will be examined for BOD, COD, and so on.

4. Step: The filtrate will be evaporated in a lab oven at a temperature of a little more than 100°C.

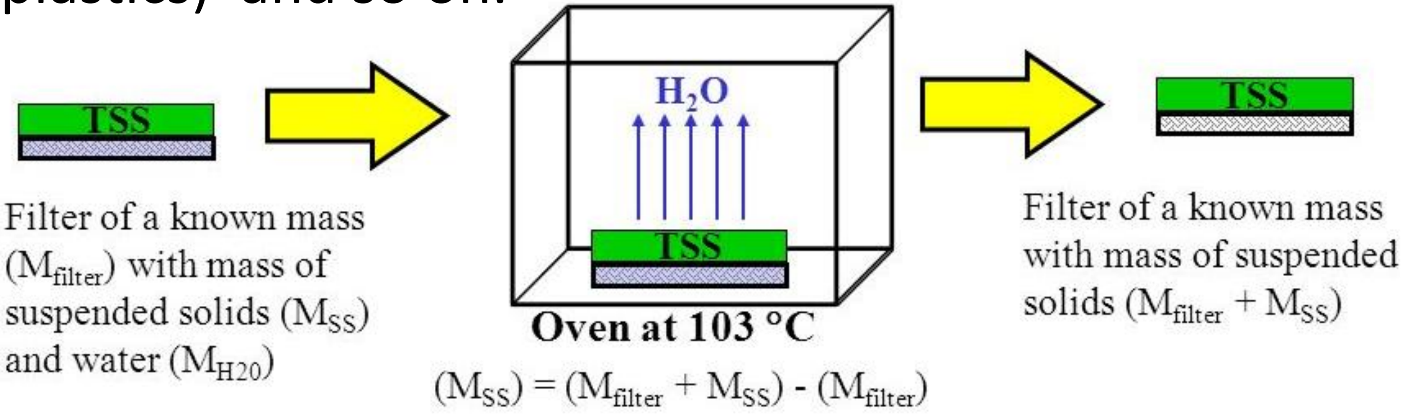
What remains is the so called **Total Dissolved Solids** (TDS). These includes particularly all kind of salt (and sometimes possibly sugar).



Lab analysis of communal wastewater

5. Step: Further investigation of the suspended solids

a. The solid phase of the sample of step 2 will be evaporated at about 100°C in a lab oven. What remains after evaporation will be weighed. This mass are the so called **Total Suspended Solids** (TSS). They consist of sand, gravel, as well as organic particles like pieces of wood, vegetables, meat, carbonaceous compounds (eg. plastics) and so on.



Filter of a known mass (M_{filter}) with mass of suspended solids (M_{SS}) and water (M_{H20})

Oven at 103 °C

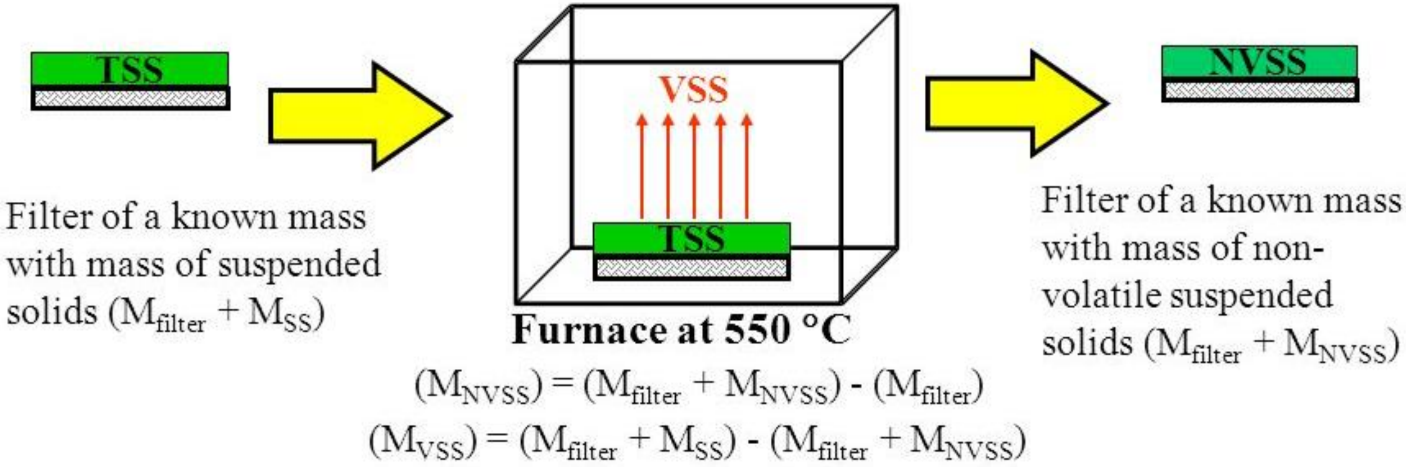
$(M_{SS}) = (M_{filter} + M_{SS}) - (M_{filter})$

Filter of a known mass with mass of suspended solids ($M_{filter} + M_{SS}$)

Lab analysis of communal wastewater

5. Step: Further investigation of the suspended solids

   b. After weighing the TSS they will be burned in a lab oven at about 550°C. All organics burn down. What remains are the so called **Non-Volatile Suspended Solids** (NVSS). They include only inert material like sand or gravel.



Filter of a known mass with mass of suspended solids ($M_{filter} + M_{SS}$)

Furnace at 550 °C

$(M_{NVSS}) = (M_{filter} + M_{NVSS}) - (M_{filter})$

$(M_{VSS}) = (M_{filter} + M_{SS}) - (M_{filter} + M_{NVSS})$

Filter of a known mass with mass of non-volatile suspended solids ($M_{filter} + M_{NVSS}$)

Lab analysis of communal wastewater

5. Step: Further investigation of the suspended solids

c. Last step is the calculation TSS minus NVSS. This must be the **Volatile Suspended Solids** (VSS), which have been burned. They consist of pieces of wood, vegetables, meat, carbonaceous compounds (eg. plastics), algae, proteins, and so on.

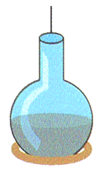
What is organic material?

All substances which include carbon we call organic or carbonaceous.

What is BOD?

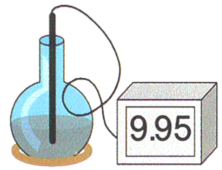
Biological Oxygen Demand in 5 days (BOD_5)

1.



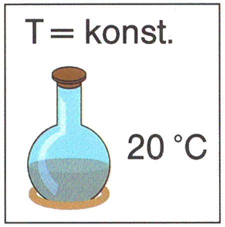
The wastewater sample is mixed with oxygen-rich water.

2.



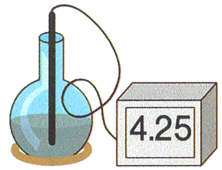
The now present content of dissolved oxygen is measured.

3.



Sample is sealed and stored at 20°C. Bacteria decompose organic ingredients, thereby consume oxygen.

4.



Content of dissolved oxygen is measured again after 5 days. BOD_5 is the Difference to the starting value.

http://www.wasser-wissen.de/abwasserlexikon/b/bsb.htm

Oxidation of NH_4-N is suppressed by addition of allylthiourea.

The picture 2, 3 an 4 are not 100% correct: No air remains after filling with oxygen-rich water . The bottle is filled completely!

Resulting BOD_5 in this example:

$$\mathbf{9,95\,\frac{mg}{l} - 4,25\,\frac{mg}{l} = 5,7\,\frac{mg}{l}}$$

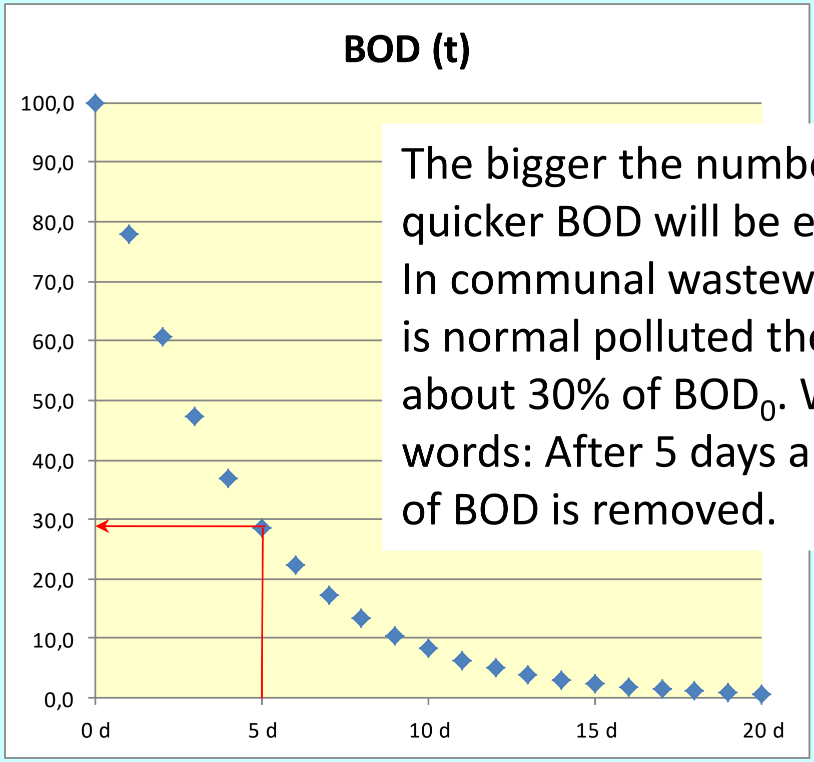
Degradation of BOD @ 20°C (idealized curve)

Starting BOD	**BOD_0**	100,0 mg/l
Degradation coefficient	**k_1**	0,25

first-order reaction:

$$BOD_t = BOD_0 * e^{-k_1 * t}$$

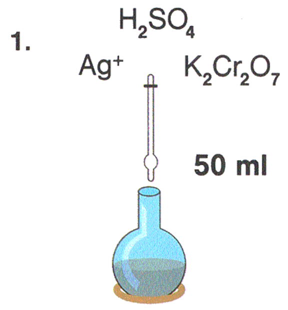
Elapsed Time	**BOD (t)**	
0 d	100,0	
1 d	77,9	
2 d	60,7	
3 d	47,2	
4 d	36,8	
5 d	28,7	**BOD_5**
6 d	22,3	
7 d	17,4	
8 d	13,5	
9 d	10,5	
10 d	8,2	
11 d	6,4	
12 d	5,0	
13 d	3,9	
14 d	3,0	
15 d	2,4	
16 d	1,8	
17 d	1,4	
18 d	1,1	
19 d	0,9	
20 d	0,7	**BOD_{20}**



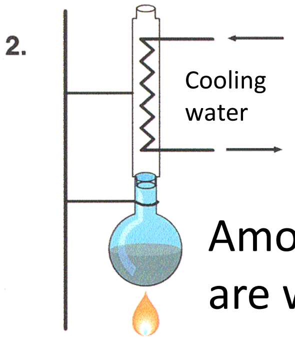
The bigger the number of k_1, the quicker BOD will be eliminated. In communal wastewater which is normal polluted the BOD_5 is about 30% of BOD_0. With other words: After 5 days about 70% of BOD is removed.

What is COD?

Chemical Oxygen Demand (COD)

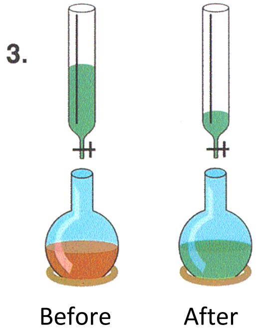


Sulfuric acid, silver ions (as catalyst) and potassium dichromate (oxidizing agent) are added to the water sample.



The sample is boiled for 2 hours at 148°C. Organic material will be oxidized.

Among other things, products are water and carbon dioxide.

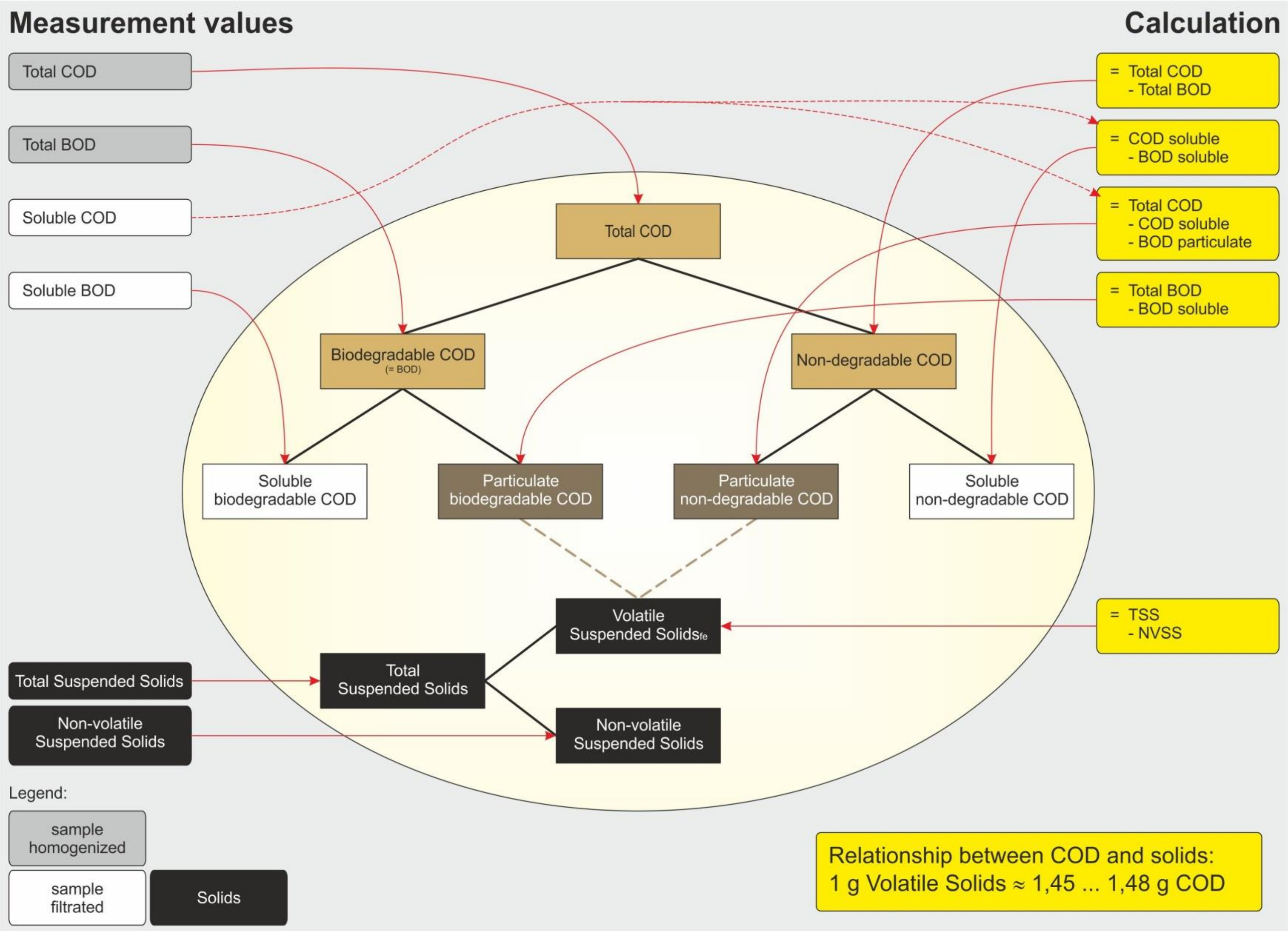


After cooling not consumed oxidizing agent will be measured by titration. The consumed $K_2Cr_2O_7$ can be calculated. The result is the COD, expressed as oxygen demand.

Both shown methods of lab analysis (BOD and COD) describe the old conventional measurements. Nowadays BOD and COD are measured in smarter way by sensor equipment.

COD oxidizes all carbonaceous substances ($K_2Cr_2O_7$ is a strong oxidizing agent). BOD only oxidizes substances, which bacteria are able to consume. BOD reflects the possibility of biological degradation.

Relationship between COD, BOD, and solids



Measurement values

- Total COD
- Total BOD
- Soluble COD
- Soluble BOD
- Total Suspended Solids
- Non-volatile Suspended Solids

Calculation

- = Total COD - Total BOD
- = COD soluble - BOD soluble
- = Total COD - COD soluble - BOD particulate
- = Total BOD - BOD soluble
- = TSS - NVSS

Total COD

Biodegradable COD (= BOD)

Non-degradable COD

Soluble biodegradable COD

Particulate biodegradable COD

Particulate non-degradable COD

Soluble non-degradable COD

Volatile Suspended Solids$_{fe}$

Total Suspended Solids

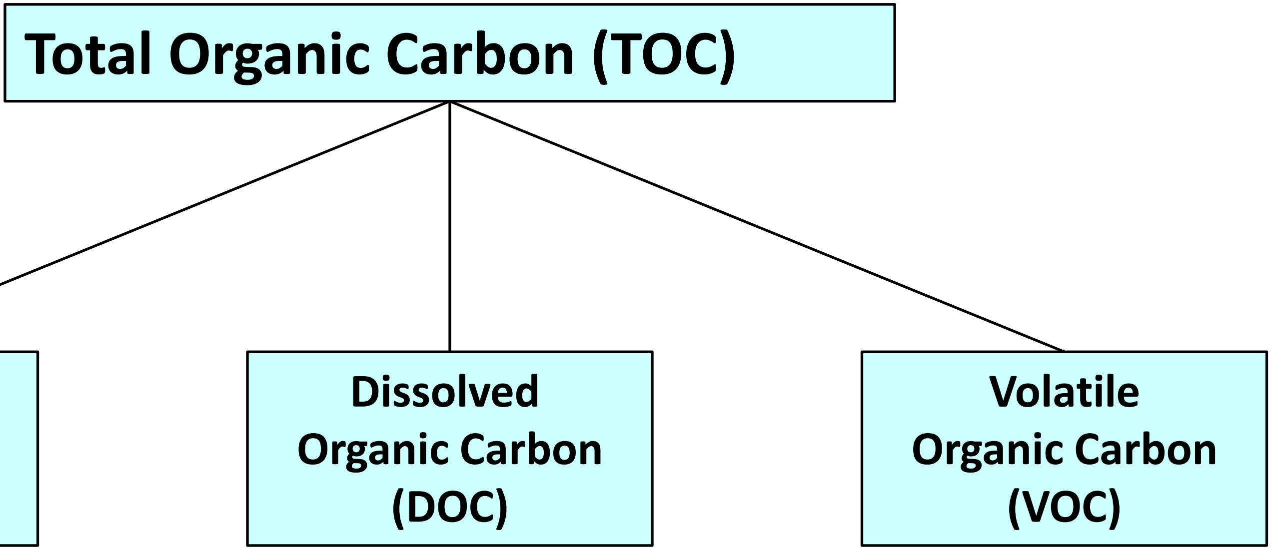
Non-volatile Suspended Solids

Legend:

- sample homogenized
- sample filtrated
- Solids

Relationship between COD and solids:
1 g Volatile Solids ≈ 1,45 ... 1,48 g COD

What is TOC?



Total Organic Carbon (TOC)

Particulate Organic Carbon (POC)

Dissolved Organic Carbon (DOC)

Volatile Organic Carbon (VOC)

Relationship between COD, BOD, and TOC

Basically:

$$BOD \ \leq COD$$

For normally polluted domestic sewage applies :

$$BOD \ \approx 0{,}5 \ldots 0{,}8 * COD$$

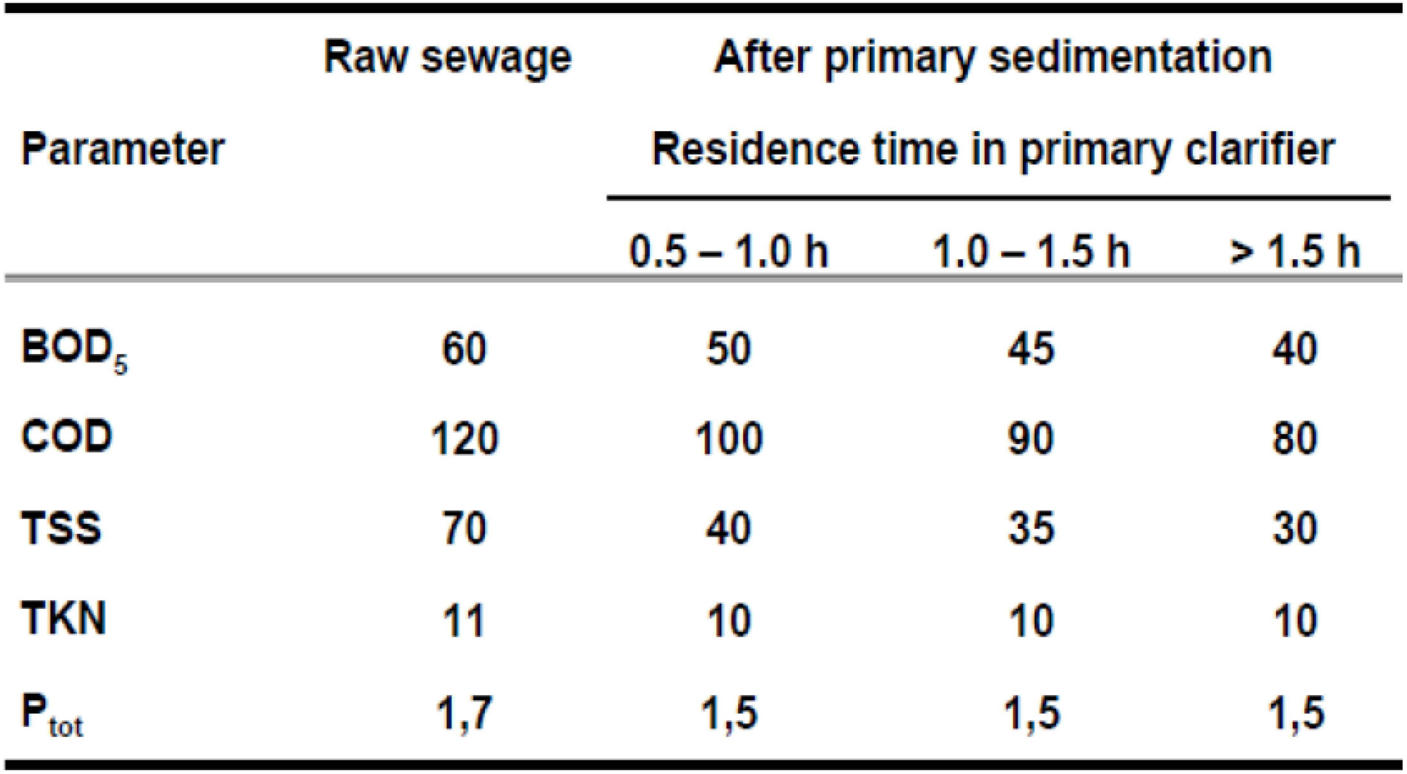
$$COD \ \approx 2 \ldots 5 \ * TOC$$

Domestic Wastewater - averages

Parameter	Population-specific loads in raw sewage	Literature
BOD_5	60 g/(P*d)	ATV-DVWK-A 131
COD	120 g/(P*d)	ATV-DVWK-A 131
TOC	40 g/(P*d)	LONDONG, 2009
TSS	70 g/(P*d)	ATV-DVWK-A 131
TKN	11 g/(P*d)	ATV-DVWK-A 131
NH_4-N	8 g/(P*d)	HABERKERN et al., 2008
P	2 g/(P*d)	ATV-DVWK-A 131

Population-specific loads that fall below 85% of the days (for normally polluted domestic sewage)

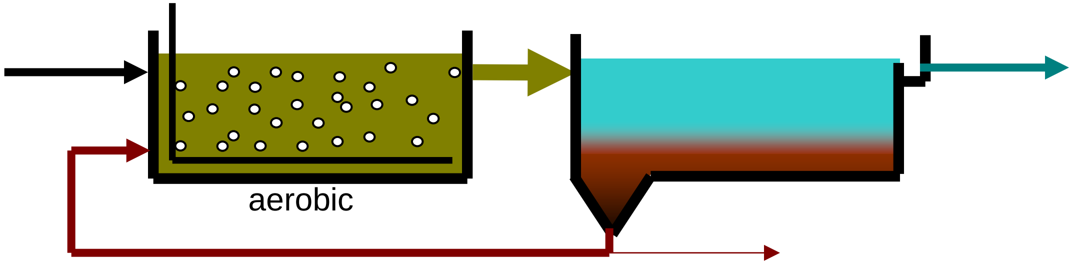
Population Equivalents in g/(Ca·d)



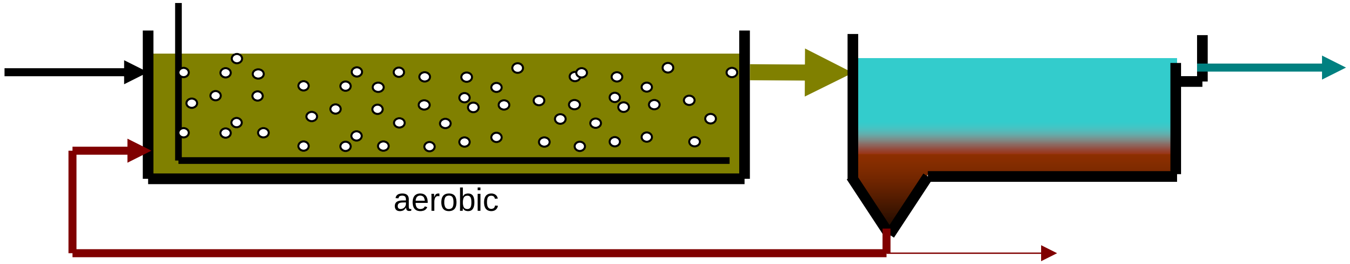
Parameter	Raw sewage	After primary sedimentation		
		Residence time in primary clarifier		
		0.5 – 1.0 h	1.0 – 1.5 h	> 1.5 h
BOD_5	60	50	45	40
COD	120	100	90	80
TSS	70	40	35	30
TKN	11	10	10	10
P_{tot}	1,7	1,5	1,5	1,5

Development of activated sludge process

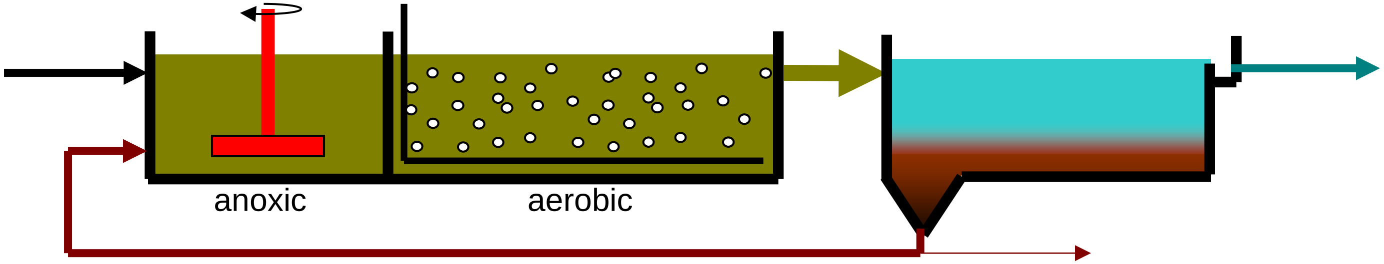
Removal of organic compounds
(carbonecous substances)



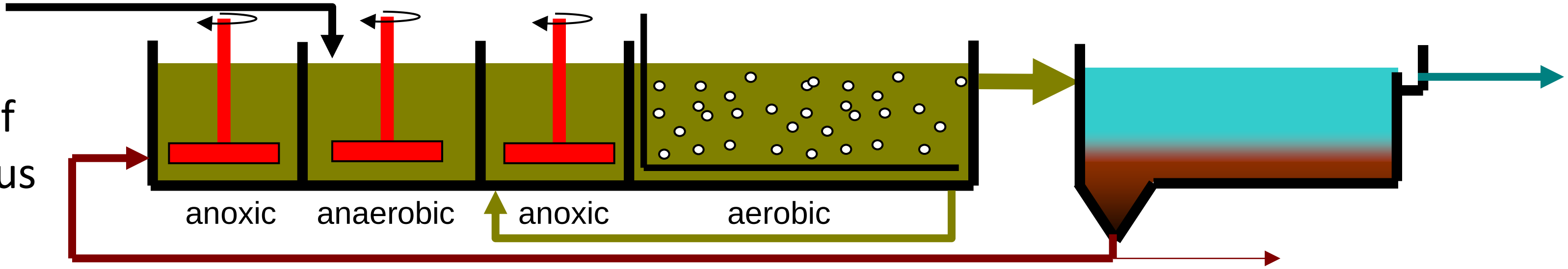
+ Nitrification



+ Denitrification



+ Biological
removal of
phosphorus



Some important terms

Mass Concentration

Concentration is often expressed in terms of parts per million parts (ppm) or mg/L. Sometimes parts per thousand (ppt) or parts per billion (ppb) are also used. The concentration of solute X in solvent Y in ppm is

$$ppm = \frac{mass\ of\ substance}{mass\ of\ solution}$$

$$x\ ppm = \frac{x\ g\ of\ X}{10^6\ g\ of\ (Y+X)}$$

DROSTE, 1997 - S. 4

Because 1 kg of solution with water as the solvent has a volume of approximately 1 liter,

$$1\ ppt \approx 1\ \frac{g}{l}$$

$$1\ ppm \approx 1\ \frac{mg}{l}$$

$$1\ ppb \approx 1\ \frac{\mu g}{l}$$

$$1\ \frac{mg}{l} = \frac{mg}{l} * \frac{1\ g}{1\,000\ mg} * \frac{1\,000\ l}{m^3} = 1\ \frac{g}{m^3}$$

$l - litre\ /\ L - load$

Some important terms

Volumetric flow rate

$$\boxed{Q\ in\ \frac{m^3}{h} = v * \frac{3\,600\ s}{h} * A}$$

v – Velocity in $\frac{m}{s}$

A – Cross-sectional area in m^2

Hydraulic Loading Rate (HLR)

$$\boxed{HLR\ in\ \frac{m}{h}\left[or\ in\ \frac{m^3}{m^2 * h}\right] = \frac{Q}{A}}$$

Q – Volumetric flow rate in $\frac{m^3}{h}$

A – Cross-sectional area of a reactor in m^2

Load (mass flow)

$$\boxed{L\ in\ \frac{kg}{h} = Q * C * \frac{kg}{1\,000\,000\ mg} * \frac{1\,000\ l}{m^3}}$$

Q – Volumetric flow rate in $\frac{m^3}{h}$

C – Concentration in $\frac{mg}{l}$

Some important terms

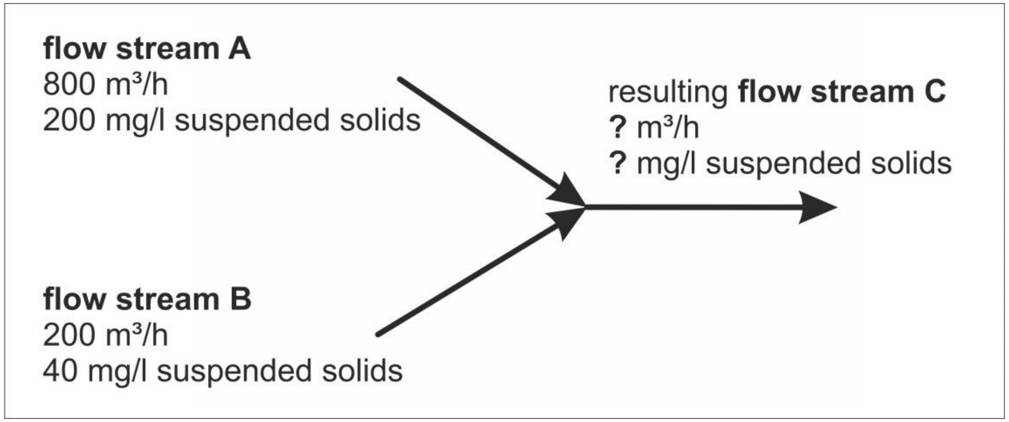
Hydraulic Retention Time (HRT)

$$\boxed{HRT\ in\ h = \frac{V}{Q}}$$

V – Volume of the reactor in m^3

Q – Volumetric flow rate in $\frac{m^3}{h}$

Mixing of two streams (example by suspended solids)



flow stream A
800 m³/h
200 mg/l suspended solids

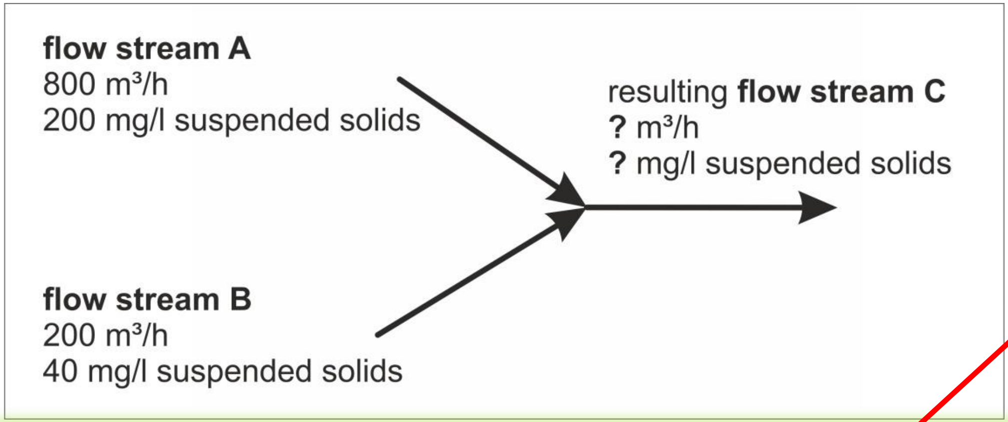
resulting **flow stream C**
? m³/h
? mg/l suspended solids

flow stream B
200 m³/h
40 mg/l suspended solids

$$\boxed{flow_{\,stream\ C} = flow_{\,stream\ A} + flow_{\,stream\ B}}$$

Some important terms

Mixing of two streams (example by suspended solids)



flow stream A
800 m³/h
200 mg/l suspended solids

resulting **flow stream C**
? m³/h
? mg/l suspended solids

flow stream B
200 m³/h
40 mg/l suspended solids

$$1\,\frac{mg}{l} = 1\,\frac{g}{m^3}$$

$$(see\ Slides\ before)$$

$$solids_{\,stream\,C} = \frac{flow_{\,stream\,A} * solids_{\,stream\,A} + flow_{\,stream\,B} * solids_{\,stream\,B}}{flow_{\,stream\,A} + flow_{\,stream\,B}}$$

$$solids_{\,stream\,C} = \frac{800\,\frac{m^3}{h} * 200\,\frac{g}{m^3} + 200\,\frac{m^3}{h} * 40\,\frac{g}{m^3}}{(800+200)\,\frac{m^3}{h}} = \frac{(160\,000 + 8\,000)\,\frac{g}{h}}{1\,000\,\frac{m^3}{h}}$$

$$solids_{\,stream\,C} = 168\,\frac{mg}{l}$$

Have a good time in mad Berlin!

2nd Lecture

Sewage composition and flow

Types of kinetics and reactors

Mechanical wastewater treatment

Short repetition

Question emerged after last lecture: What is the difference between Hydraulic Retention Time (HRT) and Hydraulic Loading Rate (HLR)???

Hydraulic Loading Rate (HLR)

$$\boxed{HLR\ in\ \frac{m}{h}\left[or\ in\ \frac{m^3}{m^2 * h}\right] = \frac{Q}{A}}$$

Q – Volumetric flow rate in $\frac{m^3}{h}$

A – Cross-sectional area of a reactor in m^2

basically a **speed**

Hydraulic Retention Time (HRT)

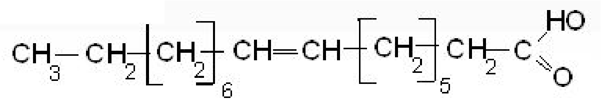
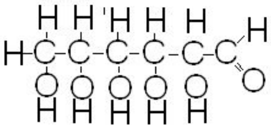
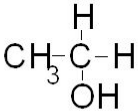
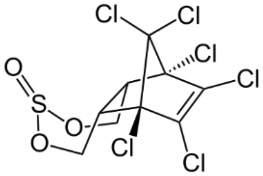
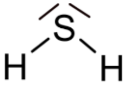
$$\boxed{HRT\ in\ h = \frac{V}{Q}}$$

V – Volume of the reactor in m^3

Q – Volumetric flow rate in $\frac{m^3}{h}$

basically a **time indication**

Correlation between BOD, COD and TOC

Substance	Chemical structure	BOD	COD	TOC
fat	 $CH_3-CH_2-[CH_2]_6-CH=CH-[CH_2]_5-CH_2-C(=O)OH$	✓	✓	✓
sugar		✓	✓	✓
alcohol (here: ethanol)		✓	✓	✓
pesticide (here: endosulfan)	 $C_9H_6Cl_6O_3S$	✗	✓	✓
sulfide (here: hydrogen sulfide)		✗	✓	✗

The detectability of substances by BOD is a yardstick of their biological degradability!

Theoretical COD

How much is the COD of a solution of 200 mg sugar ($C_6H_{12}O_6$) in 1 l water?

Hints to the oxidation reaction:

C is always oxidized to CO_2, usually the reaction also creates water.

The number of atoms must be identical for each element on both sides of the reaction equation.

Oxidation reaction:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

Atom weights: C = 12, H = 1, O = 16

Molecule weight of sugar:

$$\boxed{6 \cdot 12 + 12 \cdot 1 + 6 \cdot 16 = 180\ g\ \text{sugar}}$$

In other words: 1 Mole sugar weighs 180 g

Oxygen demand for oxidation of 1 Mole sugar:

$$\boxed{6 \cdot 2 \cdot 16 = 192\ g\ oxygen}$$

In other words: It needs 192 g O_2 to oxidize 1 Mole of sugar.

See GUJER, 2007

Theoretical COD

COD of the solution:

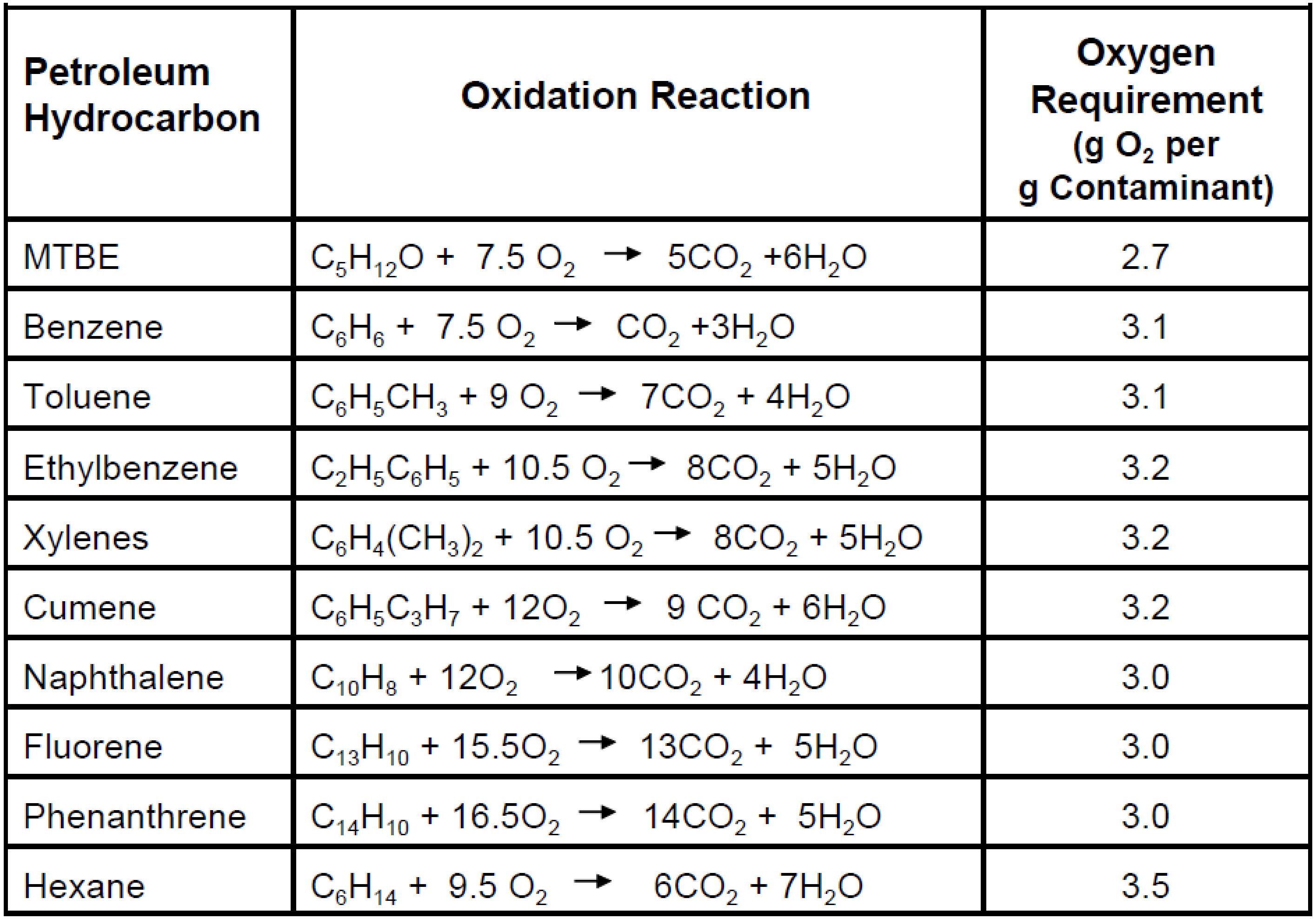
$$\frac{192\ \dfrac{g\ COD}{Mol\ sugar}}{180\ \dfrac{g\ sugar}{Mol\ sugar}} * 200\ \frac{g\ sugar}{m^3}$$

$$= \frac{192\ g\ COD}{\cancel{Mol\ sugar}} * \frac{\cancel{Mol\ sugar}}{180\ \cancel{g\ sugar}} * \frac{200\ \cancel{g\ sugar}}{m^3}$$

$$= 213\ \frac{g\ COD}{m^3} = \mathbf{213\ \frac{mg\ COD}{l}}$$

See GUJER, 2007

Chemical Oxidation of some hydrocarbons

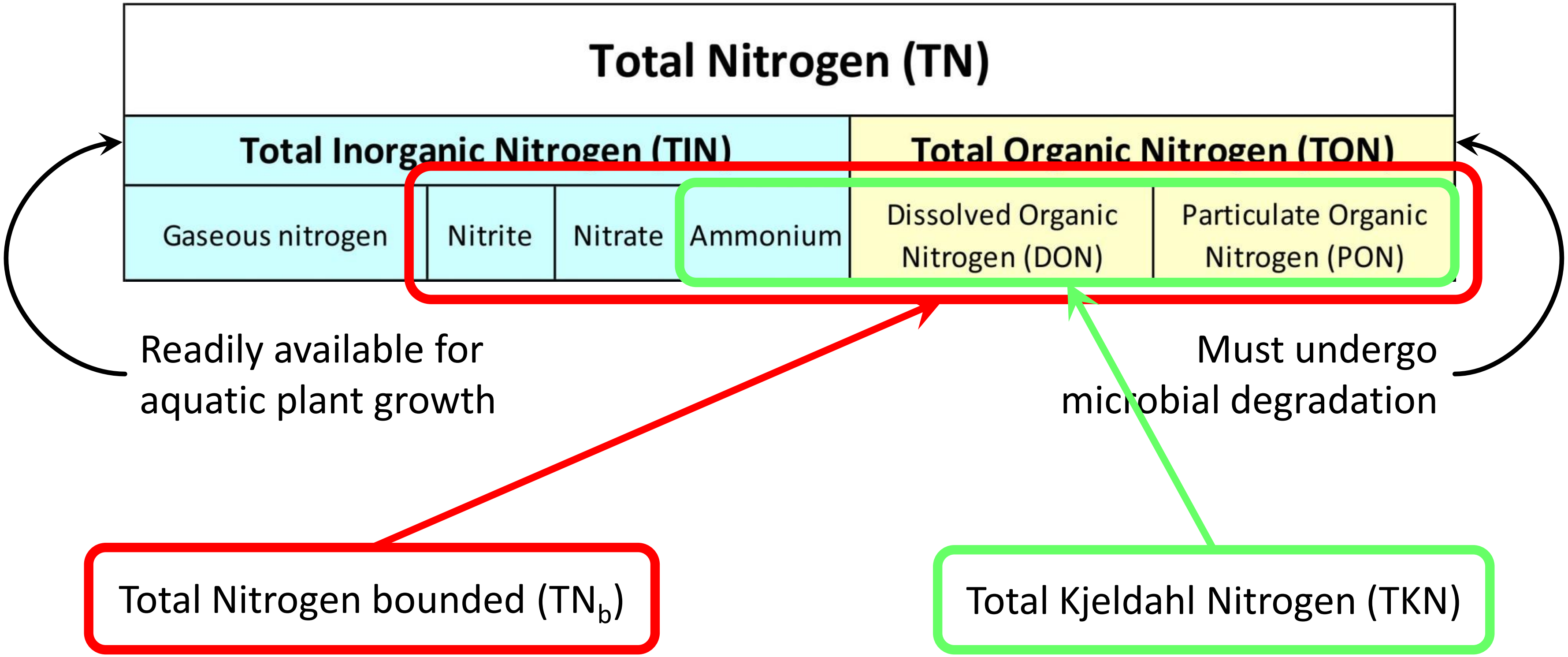


Petroleum Hydrocarbon	**Oxidation Reaction**	**Oxygen Requirement ($g\ O_2$ per g Contaminant)**
MTBE	$C_5H_{12}O + 7.5\ O_2 \rightarrow 5CO_2 + 6H_2O$	2.7
Benzene	$C_6H_6 + 7.5\ O_2 \rightarrow CO_2 + 3H_2O$	3.1
Toluene	$C_6H_5CH_3 + 9\ O_2 \rightarrow 7CO_2 + 4H_2O$	3.1
Ethylbenzene	$C_2H_5C_6H_5 + 10.5\ O_2 \rightarrow 8CO_2 + 5H_2O$	3.2
Xylenes	$C_6H_4(CH_3)_2 + 10.5\ O_2 \rightarrow 8CO_2 + 5H_2O$	3.2
Cumene	$C_6H_5C_3H_7 + 12O_2 \rightarrow 9\ CO_2 + 6H_2O$	3.2
Naphthalene	$C_{10}H_8 + 12O_2 \rightarrow 10CO_2 + 4H_2O$	3.0
Fluorene	$C_{13}H_{10} + 15.5O_2 \rightarrow 13CO_2 + 5H_2O$	3.0
Phenanthrene	$C_{14}H_{10} + 16.5O_2 \rightarrow 14CO_2 + 5H_2O$	3.0
Hexane	$C_6H_{14} + 9.5\ O_2 \rightarrow 6CO_2 + 7H_2O$	3.5

Oxygen demand for chemical oxidation of some hydrocarbon compounds

from US EPA, 2004

Fractions of nitrogen in water / wastewater



Total Nitrogen (TN)

Total Inorganic Nitrogen (TIN)

Total Organic Nitrogen (TON)

Gaseous nitrogen

Nitrite

Nitrate

Ammonium

Dissolved Organic Nitrogen (DON)

Particulate Organic Nitrogen (PON)

Readily available for aquatic plant growth

Must undergo microbial degradation

Total Nitrogen bounded (TN_b)

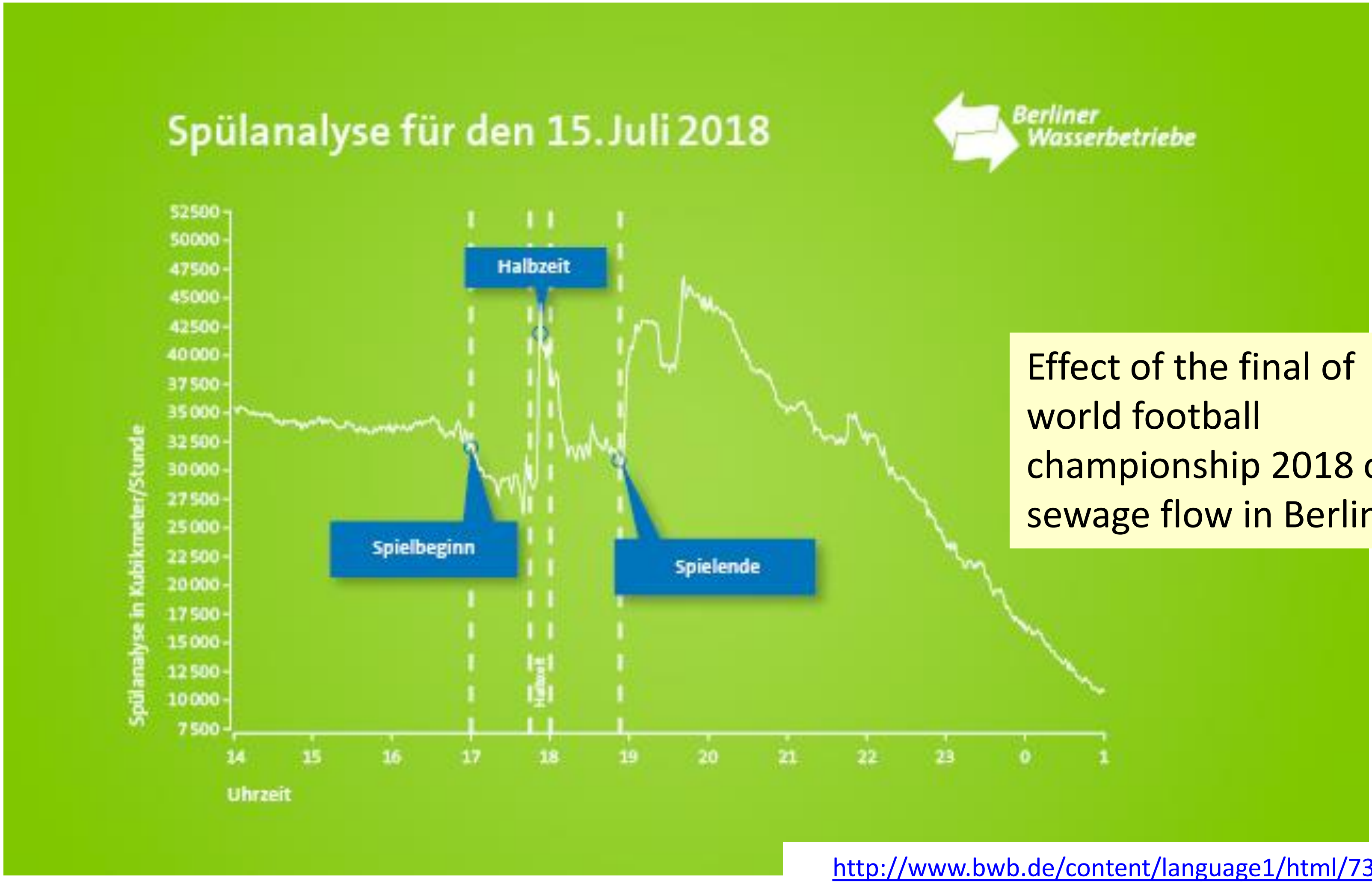
Total Kjeldahl Nitrogen (TKN)

Sewage flow

Every city and every village has it own specifics – in wastewater composition as well as in the discharge modes. Therefore measurement is needed before planning sewer systems or WWTPs! However, there are some rules of thumb which maybe helpful.

- The flow stream which enters the WWTP depends on the sewer system (separate or combined sewer systems).
- The sewage stream in a community normally follows the withdrawal of drinking water from the public network.
- The consumption of fresh water depends on a lot of factors (e. g. standard of living, pricing)
- There is a distinct course of the day, week, and the course of the year.
  (day – night / working days – Sundays and public holidays / summer – winter)
- We guess, that about 80…85 percent of the fresh water supply becomes wastewater (difference: network losses, drinking water consumption).
- Special events may influence the flow stream (e. g. final of world football championship)

Sewage flow

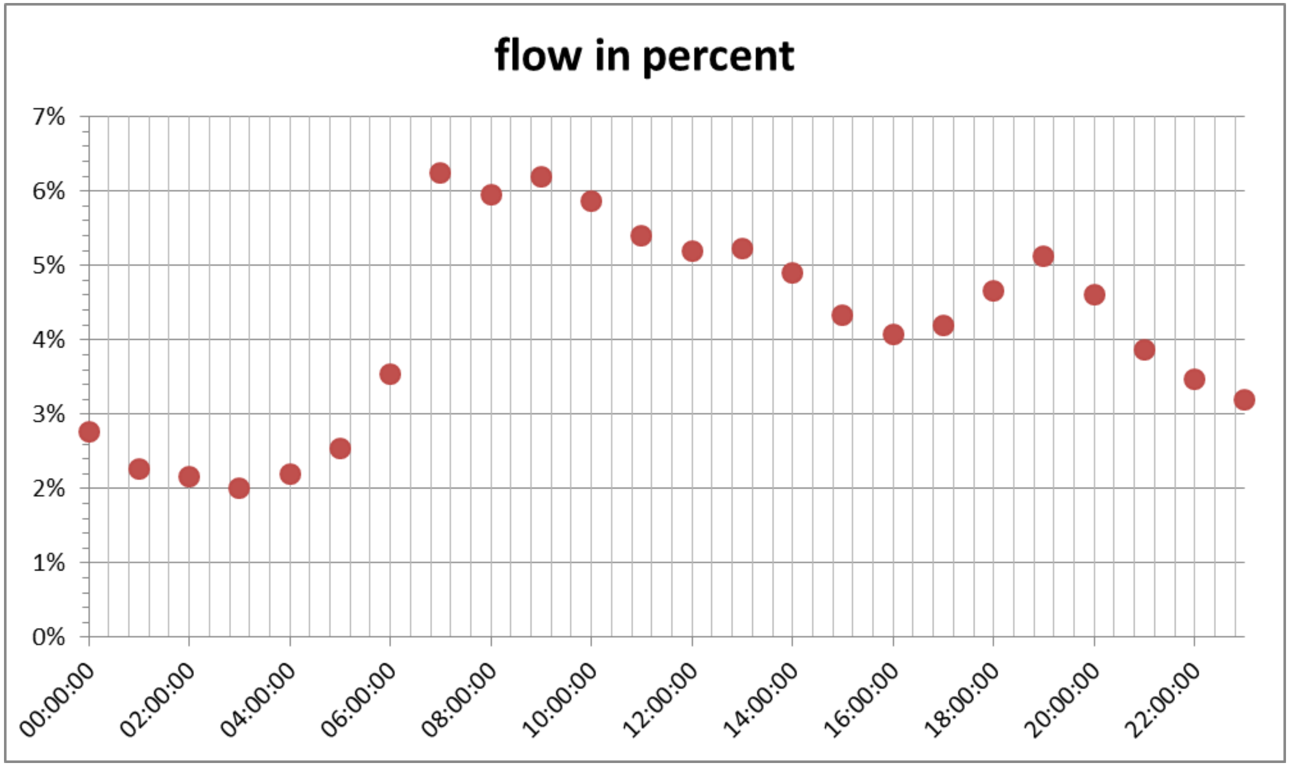


Effect of the final of world football championship 2018 on sewage flow in Berlin

http://www.bwb.de/content/language1/html/7338.php

Sewage flow

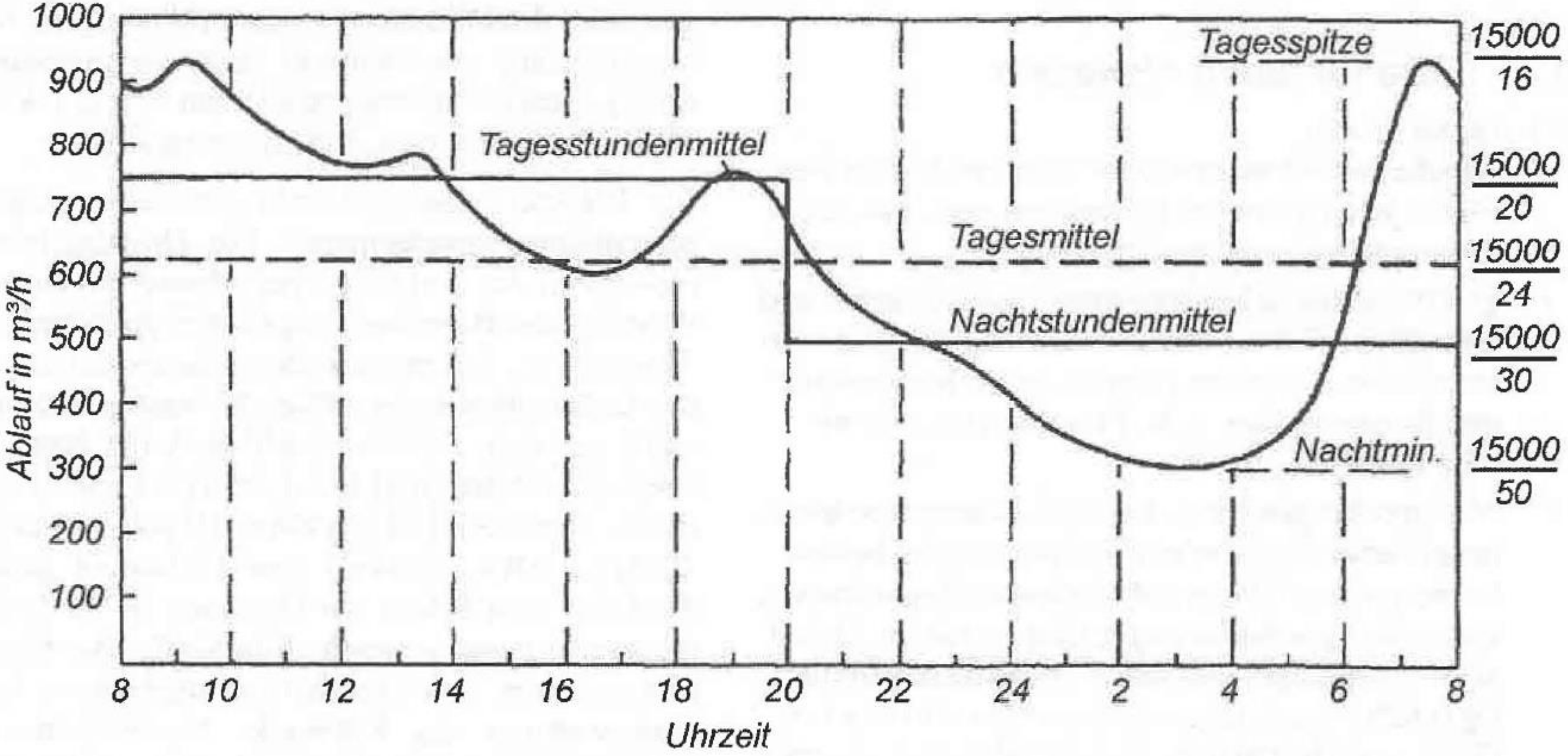
time	flow	flow in percent
00:00:00	415 m^3/h	2,77%
01:00:00	340 m^3/h	2,27%
02:00:00	325 m^3/h	2,17%
03:00:00	300 m^3/h	2,00%
04:00:00	330 m^3/h	2,20%
05:00:00	380 m^3/h	2,53%
06:00:00	530 m^3/h	3,53%
07:00:00	938 m^3/h	6,25%
08:00:00	892 m^3/h	5,95%
09:00:00	930 m^3/h	6,20%
10:00:00	880 m^3/h	5,87%
11:00:00	810 m^3/h	5,40%
12:00:00	780 m^3/h	5,20%
13:00:00	785 m^3/h	5,23%
14:00:00	735 m^3/h	4,90%
15:00:00	650 m^3/h	4,33%
16:00:00	610 m^3/h	4,07%
17:00:00	630 m^3/h	4,20%
18:00:00	700 m^3/h	4,67%
19:00:00	770 m^3/h	5,13%
20:00:00	690 m^3/h	4,60%
21:00:00	580 m^3/h	3,87%
22:00:00	520 m^3/h	3,47%
23:00:00	480 m^3/h	3,20%
Σ	15.000 m^3/h	100,00%
Average	**625 m^3/h**	4,17%
Min	**300 m^3/h**	2,00%
Max	**938 m^3/h**	6,25%



Daily variations in dry weather runoff in a community with a total wastewater volume of 15000 m^3 / d

See e. g. LONDONG et al., 2009

Sewage flow



Diurnal variation of dry weather runoff in a community with a flow of 15000 m³/d

from LONDONG et al., 2009

Types of kinetics / Orders of differential equations in environmental engineering

A general reaction rate model is

$$\boxed{\frac{dC_A}{dt} = \pm k * {C_A}^a * {C_B}^b * \ldots * {C_N}^n}$$

where

k – rate constant in $\frac{1}{d}$
C_A – Concentration of substance A, etc., in $\frac{g}{m^3}$
t – time in d

The exponents in the above equation may have any value (not necessarily an integer). The sum of the exponents gives the order of the reaction. The reaction is of order a with respect to substance A, order b with respect to B and so on. The rate constant applies at the experimental conditions.
If k is positive, the reaction describes production; a negative k describes removal.

see DROSTE, 1997 - S. 15

Types of kinetics / Orders of differential equations in environmental engineering

Zero-Order Formulation:

$$\frac{dC_A}{dt} = \pm k$$

Rate of change of the concentration of substance A is not significantly influenced by other substances present.

First-Order Formulation:

$$\frac{dC_A}{dt} = \pm kC_A$$

This equation is one of the most often used formulations in environmental engineering to fit data from complex reactions. Example: BOD

Second-Order Formulation:

$$\frac{dC_A}{dt} = \pm k{C_A}^2$$

$$\frac{dC_A}{dt} = \pm k{C_B}^2$$

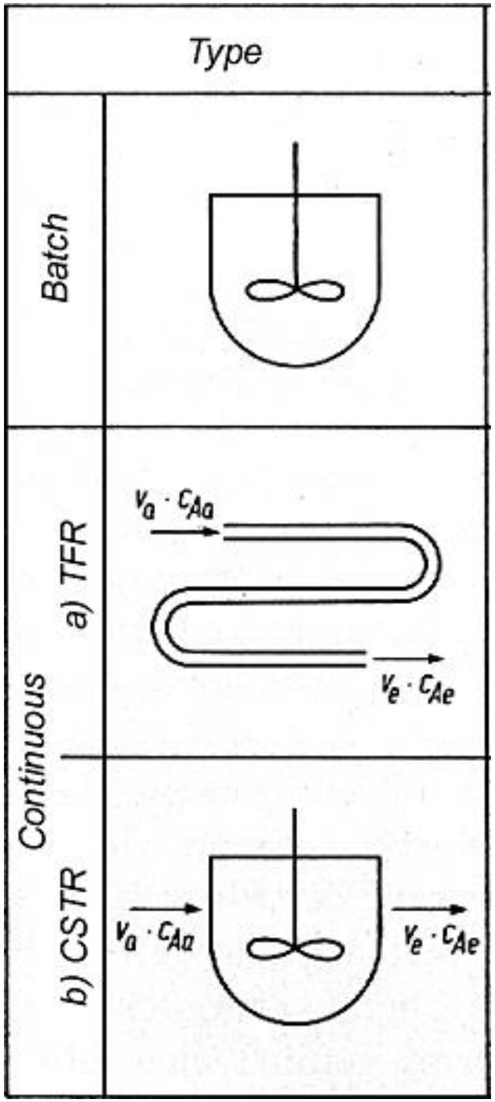
$$\frac{dC_A}{dt} = \pm k{C_A}^a * {C_B}^b$$

(Here $a + b$ must sum to 2)

Any of the these expressions describe second-order reactions.

E. g. see DROSTE, 1997 - S. 16

Basic types of chemical reactors



Batch reactor

Plug-flow-reactor (PF)

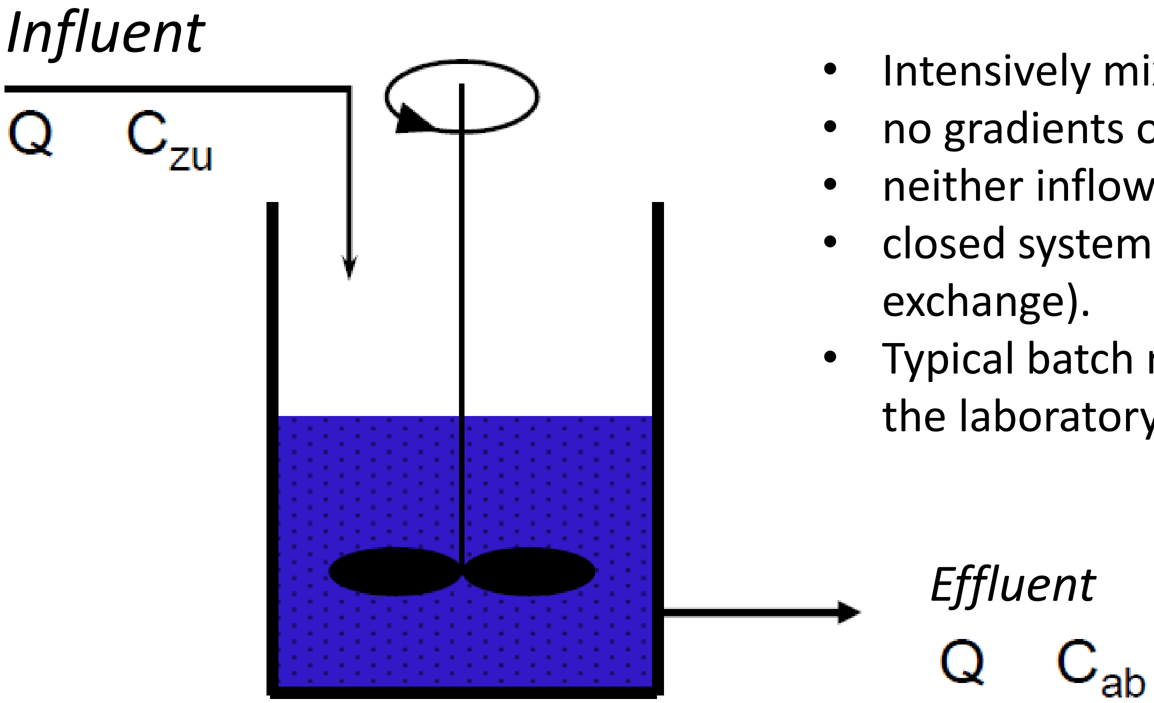
Continuously stirred Tank reactor (CSTR)

All of these types of reactors are used in water treatment as well as in wastewater treatment

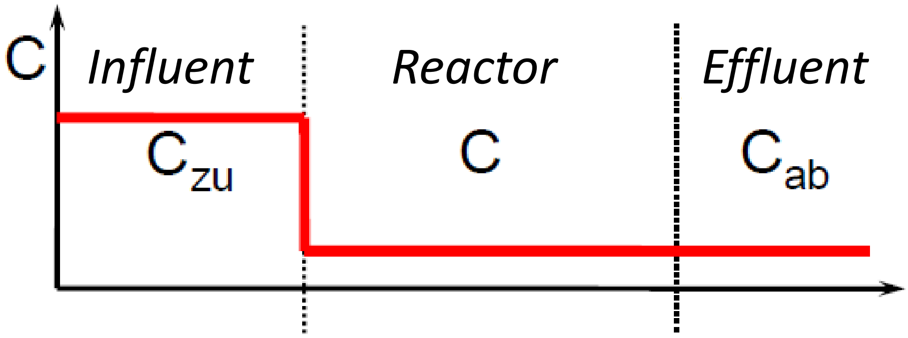
A special type of reactors which is used in wastewater treatment is the Sequencing Batch Reactor (SBR).

http://www.ernst-bratz.de/react_tech/reacteng1.html

Types of reactors in wastewater treatment



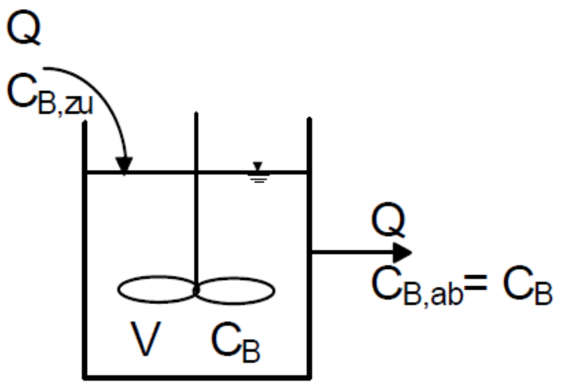
- Intensively mixed reactor volume,
- no gradients of state variables,
- neither inflow nor outflow,
- closed system (exception for gas exchange).
- Typical batch reactors are test tubes in the laboratory.



Batch reactor

From KAINZ & GRUBER, 2011

Types of reactors in wastewater treatment



- Constant, intensively mixed reactor volume,
- no gradients of state variables,
- inflow and outflow are the same,
- no concentration gradients in the reactor,
- the reactor concentration equals the effluent concentration

$$\frac{dM_B}{dt} = \frac{dV \cdot C_B}{dt} + V\frac{dC_B}{dt} = Q \cdot C_{B,zu} - Q \cdot C_B + r_B \cdot V$$

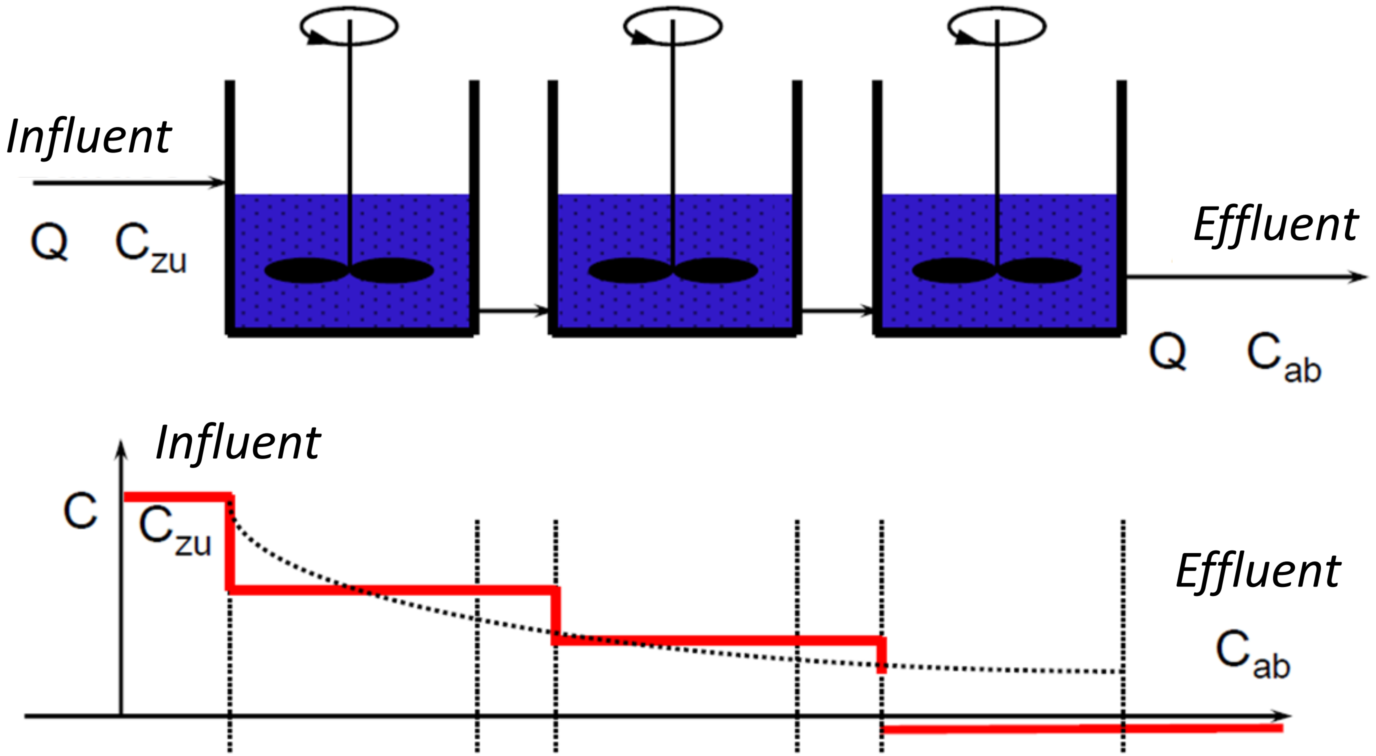
In steady state (dCB/dt = 0), the equation simplifies to:

$$Q \cdot (C_{B,zu} - C_B) = - r_B \cdot V$$

Continuously stirred Tank reactor (CSTR)

From KAINZ & GRUBER, 2011

Types of reactors in wastewater treatment

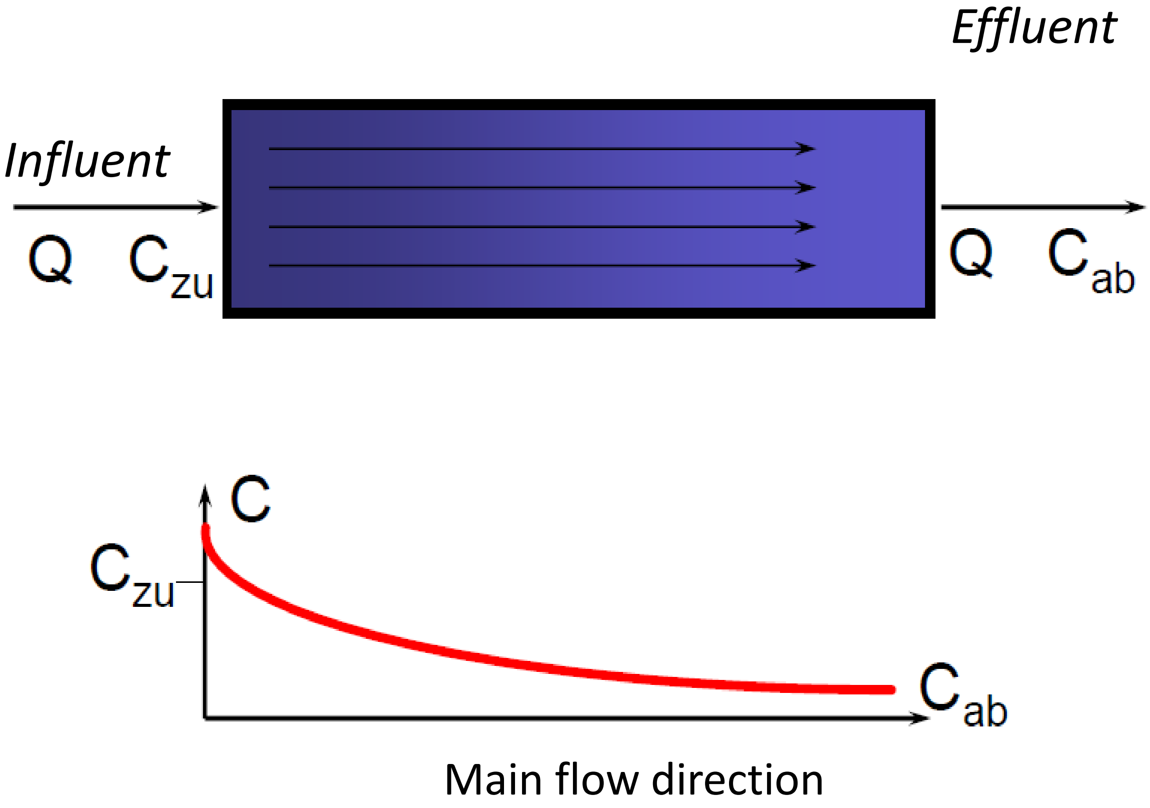


The stirred tank cascade is a series of often identical stirred tanks, i.e. a combined reactor. No water is mixed back from a later to an earlier reactor.

Cascading stirred tank reactors

From KAINZ & GRUBER, 2011

Types of reactors in wastewater treatment

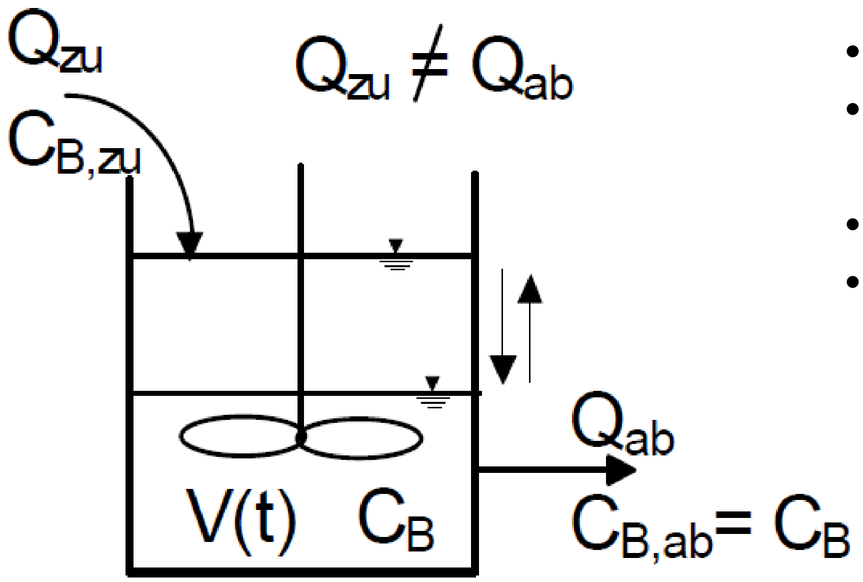


- Constant reactor volume,
- inflow and outflow are the same,
- homogeneous mixing only across the flow direction,
- Gradients of state variables along the main axis possible,
- Concentration gradients in the reactor.

Plug-flow-reactor (PF)

From KAINZ & GRUBER, 2011

Types of reactors in wastewater treatment

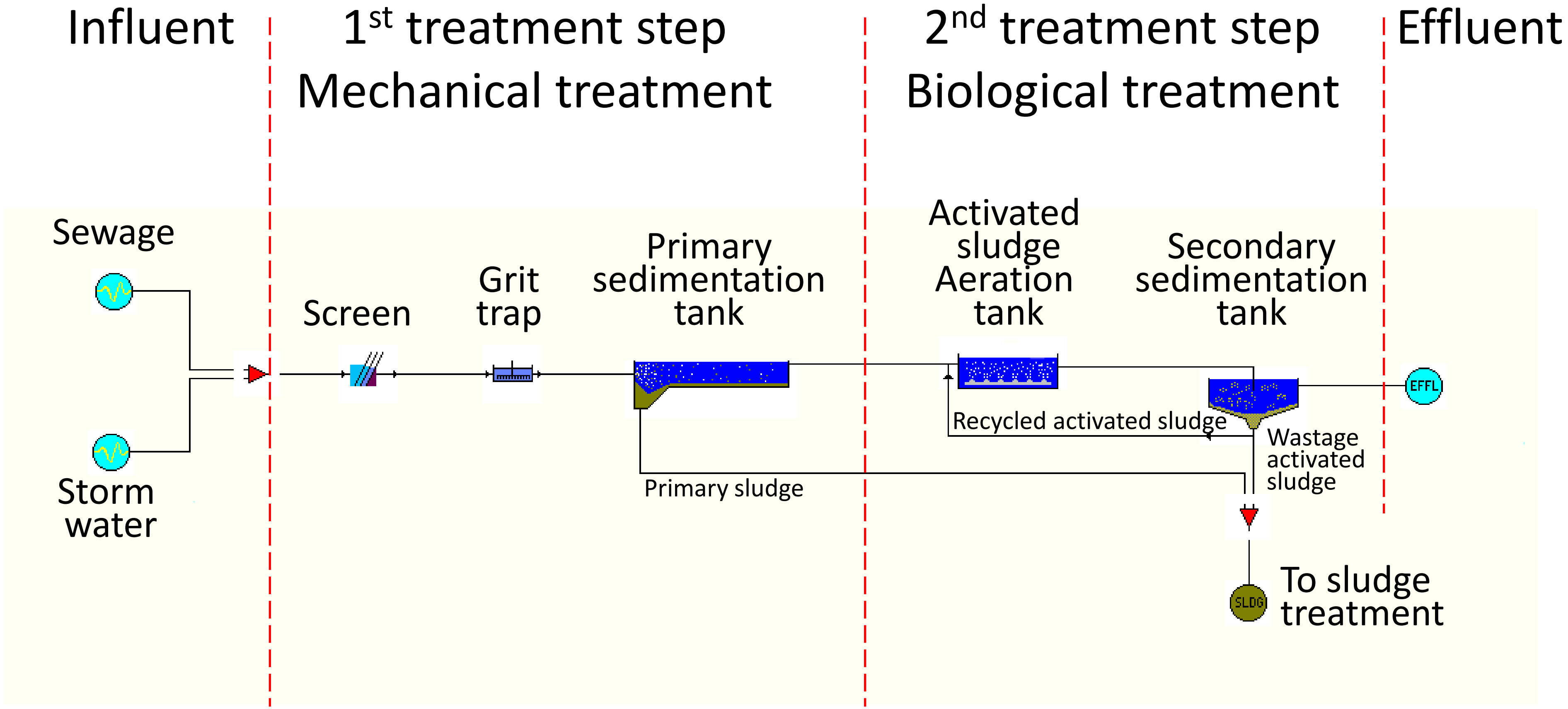


- variable volume
- cyclically variable inflows and outflows
- homogeneous mixing
- no gradients of state variables

Sequencing Batch Reactor (SBR)

From KAINZ & GRUBER, 2011

Processes in wastewater treatment plants



Influent

1st treatment step
Mechanical treatment

2nd treatment step
Biological treatment

Effluent

Sewage

Storm water

Screen

Grit trap

Primary sedimentation tank

Activated sludge Aeration tank

Secondary sedimentation tank

Recycled activated sludge

Wastage activated sludge

Primary sludge

To sludge treatment

Main treatment steps of a communal WWTP (simplified)

1st treatment step: Mechanical treatment

As seen before mechanical treatment of sewage normally consists of

- **Screen**
- **Grit removal**
- **Primary sedimentation tank**

Now let’s have a look inside the processes mentioned above.

Little museum of screenings found in the inflow of the sewage treatment plant Fürstenwalde/Spree

3rd Lecture

Mechanical wastewater treatment – Sedimentation / Effects

What we have seen at WWTP Stahnsdorf

Some secrets of biological wastewater treatment

Sedimentation

Sedimentation

Sedimentation is the physical separation of suspended material from a water by the action of gravity. It is a common operation for water treatment and found in almost all wastewater treatment plants. It is less costly than many other treatment operations.

Type I sedimentation

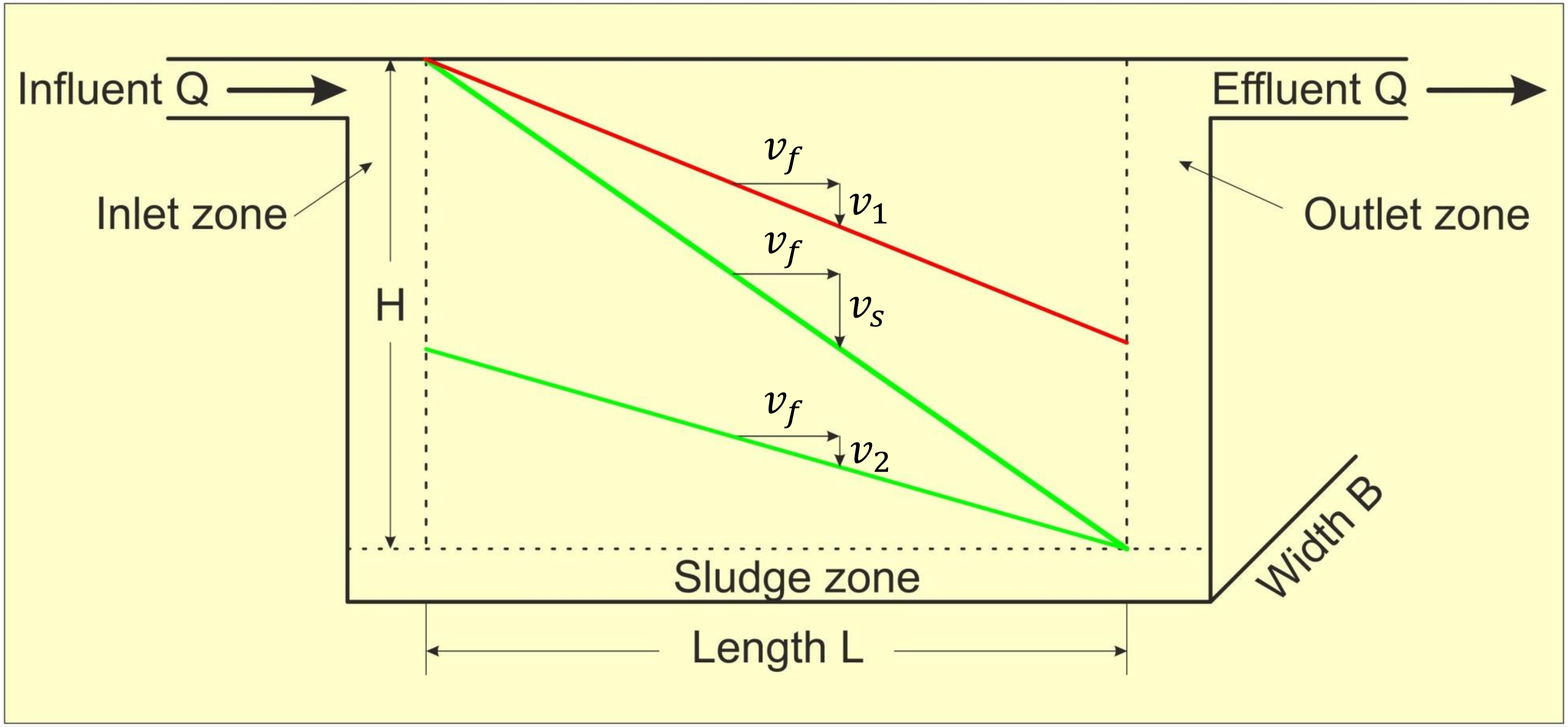
Type I sedimentation refers to discrete particle settling

Type II sedimentation

Under quiescent conditions suspended particles in many waters exhibit a natural tendency to agglomerate or the addition of chemical agents promotes this tendency. This phenomenon is known as flocculent or type II sedimentation. Analysis of type II sedimentation proceeds from the principles of type I sedimentation.

Sedimentation

The design volume must be related to the influent flow rate and the particle settling velocity. The particle that takes the longest time to remove will be one that enters at the top of the effective settling zone. The design settling velocity is v_s, which is the sinking velocity of the particle that settles through the total effective depth of the tank in the theoretical detention time. The flow-through velocity is v_f.



Sedimentation

Flow-through velocity

$$v_f = \frac{Q}{A} = \frac{Q}{H * B}$$

Q – Volumetric flow rate in $\frac{m^3}{h}$

A – Cross-sectional area in m^2

Theoretical detention time

$$t_d = \frac{V}{Q}$$

V – Volume of the settlement part of the tank in m^3

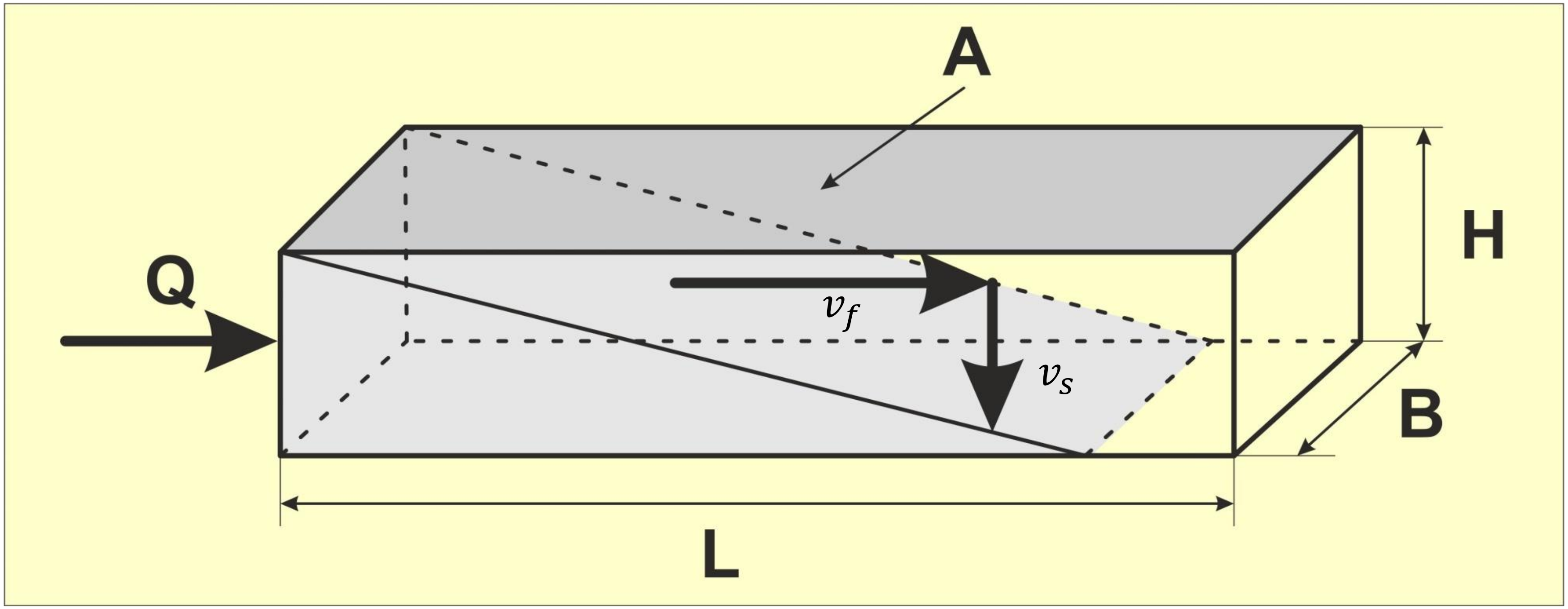
Q – Volumetric flow rate in $\frac{m^3}{h}$

Because the particle must travel the length and depth of the basin in the time t_d

$$\left.\begin{aligned} v_f * t_d &= L \\ v_s * t_d &= H \end{aligned}\right\} \quad t_d = \frac{L}{v_f} = \frac{H}{v_s}$$

$$\boldsymbol{v_s} = \frac{H * v_f}{L} = \frac{H * Q}{L * H * B} = \frac{\boldsymbol{Q}}{\boldsymbol{L} * \boldsymbol{B}}$$

Sedimentation



$$\boxed{\frac{Q}{L * B} \leq v_s}$$

In summary, in an ideal sedimentation tank, 100% particles are removed when the load per area (is similar to the Hydraulic Loading Rate) of this basin is smaller than or equal to settling velocity v_s.

Sedimentation

Settling velocity v_s depends on density of the particle, density of the water, volume of the particle, cross-sectional area of the particle, shape of the particle and so on.
Settling velocity v_s

- can be derived from Settling tests (preferred!),
- can be calculated

$$\boxed{v_s = \frac{Re_T * \eta_F}{\emptyset * \rho_F}}$$

Where

Re_T - Reynolds number (dimensionless)

η_F - dynamical viscosity of the fluid in $\frac{kg}{m * s}$

$\emptyset$ - cross-sectional diameter of the particle in m

ρ_F - density of the fluid in $\frac{kg}{m^3}$

Sedimentation

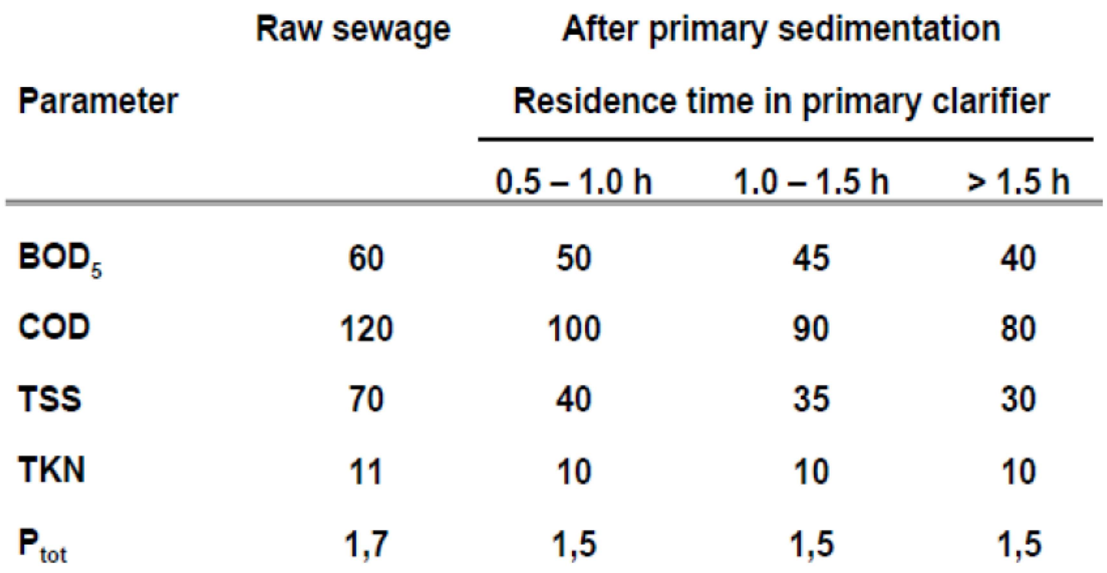
Besides this settling velocity v_s can be taken from rules of thumb:

Rule of thumb for settling velocity $v_s \approx 0.01 \ \ldots \ 0.03 \ \frac{m}{s}$
(the smaller value applies for smaller and lighter particles)

Rules of thumb for design of a rectangular primary sedimentation tank:
  Dry weather hydraulic retention time ≥ 1 h
  Stormy weather hydraulic retention time ≥ 0.3 h
  Dry weather velocity ≤ 0.01 $\frac{m}{s}$
  Stormy weather velocity ≤ 0.03 $\frac{m}{s}$
  Hydraulic loading rate ≈ 2 … 4 $\frac{m}{h}$
  Basin depth ≥ 3 m
  Basin width ≥ 8 m
  Basin length = 3 … 6 * basin width
  Basin length = 10 … 25 * basin depth

LONDONG et al., 2009

Effects of mechanical treatment (1^{st} step)



Parameter	Raw sewage	After primary sedimentation		
		Residence time in primary clarifier		
		0.5 – 1.0 h	1.0 – 1.5 h	> 1.5 h
BOD_5	60	50	45	40
COD	120	100	90	80
TSS	70	40	35	30
TKN	11	10	10	10
P_{tot}	1,7	1,5	1,5	1,5

Removal Effects of primary sedimentation

(Normally polluted sewage,
loads per capita and day
compare Lecture 01, slide 27)

Rule of thumb: Primary sedimentation removes

- 25% up to 33% of organic load (measured as BOD_5 or as COD)
- 50% of suspended solids
- Nitrogen and phosphorus are only influenced marginally

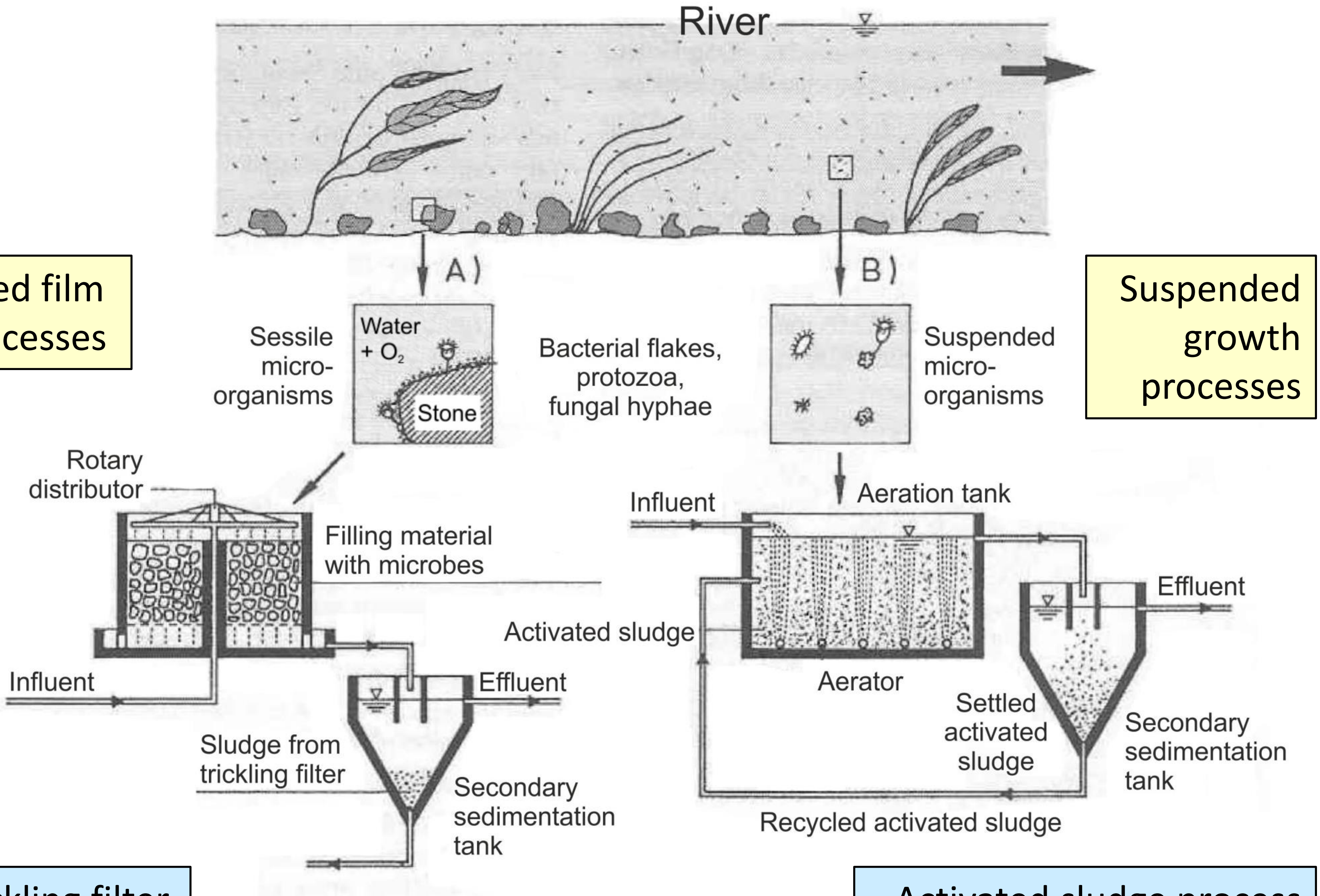
Effects of mechanical treatment (1st step)

In other words, mechanical treatment removes essentially only visible soiling

- Screen: coarse pieces of wood, fabrics
- Aerated grit trap: sand, gravel, oil, grease
- Sedimentation tank: turbidity (up to 60% of suspended solids)

After mechanical treatment most of the pollution in sewage remains

- $\frac{2}{3}$ up to $\frac{3}{4}$ of organic load (oxygen demand)
- Nearly the total load of nutrients (nitrogen and phosphorus)



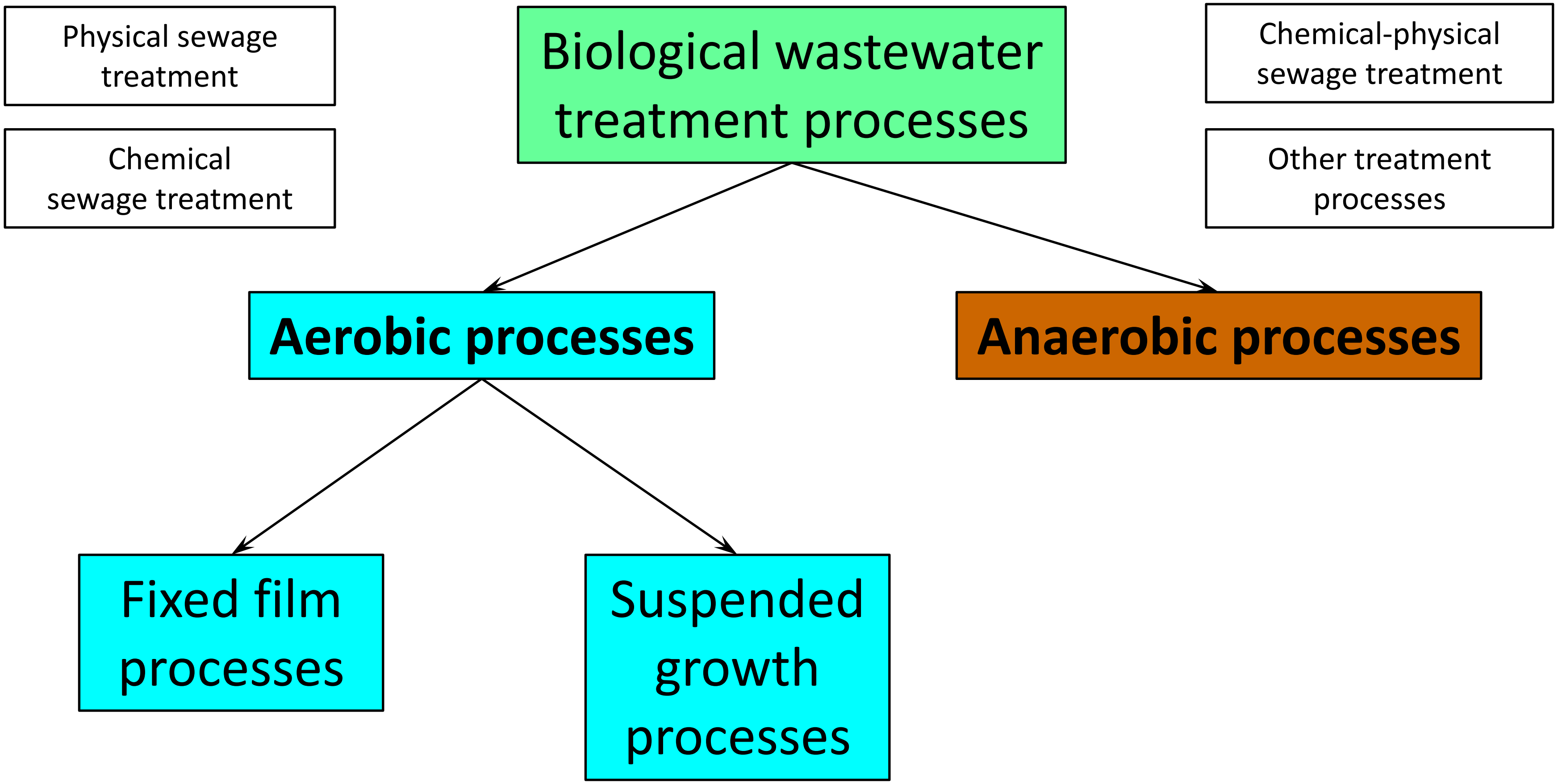
Fixed film processes

Suspended growth processes

Trickling filter

Activated sludge process

Rough outline



Physical sewage treatment

Chemical sewage treatment

Biological wastewater treatment processes

Chemical-physical sewage treatment

Other treatment processes

Aerobic processes

Anaerobic processes

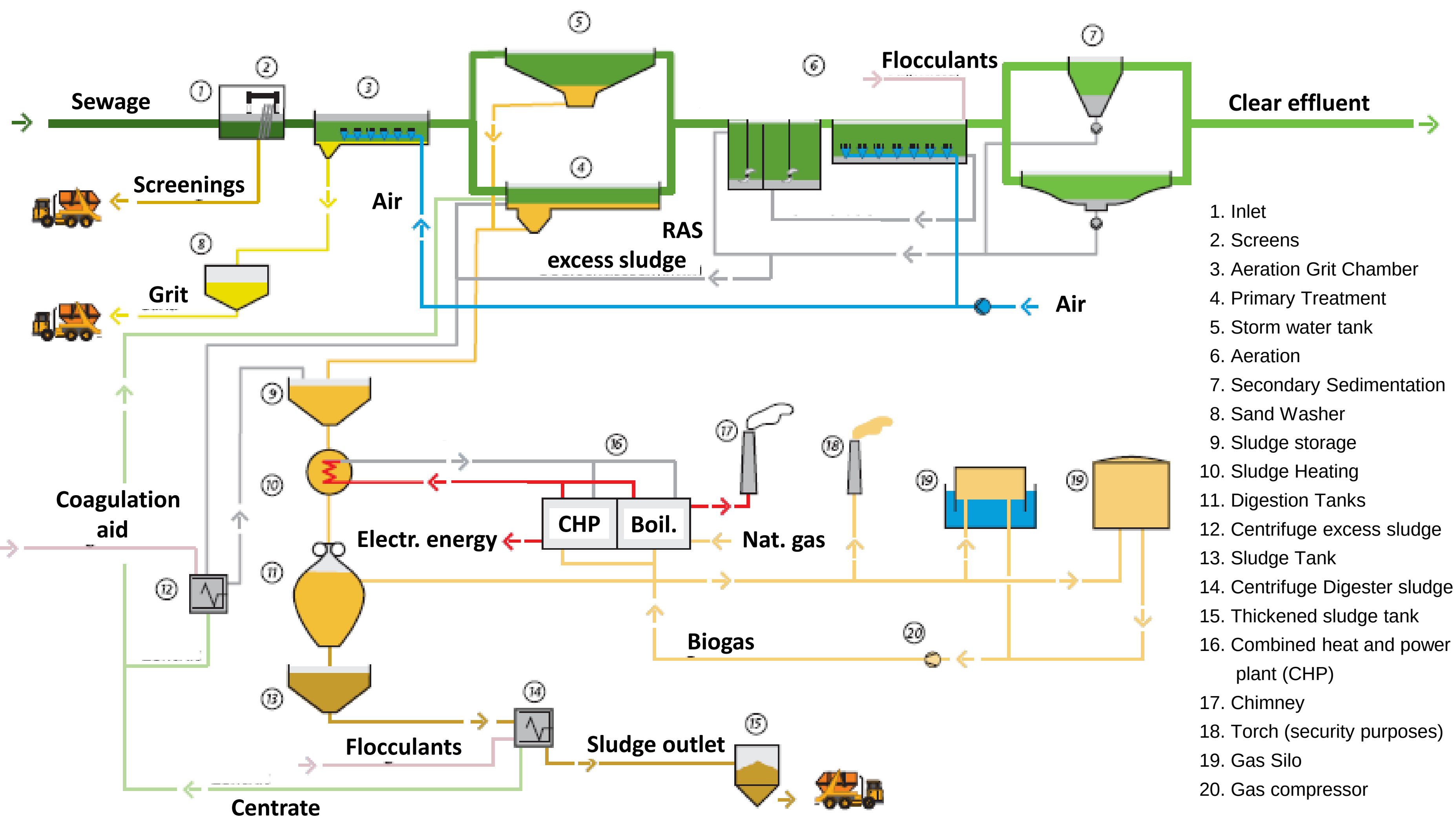
Fixed film processes

Suspended growth processes

WWTP Stahnsdorf

Excursion on 10 October
to WWTP Stahnsdorf

WWTP Stahnsdorf



1. Inlet
2. Screens
3. Aeration Grit Chamber
4. Primary Treatment
5. Storm water tank
6. Aeration
7. Secondary Sedimentation
8. Sand Washer
9. Sludge storage
10. Sludge Heating
11. Digestion Tanks
12. Centrifuge excess sludge
13. Sludge Tank
14. Centrifuge Digester sludge
15. Thickened sludge tank
16. Combined heat and power plant (CHP)
17. Chimney
18. Torch (security purposes)
19. Gas Silo
20. Gas compressor

WWTP Stahnsdorf

Symbol in A 131	Meaning	Value
EW	Population equivalent (PE)	420,000 PE
Q_d	Daily wastewater inflow in dry weather	52,000 m³/d
Q_m	Design wastewater inflow in stormy weather	156,000 m³/d
$B_{d,CSB,Z}$	Daily COD load	54.68 t/d
$B_{d,BSB,Z}$	Daily BOD load	22.8 t/d
$B_{d,TKN,Z}$	Daily TKN load	4.7 t/d
$B_{d,NO3-N,Z}$	Daily nitrate load	0 kg/d
$B_{d,P,Z}$	Daily phosphorus load	0.6 kg/d
$B_{d,AFS,Z}$	Daily total solids load	23.9 t/d

WWTP Stahnsdorf

Symbol in A 131	Meaning	Value
$C_{CSB,ÜW}$	Limit value COD	68 mg/l
$S_{Nanorg.,ÜW}$	Limit value nitrogen	13 mg/l
$C_{P,ÜW}$	Limit value phosphorus	1 mg/l
Q_{ZB}	Influent flow to activated sludge aeration tank	52,000 m³/d
Q_{RS}	Recycled activated sludge (RAS) flow	70% of influent
$Q_{ÜS}$	Wasted activated sludge (WAS) flow	1,900 m³/d
TS_{BB}	Mixed Liquor Suspended Solids	3.5-5.0 g/l
TS_{RS}	RAS solids	8 g/l
$X_{TS,AN}$	Effluent solids	11.6 mg/l
$T_{Bem.,tief}$	Lowest dimensioning temperature	12°C

WWTP Stahnsdorf

Symbol in A 131	Meaning	Value
	Bar distance of the screen	8 cm
	Volume of grit trap	2 x 920 m^3
	Volume of Primary sedimentation tank	2,500 m^3
	Volume optional pre-treatment or storage tank in stormy weather	7,800 m^3
	Total volume of activated sludge tanks	66,200 m^3
	Anaerobic	6,000 m^3
	Anoxic	23,000 m^3
	Aerobic	37,200 m^3
	Volume of secondary sedimentation tank	17,600 m^3

WWTP Stahnsdorf

Parameter	**Influent loads according paper from 10/10/2018:**	**Resulting influent concentration at 52,000 m³/d (average)**	**Effluent values rounded**	**Removal**
Total BOD	22,80 t/d	438 mg/l	5 mg/l	98,9%
Total COD	54,68 t/d	1052 mg/l	41 mg/l	96,1%
TKN	4,70 t/d	90 mg/l		
NH_4-N	3,42 t/d	66 mg/l	0,2 mg/l	99,7%
TIN	3,42 t/d	66 mg/l	11,3 mg/l	82,9%
Total P	0,60 t/d	12 mg/l	0,6 mg/l	95,0%
Total Suspended Solids	23,90 t/d	460 mg/l	7 mg/l	98,5%

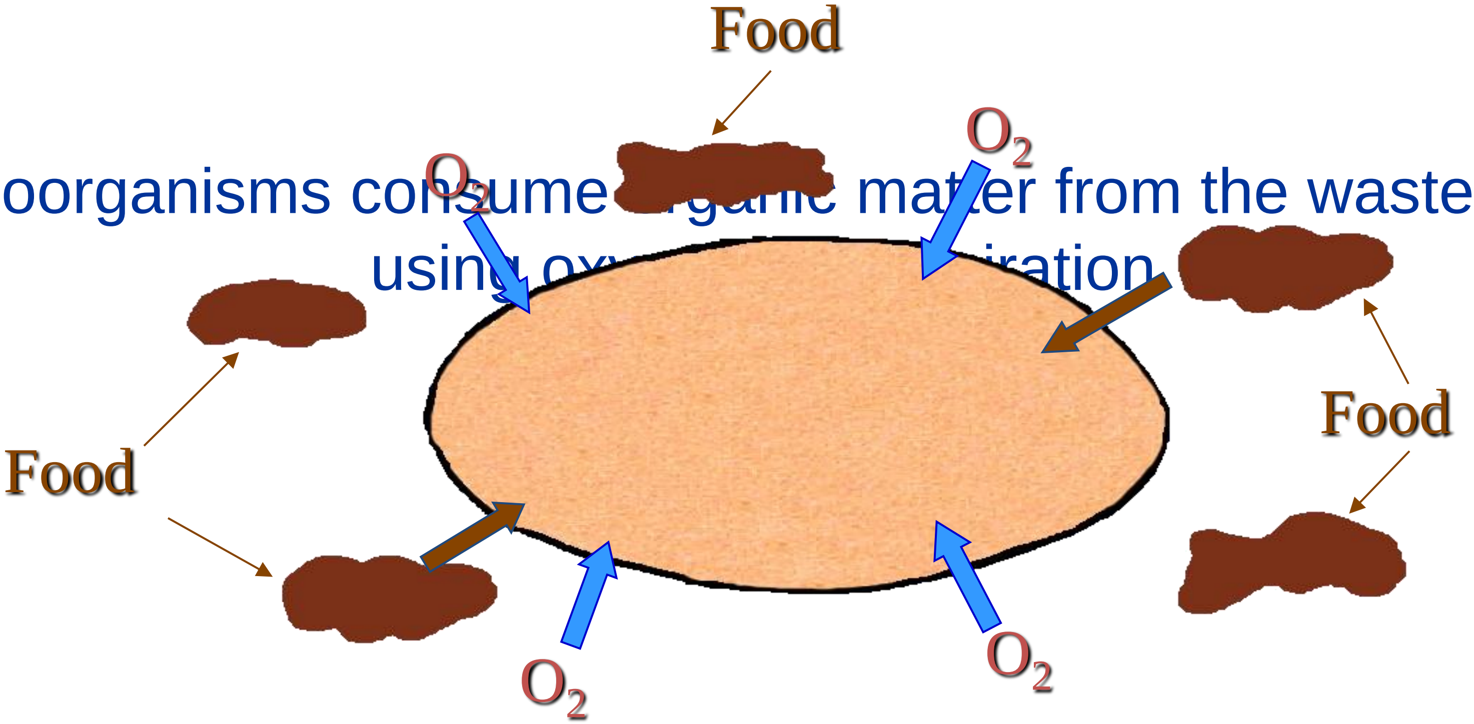
$$\eta = \frac{L_{Influent} - L_{Effluent}}{L_{Influent}} * 100$$

$$\eta = \frac{C_{Influent} - C_{Effluent}}{C_{Influent}} * 100$$

η – Removal in %

SECONDARY TREATMENT

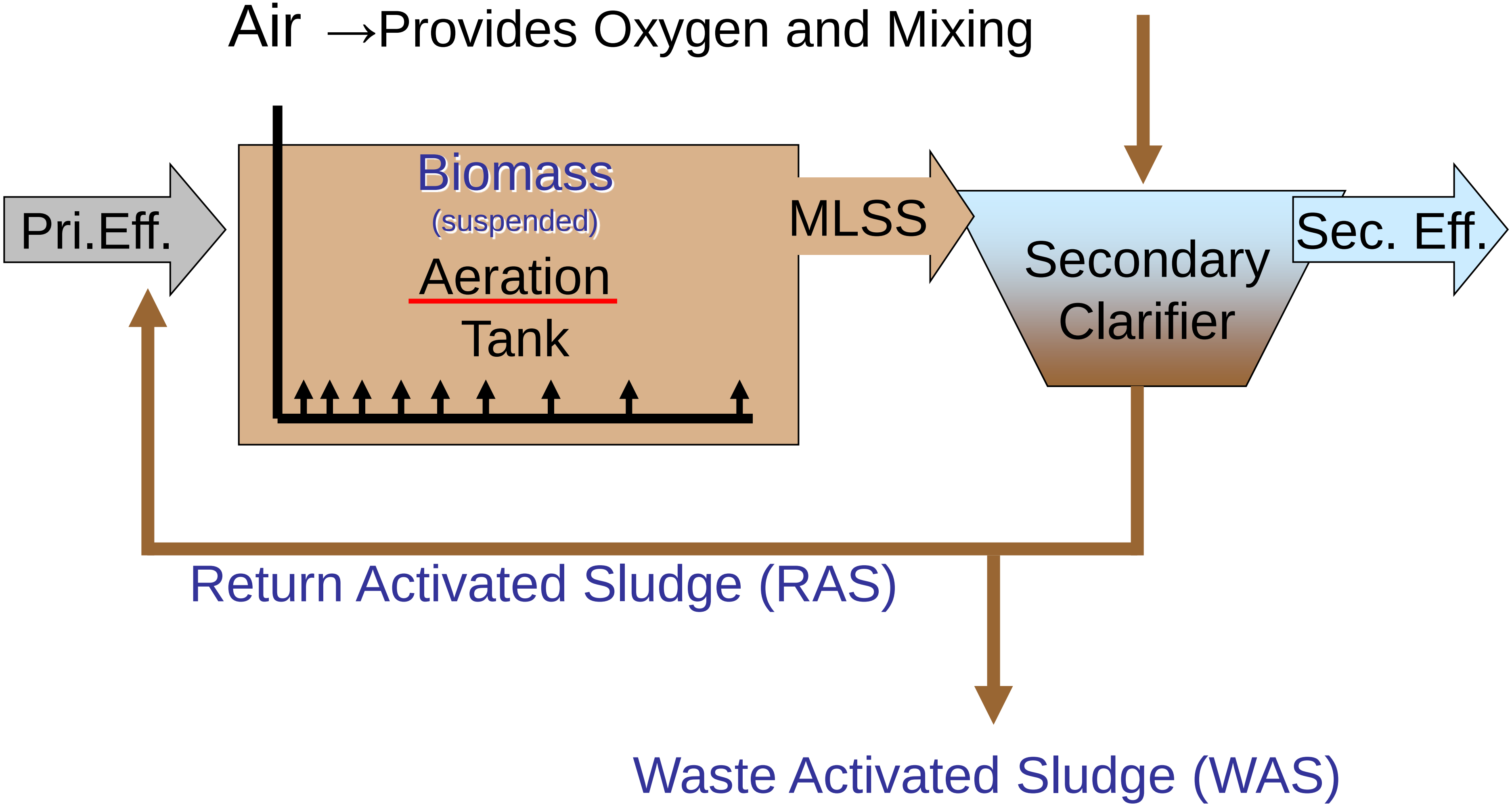
Biological Wastewater Treatment

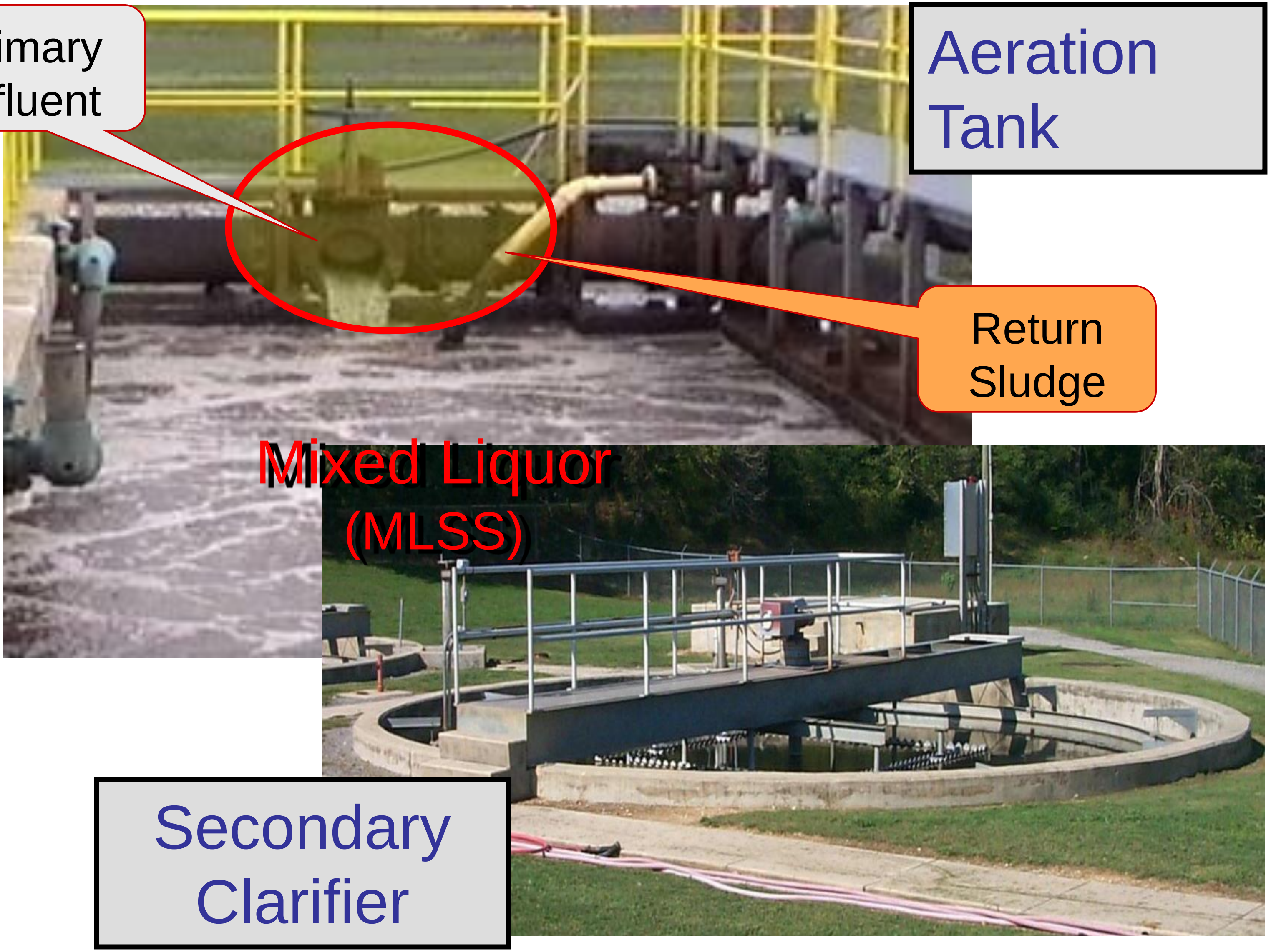


Microorganisms consume organic matter from the wastewater, using ox[illegible]iration

Millions of aerobic and facultative micro-organisms remove pollutants through living and growing process

Activated Sludge System





Primary Effluent

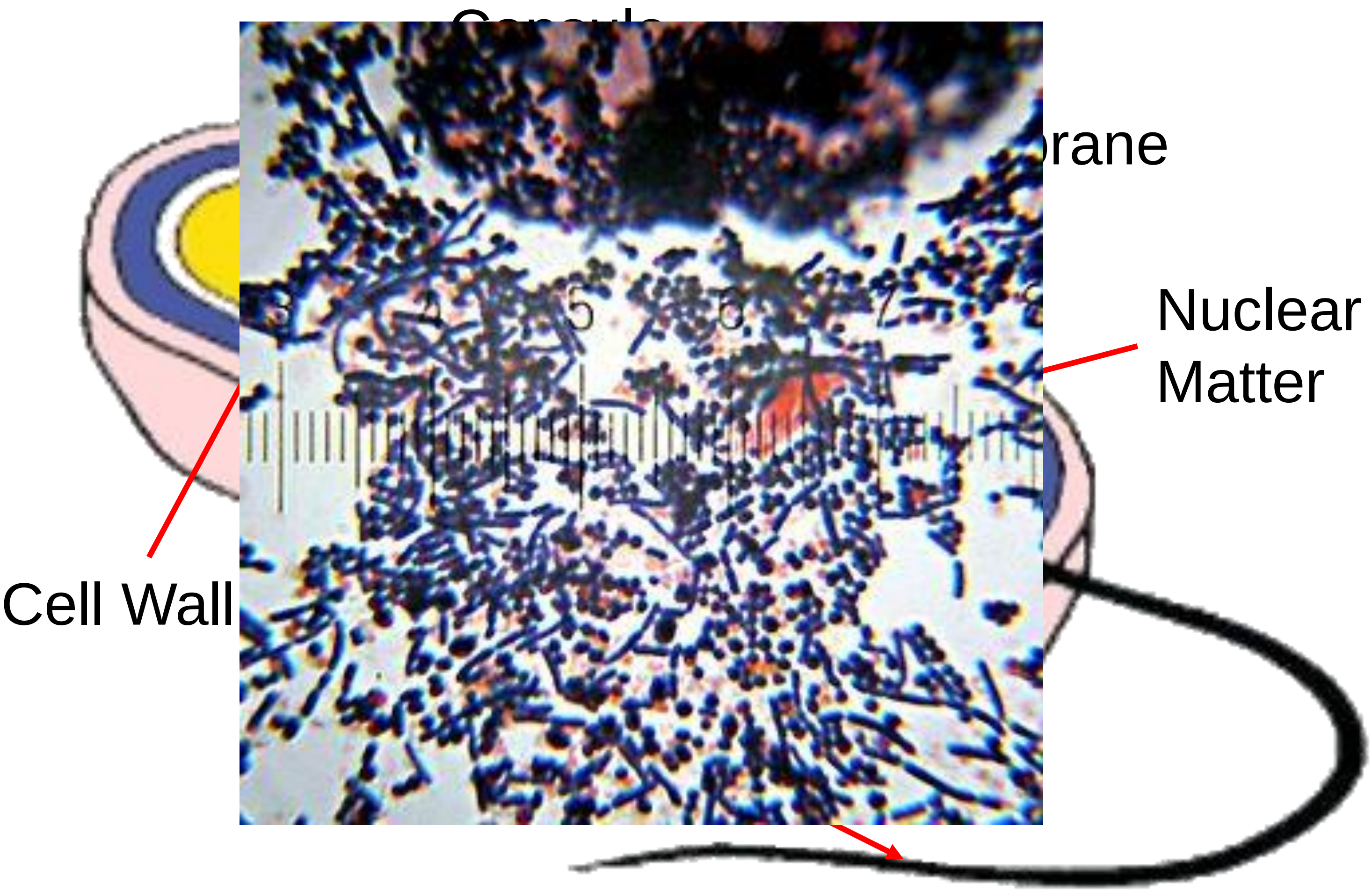
Aeration Tank

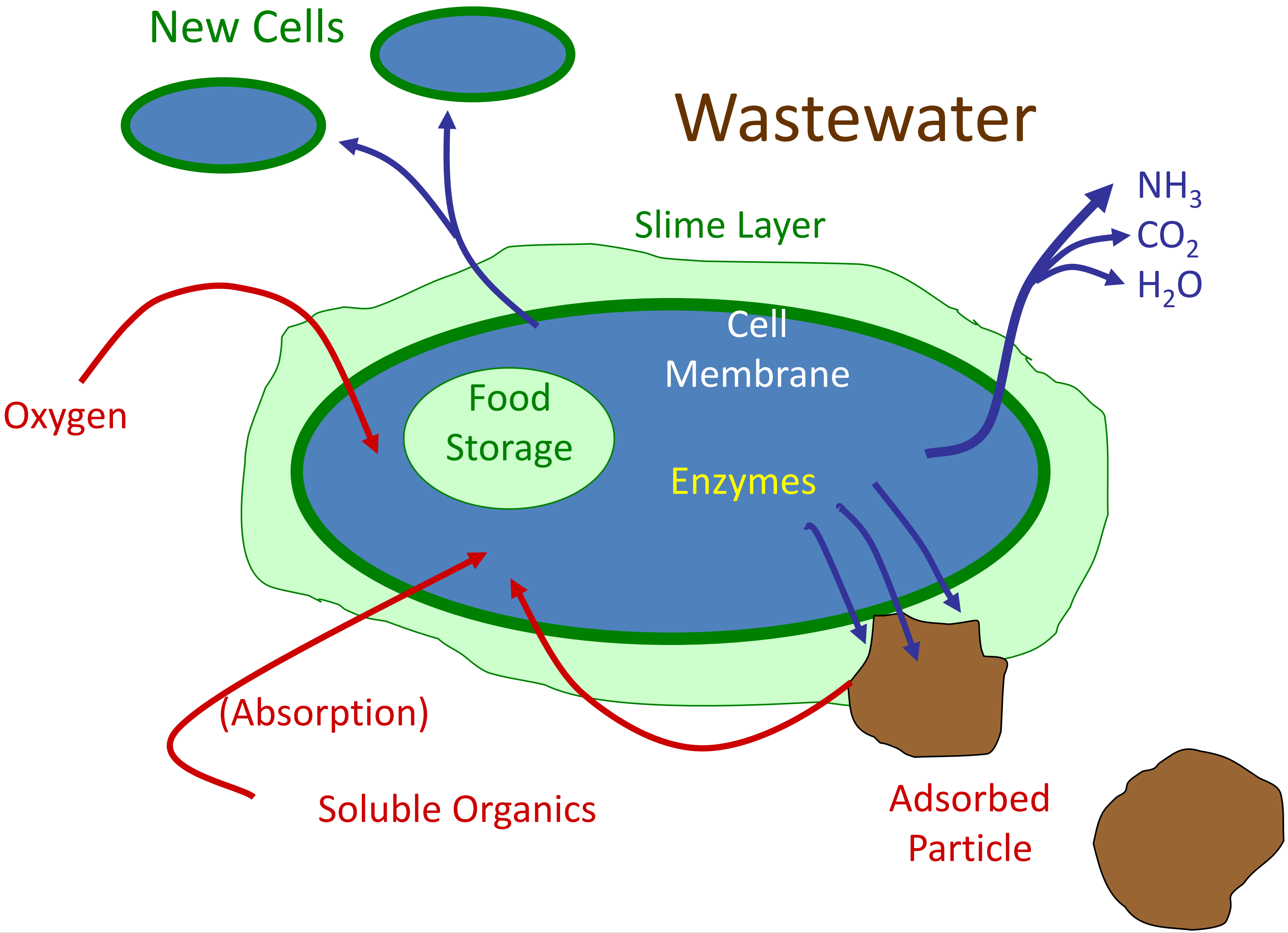
Return Sludge

Mixed Liquor (MLSS)

Secondary Clarifier

PARTS OF A GENERALIZED BACTERIAL CELL OF THE BACILLUS TYPE

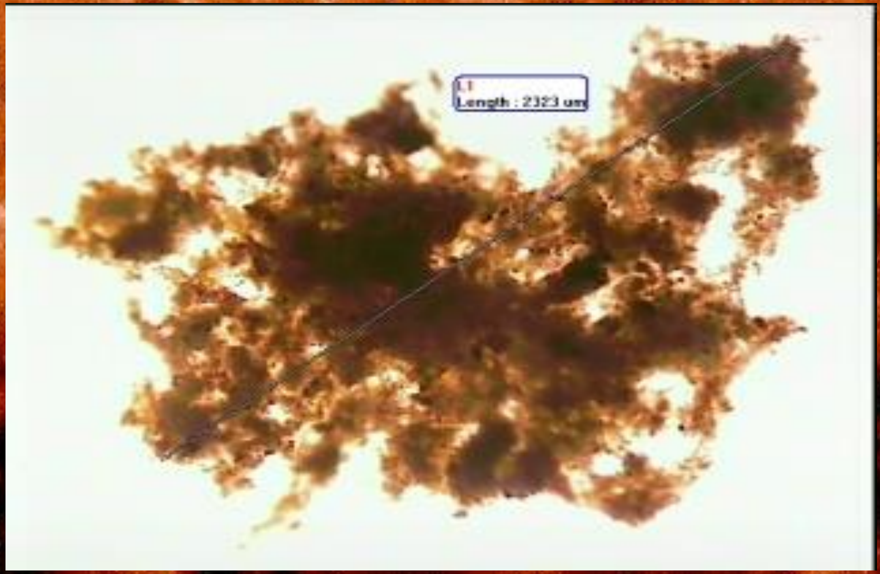


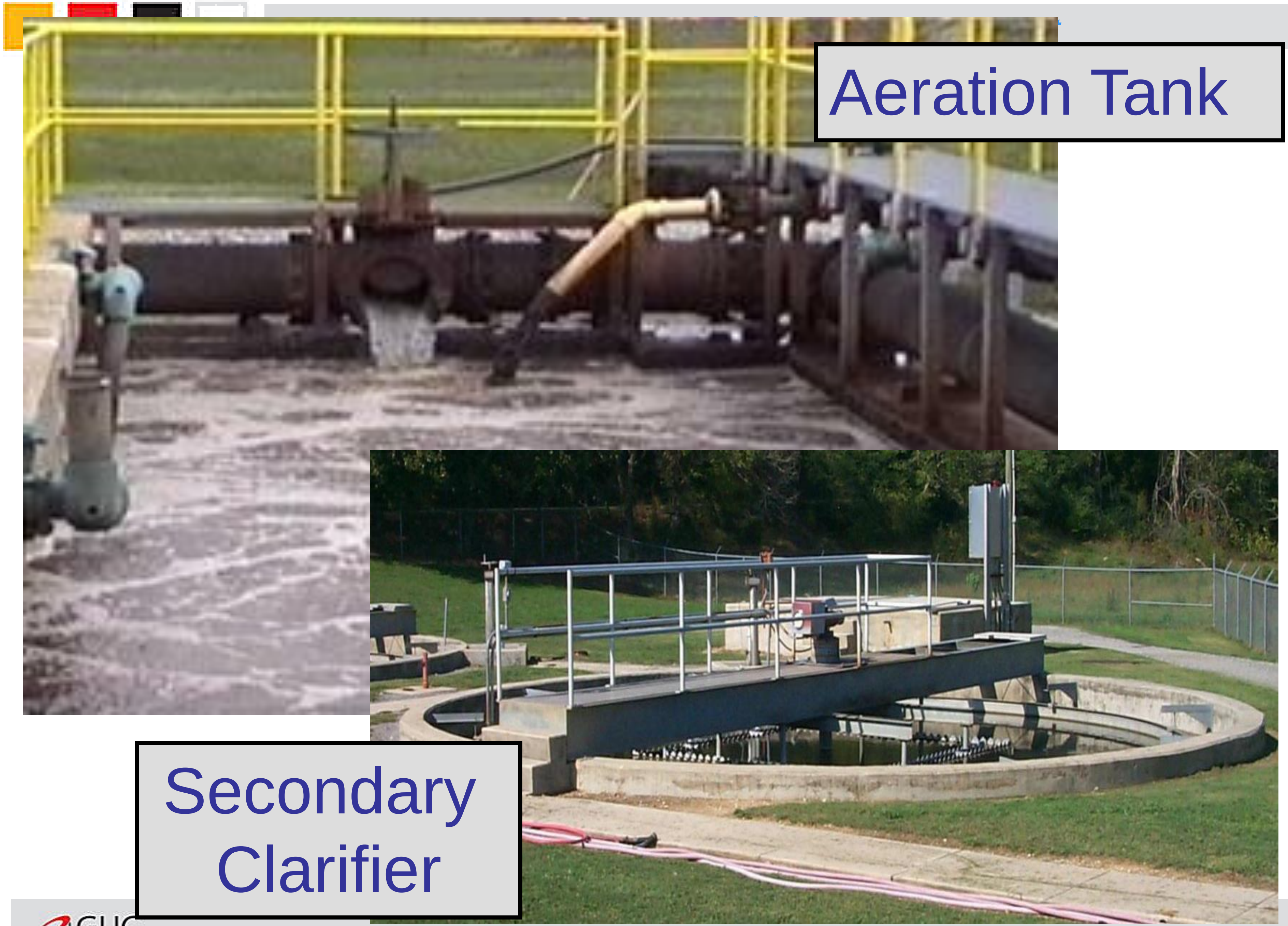

New Cells
Wastewater
Slime Layer
NH_3
CO_2
H_2O
Cell Membrane
Food Storage
Oxygen
Enzymes
(Absorption)
Soluble Organics
Adsorbed Particle

Mixed Liquor

Flocculation

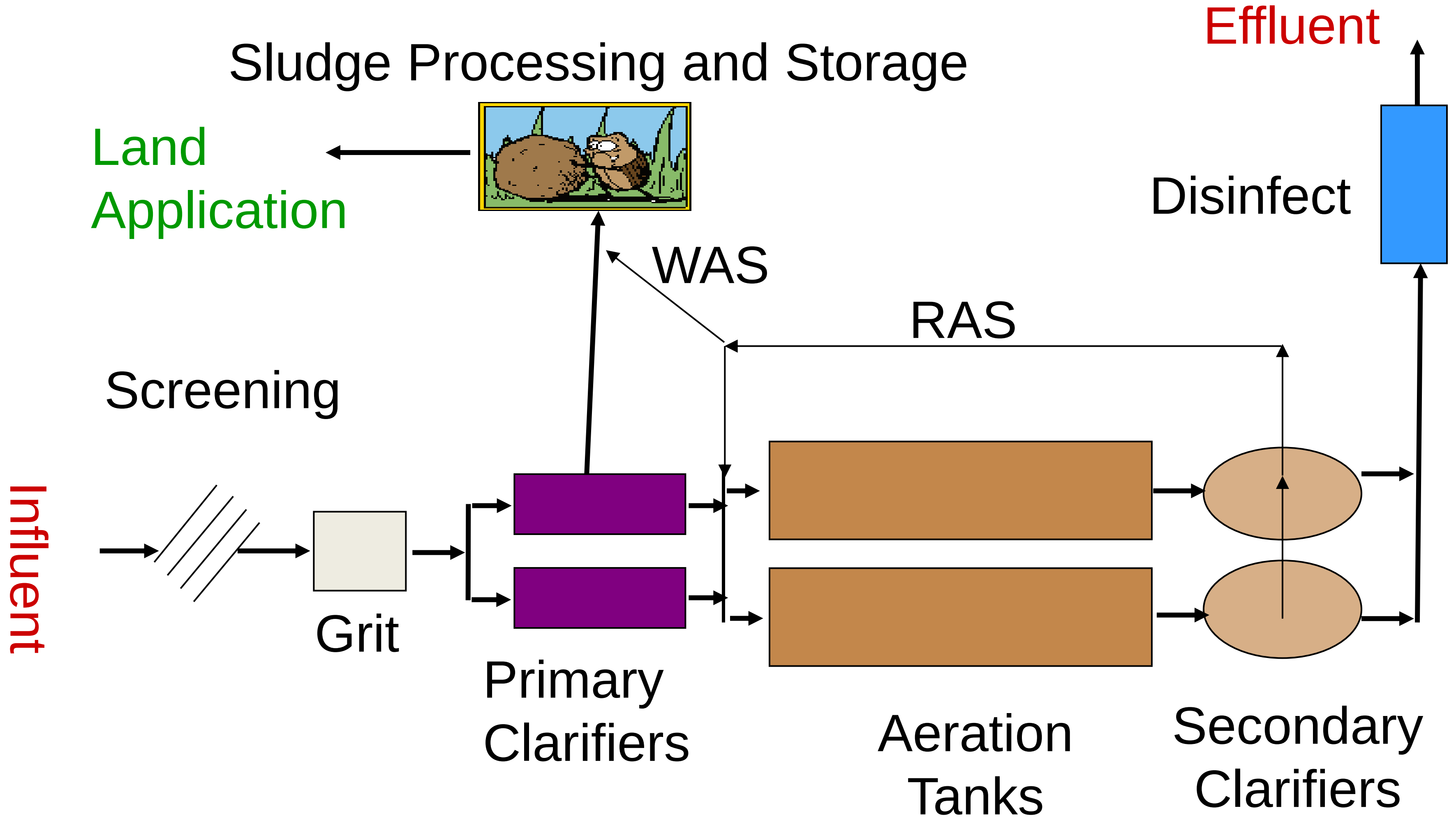
A process of contact and adhesion whereby the particles of a dispersion form larger-size clusters.





Aeration Tank

Secondary Clarifier



Typical Flow-Through Activated Sludge Plant

Biological Wastewater Treatment

Three Steps

1. Transfer of Food from Wastewater to Cell.

Prerequisites:

- Adequate Mixing
- Enough Detention Time

Biological Wastewater Treatment

2. Conversion of Food to New Cells and Byproducts.

Prerequisites:

- Acclimated Biomass
- Useable Food Supply
- Adequate D.O.
- Proper Nutrient Balance
  C : N : P = 100 : 5 : 1

Biological Wastewater Treatment

3. Flocculation and Solids Removal

Prerequisites:

- Proper Mixing
- Proper Growth Environment
- Secondary Clarification

Biological Wastewater Treatment

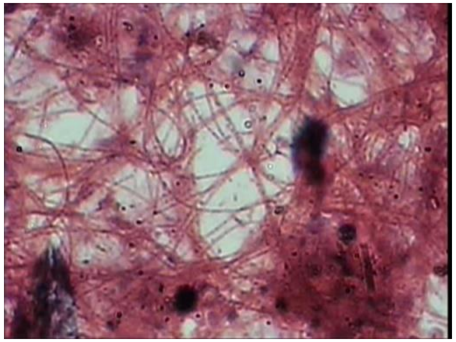
3. Flocculation and Solids Removal

Must Have Controls

Proper Growth Environment

Filamentous Bacteria – Form Strings

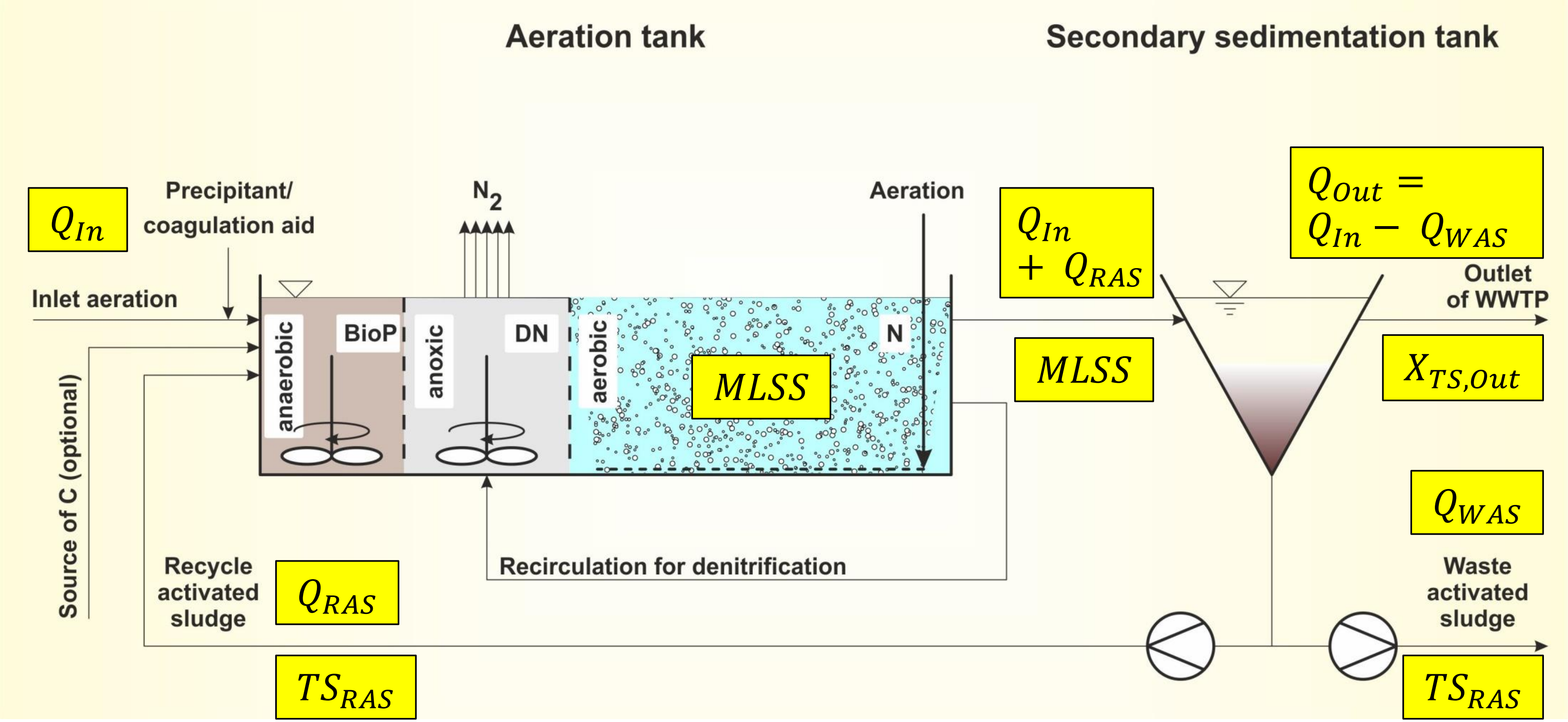
Mixed Liquor Does Not Compact - Bulking



4th Lecture

Biological wastewater treatment
Balance of flow and solids in activated sludge process
Sludge retention time

Balance of flow and solids in activated sludge process



Q_{In} - Flow inlet aeration tank

$MLSS$ – Mixed Liquor Suspended Solids

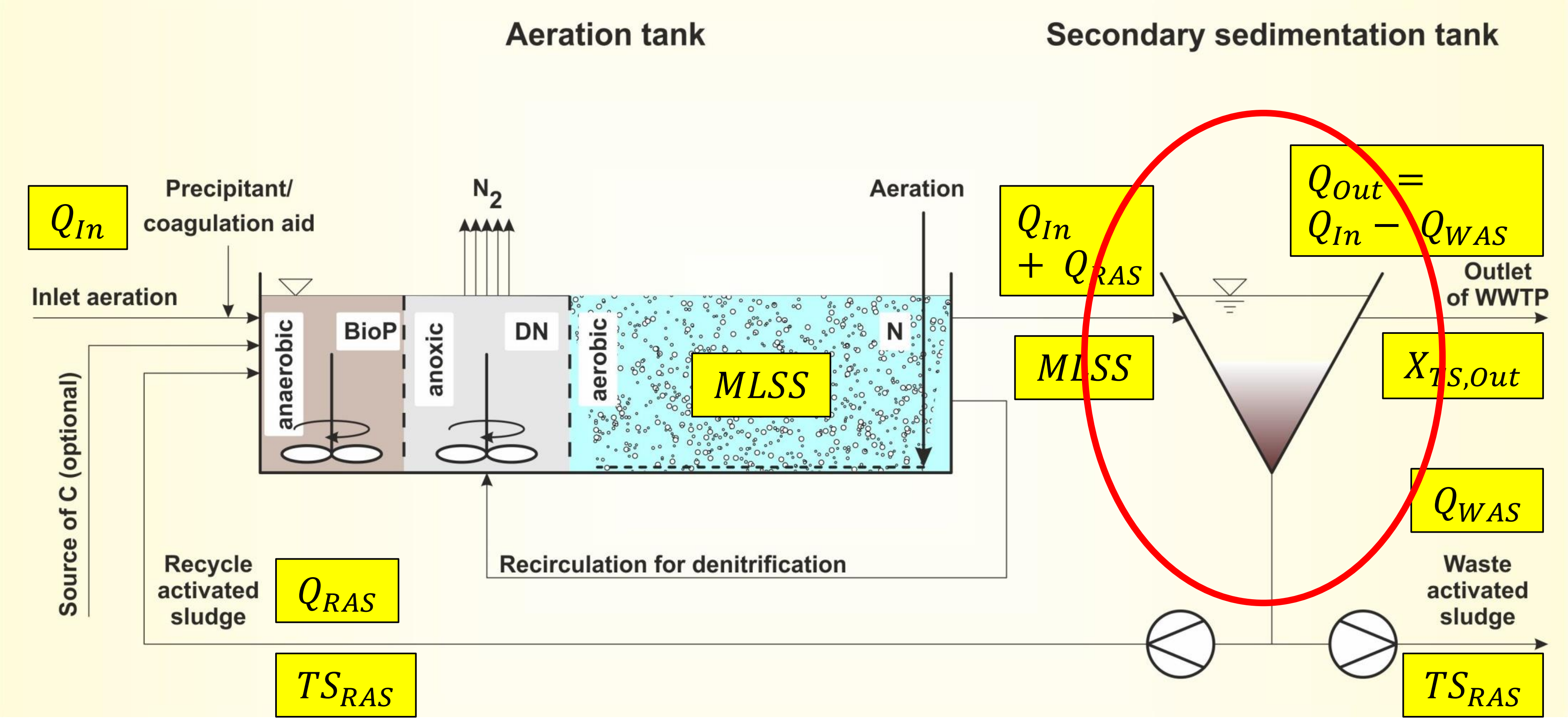
Q_{WAS} - Flow of waste activated sludge

Q_{RAS} - Flow of recycle activated sludge

TS_{RAS} - Total Solids of recycle activated sludge

$X_{TS,Out}$ - Total Solids of outlet of WWTP

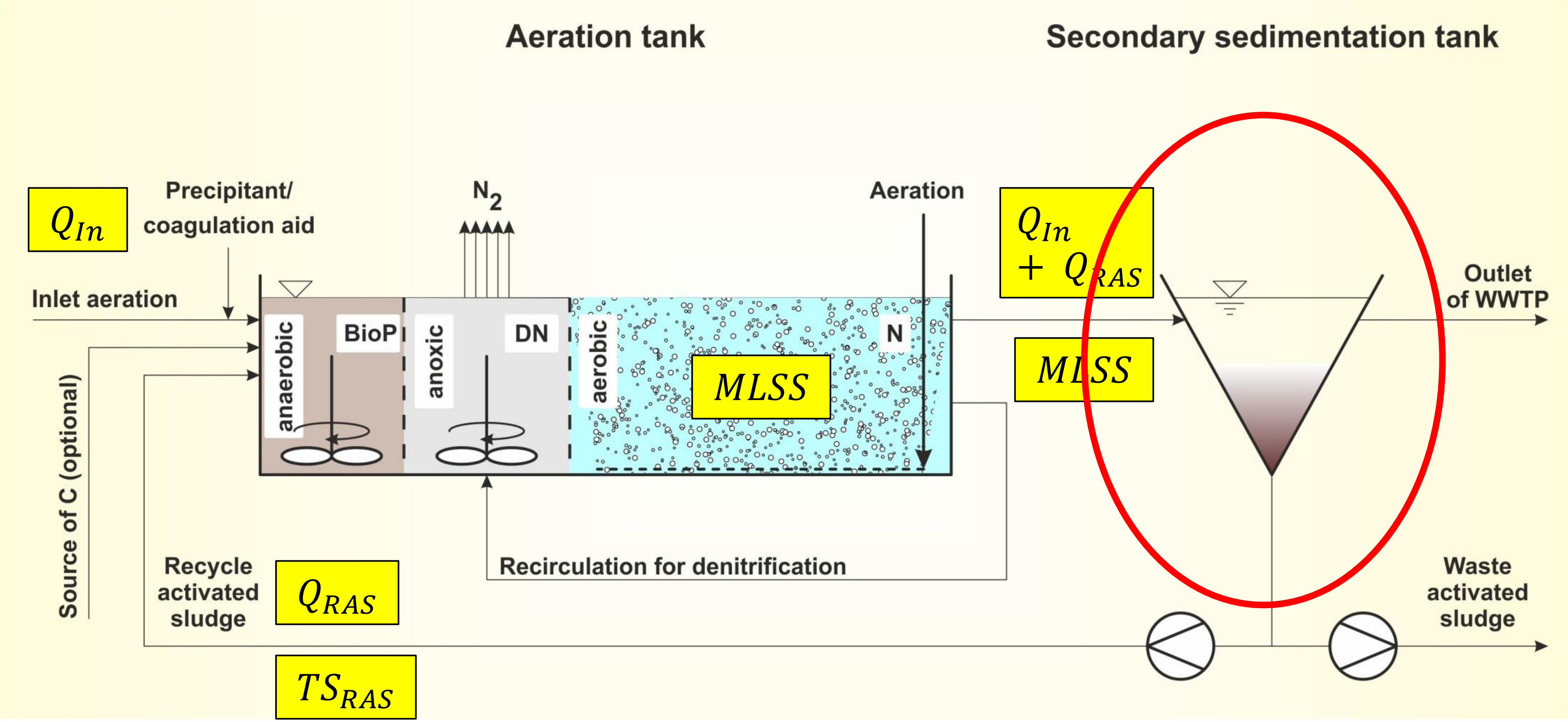
Balance of flow and solids in activated sludge process



Complete balance of solids in and out of secondary sedimentation tank:

$$(Q_{In} + Q_{RAS}) * MLSS = (Q_{RAS} + Q_{WAS}) * TS_{RAS} + (Q_{In} - Q_{WAS}) * X_{TS,Out}$$

Balance of flow and solids in activated sludge process



Introduction of $\boldsymbol{Q_{RAS} = Q_{In} * RR}$ (RAS Recycle ratio) changes the balance sheet to:

$$(1 + RR) * Q_{In} * MLSS = Q_{In} * RR * TS_{RAS}$$

Balance of flow and solids in activated sludge process

$$\boxed{(1 + RR) * Q_{In} * MLSS = Q_{In} * RR * TS_{RAS}}$$

Shortening of Q_{In} in the formula above results in

$$\boxed{(1 + \mathrm{RR}) * MLSS = RR * TS_{RAS}}$$

Dissolving to TS_{AT} leads to the following formula which is very important for planning and design of WWTP's

$$\boxed{MLSS = \frac{RR * TS_{RAS}}{1 + RR}}$$

Balance of flow and solids in activated sludge process

We can change the formula which is derived from the simplified solids balance also to TS_{RAS}

$$\boxed{TS_{RAS} = MLSS * \frac{1 + RR}{RR}}$$

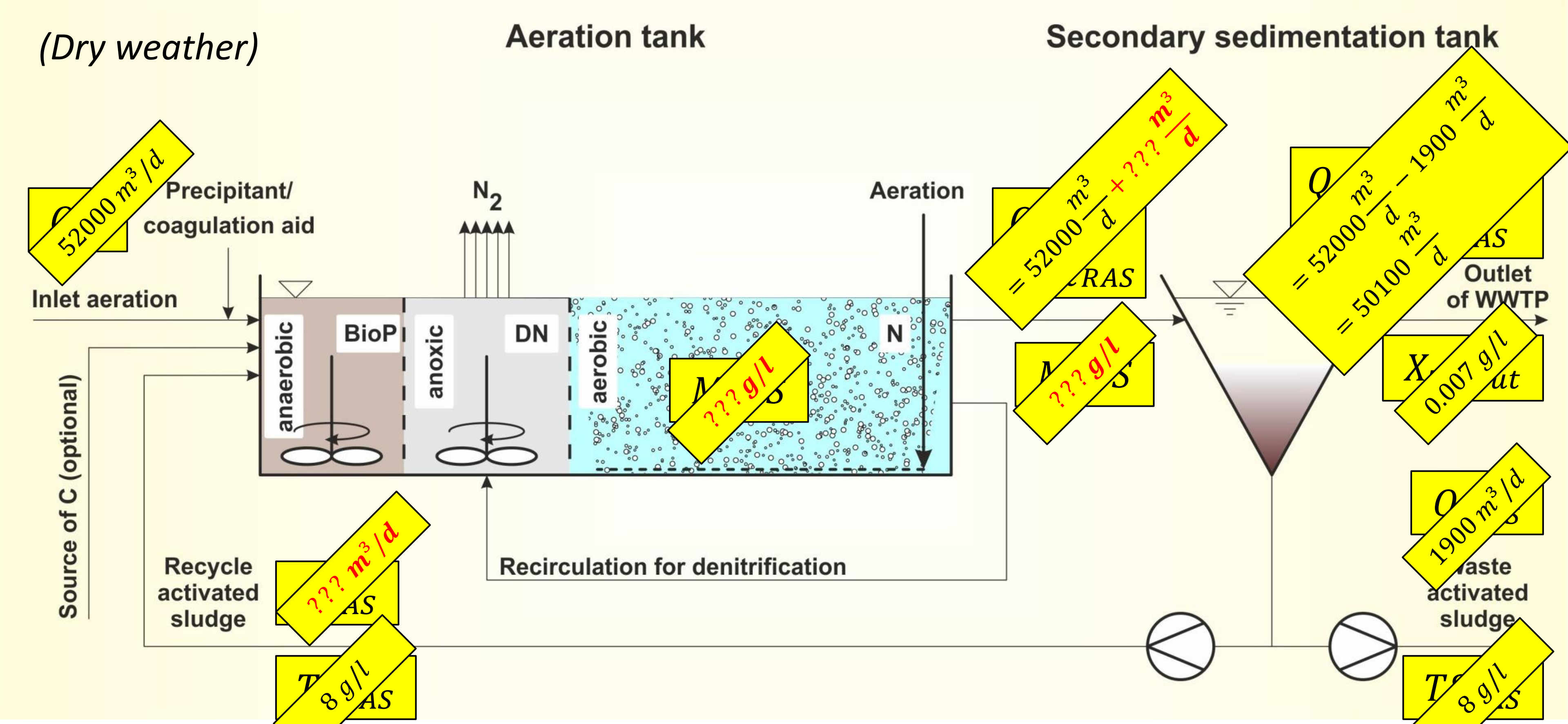
Or to RR:

$$\boxed{RR = \frac{MLSS}{TS_{RAS} - MLSS}}$$

Now we are able to calculate some important boundary conditions regarding the aeration tank of a WWTP.

Balance of flow and solids in WWTP Stahnsdorf

First let’s have a look on our example WWTP Stahnsdorf (at dry weather)!
We fill in our scheme all data we can pick up from the data sheet:



Balance of flow and solids in WWTP Stahnsdorf

Because we know from the data sheet that $RR = 70\%$ we can calculate Q_{RAS}:

$$\boxed{Q_{RAS} = RR * Q_{In} = 0.7 * 52000 = 36400 \frac{m^3}{d}}$$

Now we can calculate which flow leaves the aeration tank:

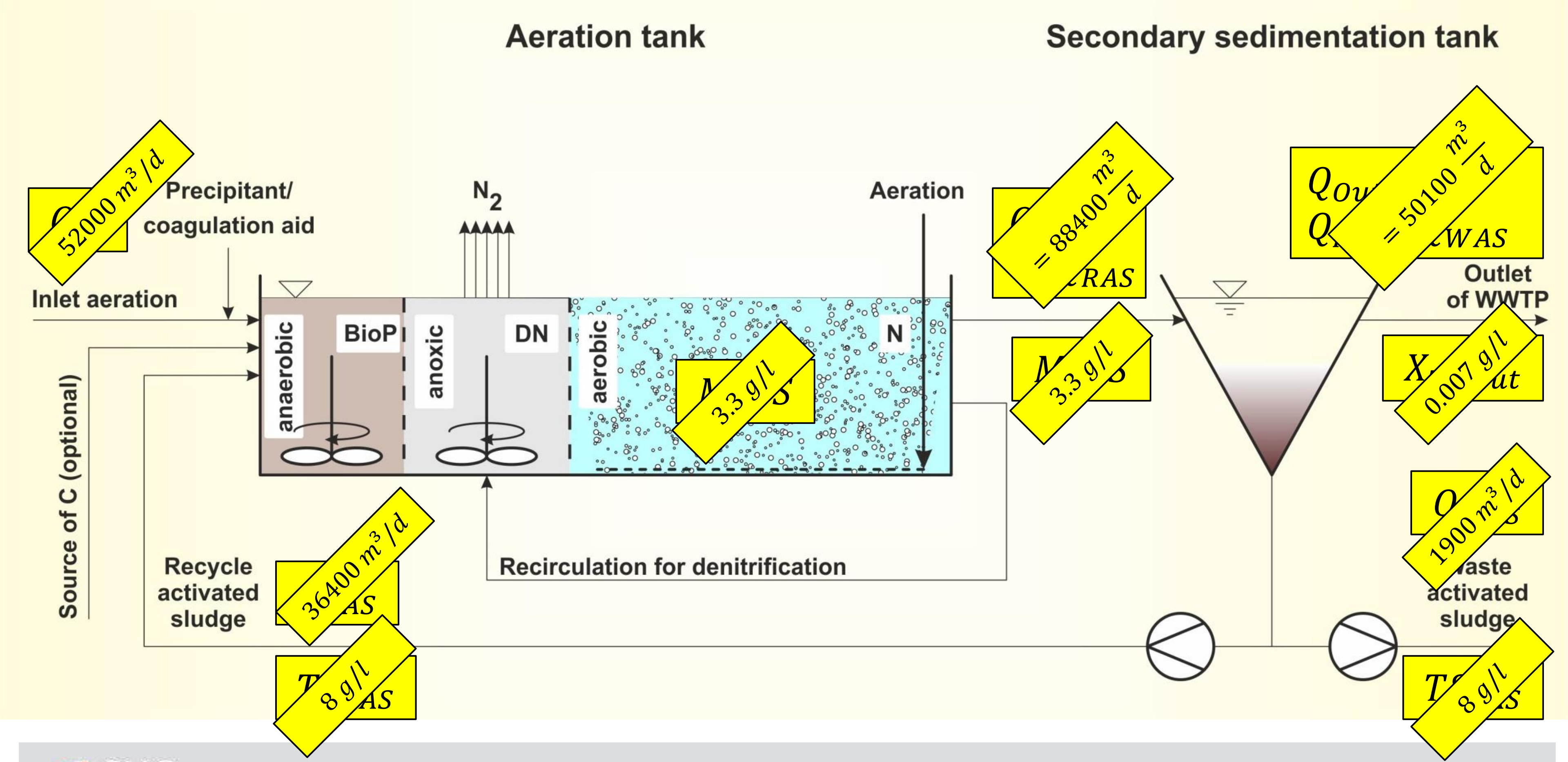
$$\boxed{Q_{In} + Q_{RAS} = 52000 \frac{m^3}{d} + 36400 \frac{m^3}{d} = 88400 \frac{m^3}{d}}$$

And basing on our balancing formula we even are able to calculate the concentration of suspended solids in the aeration tanks of WWTP Stahnsdorf:

$$\boxed{MLSS = \frac{0.7 * 8 \frac{g}{l}}{1 + 0.7} = 3{,}3 \frac{g}{l}}$$

Balance of flow and solids in WWTP Stahnsdorf

Now we can complete the flowsheet of WWTP Stahnsdorf:



Mass of solids in WWTP Stahnsdorf

We know the solids concentration in the biological treatment step of WWTP Stahnsdorf and we know the volume of activated sludge tanks (see Data sheet). Therefore we can calculate the total mass of solids within the activated sludge tanks :

$$\boxed{M_{TS} \;= Total\, V_{BT} * MLSS}$$

M_{TS} - Mass of solids within the tanks for biological treatment

$Total\, V_{BT}$ - Total volume of the tanks for biological treatment

$MLSS$ – Mixed Liquor Suspended Solids

$$\boxed{M_{TS} \;= 66200\, m^3 * 3.3\, \frac{kg}{m^3} = 218460\, kg \approx 218.5\, t}$$

Sludge retention time in WWTP Stahnsdorf

After we have calculated the total mass of solids within the aeration tank of WWTP Stahnsdorf, we can estimate the sludge retention time (SRT):

$$SRT_{BT} = \frac{M_{TS,AT}}{M_{TS,WAS}} = \frac{V_{AT} * MLSS}{Q_{WAS} * TS_{RAS}}$$

SRT_{BT} - Sludge retention time in the tanks for biological treatment

M_{TS} - Mass of solids within the tanks for biological treatment

$M_{TS,WAS}$ - Mass of solids which is removed by wastage of activated sludge

Q_{WAS} - Flow of excess sludge

TS_{RAS} - Concentration of Suspended Solids in WAS (is the same as in RAS)

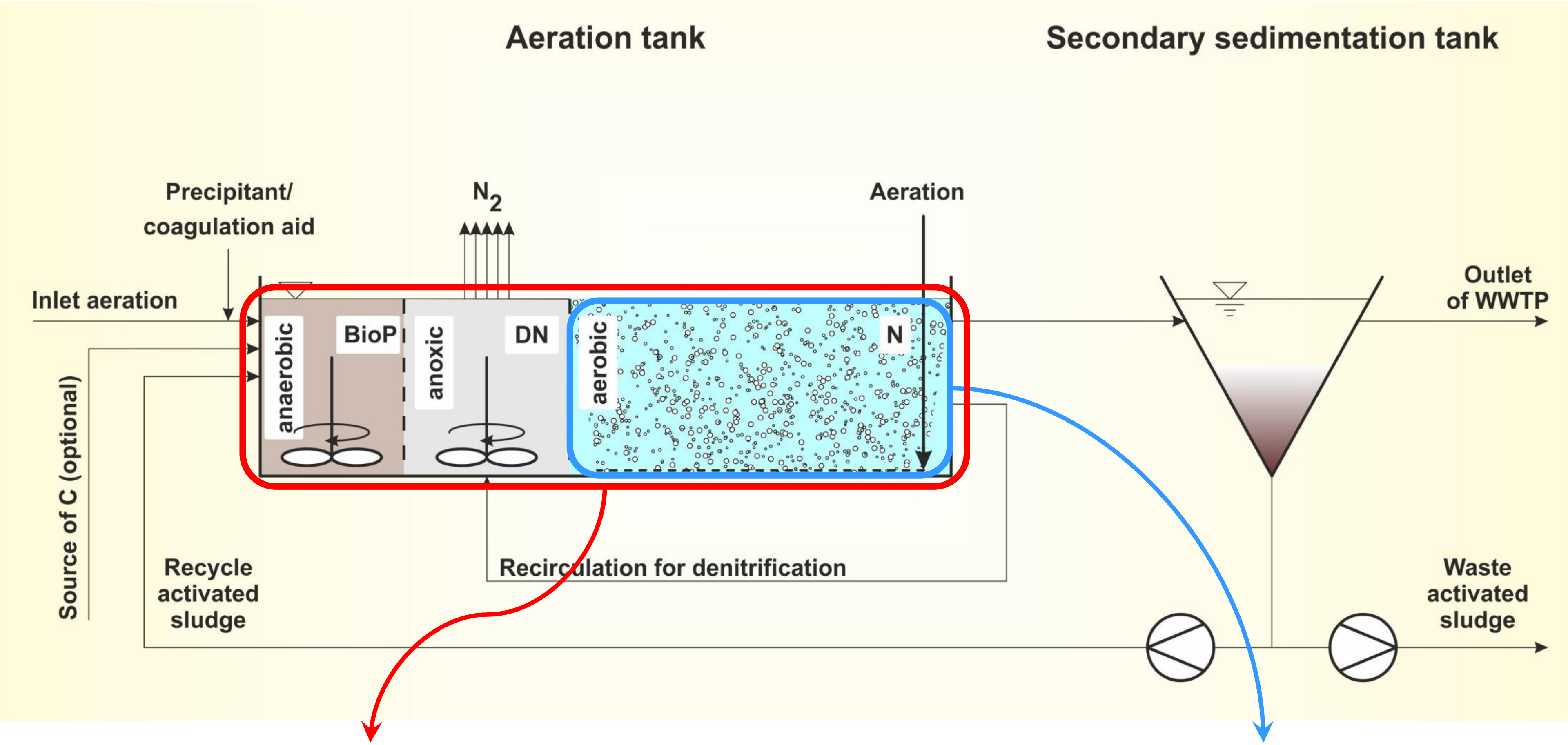
$$SRT_{BT} = \frac{218460\ kg}{1900\ \frac{m^3}{d} * 8\ \frac{kg}{m^3}} = 14.4\ d$$

Sludge retention time in activated sludge process

Why it is important to know SRT (in Germany called “age of the sludge”)?

1. SRT is nowadays the most important design parameter of activated sludge process, because it allows for estimation of performance
2. If SRT is too short, the microorganisms in the aeration tank can not multiply because they are washed out by WAS
3. The first effect of “wash out” is deterioration of NH4-N in effluent. Autotrophs are responsible for nitrification (= biochemical oxidation of NH4-N). They have the longest generation time of all microorganisms within activated sludge process.
4. When SRT is too long, microorganisms become too old, they "outgrow". This means that they do not remove the pollution in the wastewater properly.

Mass of solids in activated sludge process



V_{BT} - Volume of the whole aeration tank for biological treatment

V_{aerob} - Volume of the aerobic tank as part of part of the whole aeration tank

Sludge retention time in WWTP Stahnsdorf

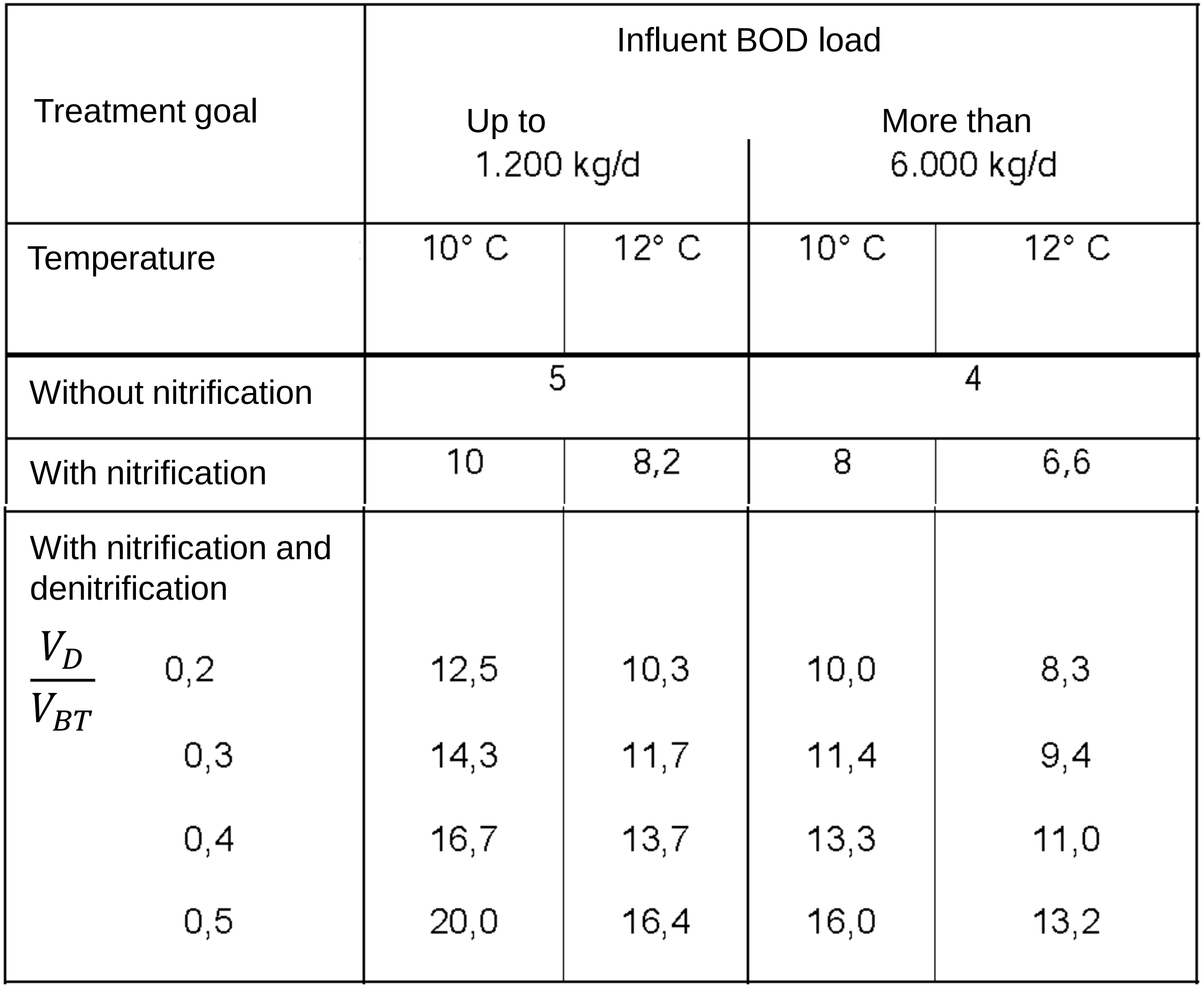
As part of the retention time of solids in the whole aeration tank we can calculate the aerobic retention time

$$\boxed{SRT_{aerob} = SRT_{BT} * \frac{V_N}{Total\ V_{BT}} = 14{,}4\ d\ * \frac{37200\ m^3}{66200\ m^3} = 8.1\ d}$$

Share of the volume of the denitrification tank of total volume of the aeration tank

$$\boxed{\frac{V_D}{Total\ V_{BT}} = \frac{23000}{66200} = 0.35}$$

Sludge retention time in activated sludge process



Treatment goal	Influent BOD load Up to 1.200 kg/d		More than 6.000 kg/d	
Temperature	10° C	12° C	10° C	12° C
Without nitrification	5		4	
With nitrification	10	8,2	8	6,6
With nitrification and denitrification				
$\frac{V_D}{V_{BT}}$ 0,2	12,5	10,3	10,0	8,3
0,3	14,3	11,7	11,4	9,4
0,4	16,7	13,7	13,3	11,0
0,5	20,0	16,4	16,0	13,2

Design sludge retention time in days depending on the treatment goal and the temperature and the plant size (intermediate values are to be estimated)

Excerpt of table no. 2 in "ATV-DVWK-A 131 Bemessung von einstufigen Belebungsanlagen"

For WWTP Stahnsdorf applies $\frac{V_D}{V_{BT}} = 0.35$ therefore SRT should be between 10.2 and 12,4 d (we calculated 14.4 d, this is fine, because it's more)

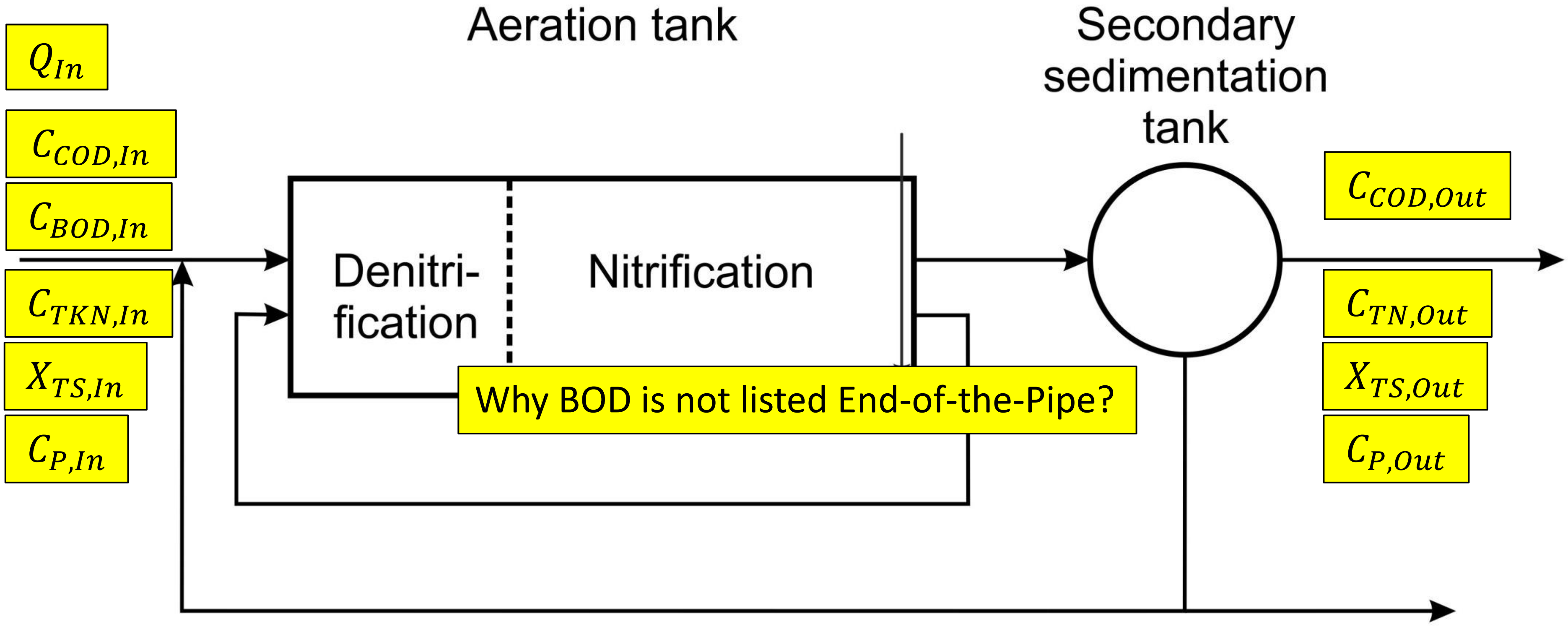
Preparation for midterm exams

Exercises

5th Lecture

Biological wastewater treatment:
Relationship of essential design parameters
Stoichiometry of Nitrification/Denitrification

Target variables for design of activated sludge plants

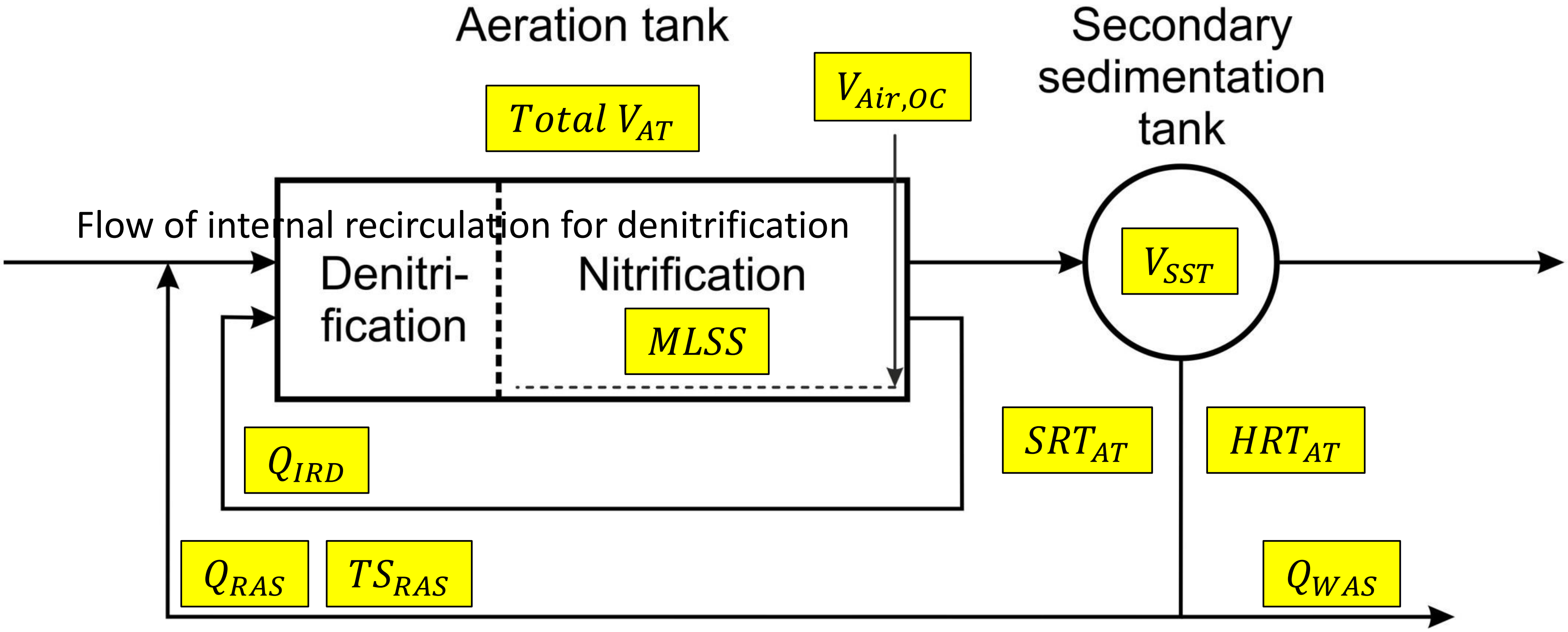


Why BOD is not listed End-of-the-Pipe?

Q_{In} - Flow inlet aeration tank
$C_{BOD,In}$ - Concentration of inlet BOD
$X_{TS,In}$ - Concentration of inlet Solids
$C_{COD,Out}$ - Concentration of outlet COD
$X_{TS,Out}$ - Concentration of outlet Solids

$C_{COD,In}$ - Concentration of inlet COD
$C_{TKN,In}$ - Concentration of inlet TKN
$C_{P,In}$ - Concentration of inlet Phosphorus
$C_{TN,Out}$ - Concentration of outlet Nitrogen
$C_{P,Out}$ - Concentration of outlet Phosphorus

Essential design parameters of activated sludge plants



$MLSS$ – Mixed Liquor Suspended Solids

Q_{WAS} - Flow of waste activated sludge

$Total\ V_{AT}$ - Total volume of aeration tank

V_{SST} - Volume of sec. sedimentation tank

HRT_{AT} - Hydraulic retention time

Q_{RAS} - Flow of recycle activated sludge

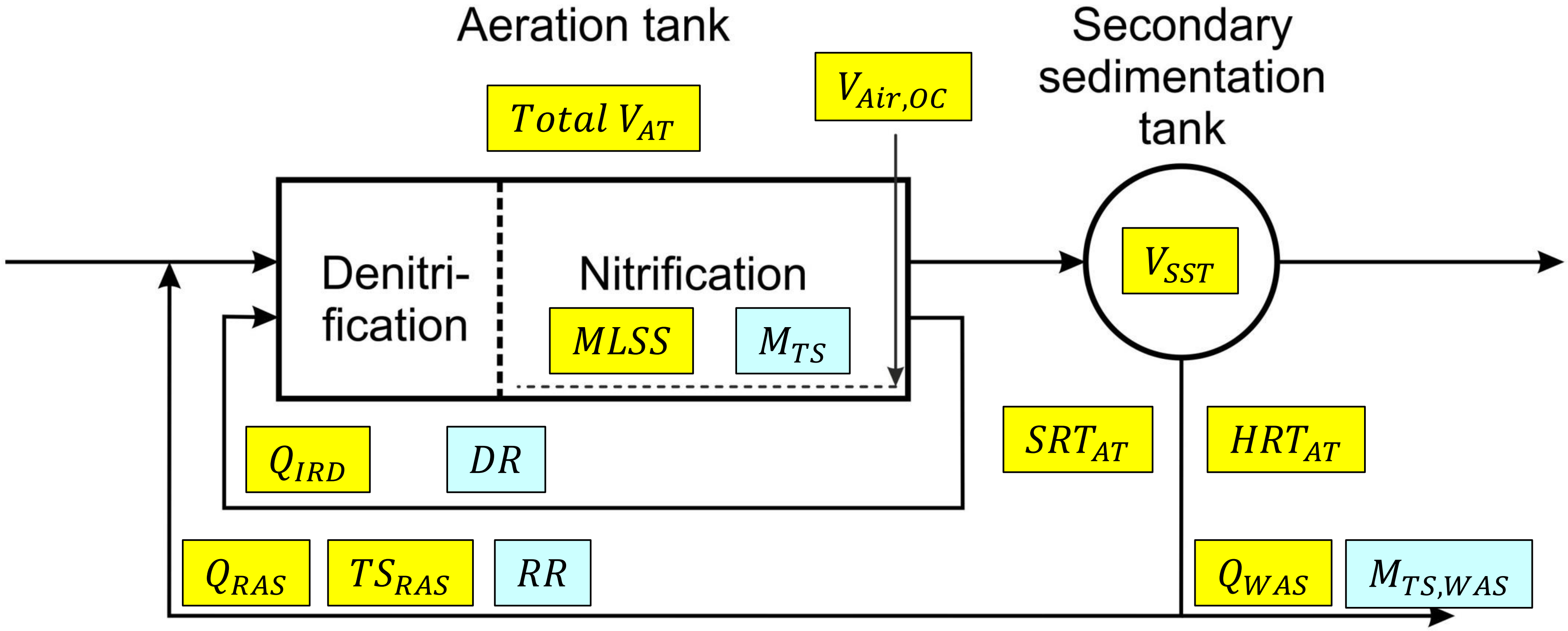
TS_{RAS} - Total Solids of recycle activated sludge

Q_{IRD} - Flow of internal recirculation for DN

$V_{Air.OC}$ - Volume of air / Oxidation capacity

SRT_{AT} - Sludge retention time

Dependent parameters of activated sludge plants



RR – RAS recycle ratio

M_{TS} – Mass of solids in the aeration tank

DR – Internal recirculation ratio for denitrification

$M_{TS,WAS}$ – Mass of solids removed by WAS

Sludge retention time in activated sludge process

Correction of my slide from last week

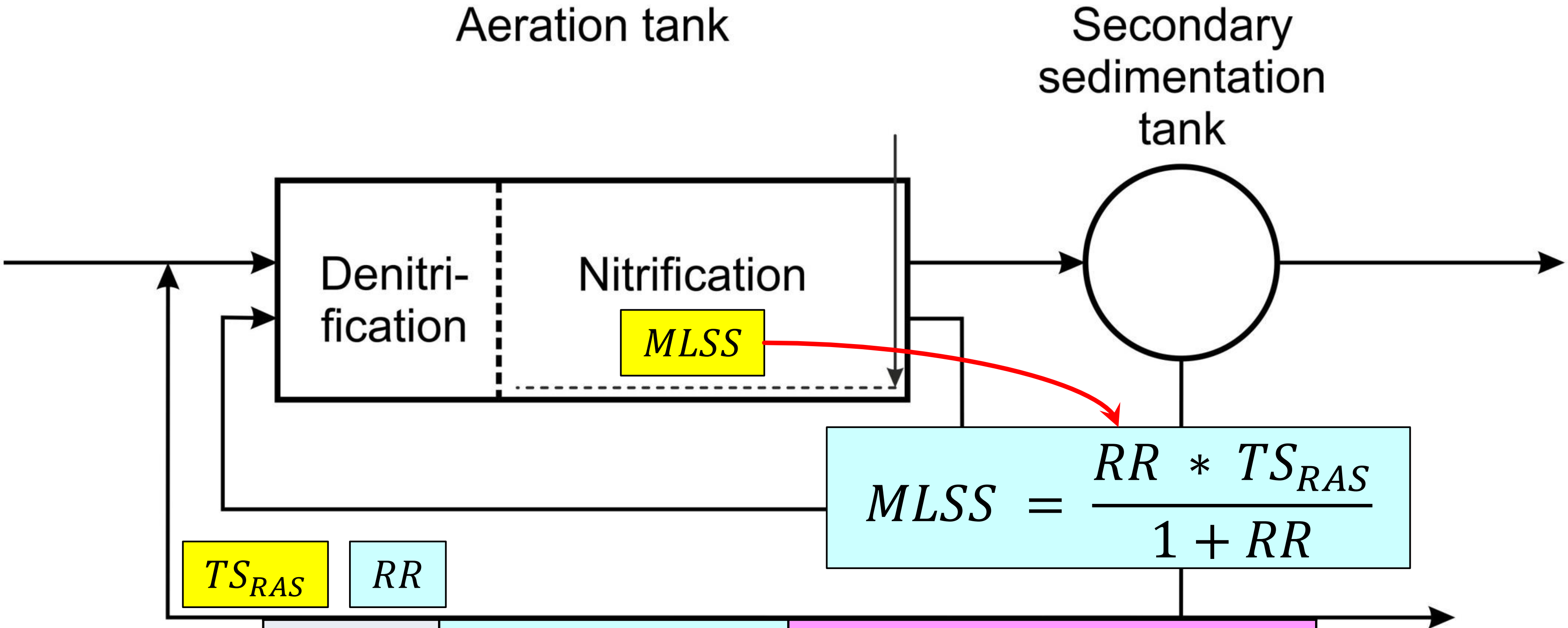
Treatment goal		Influent BOD load			
		Up to 1.200 kg/d		More than 6.000 kg/d	
Temperature		10° C	12° C	10° C	12° C
Without nitrification		5		4	
With nitrification		10	8,2	8	6,6
With nitrification and denitrification					
$\frac{V_D}{V_{BT}}$	0,2	12,5	10,3	10,0	8,3
	0,3	14,3	11,7	11,4	9,4
	0,4	16,7	13,7	13,3	11,0
	0,5	20,0	16,4	16,0	13,2

Design sludge retention time in days depending on the treatment goal and the temperature and the plant size (intermediate values are to be estimated)

Excerpt of table no. 2 in "ATV-DVWK-A 131 Bemessung von einstufigen Belebungsanlagen"

For WWTP Stahnsdorf applies $\frac{V_D}{V_{BT}} = 0.35$ therefore SRT should be between 11.4 and 13,3 d (we calculated 14.4 d, this is fine, because it's more)

What can WWTP Stahnsdorf do for increasing MLSS?



$$MLSS = \frac{RR * TS_{RAS}}{1 + RR}$$

$MLSS$ – Mixe

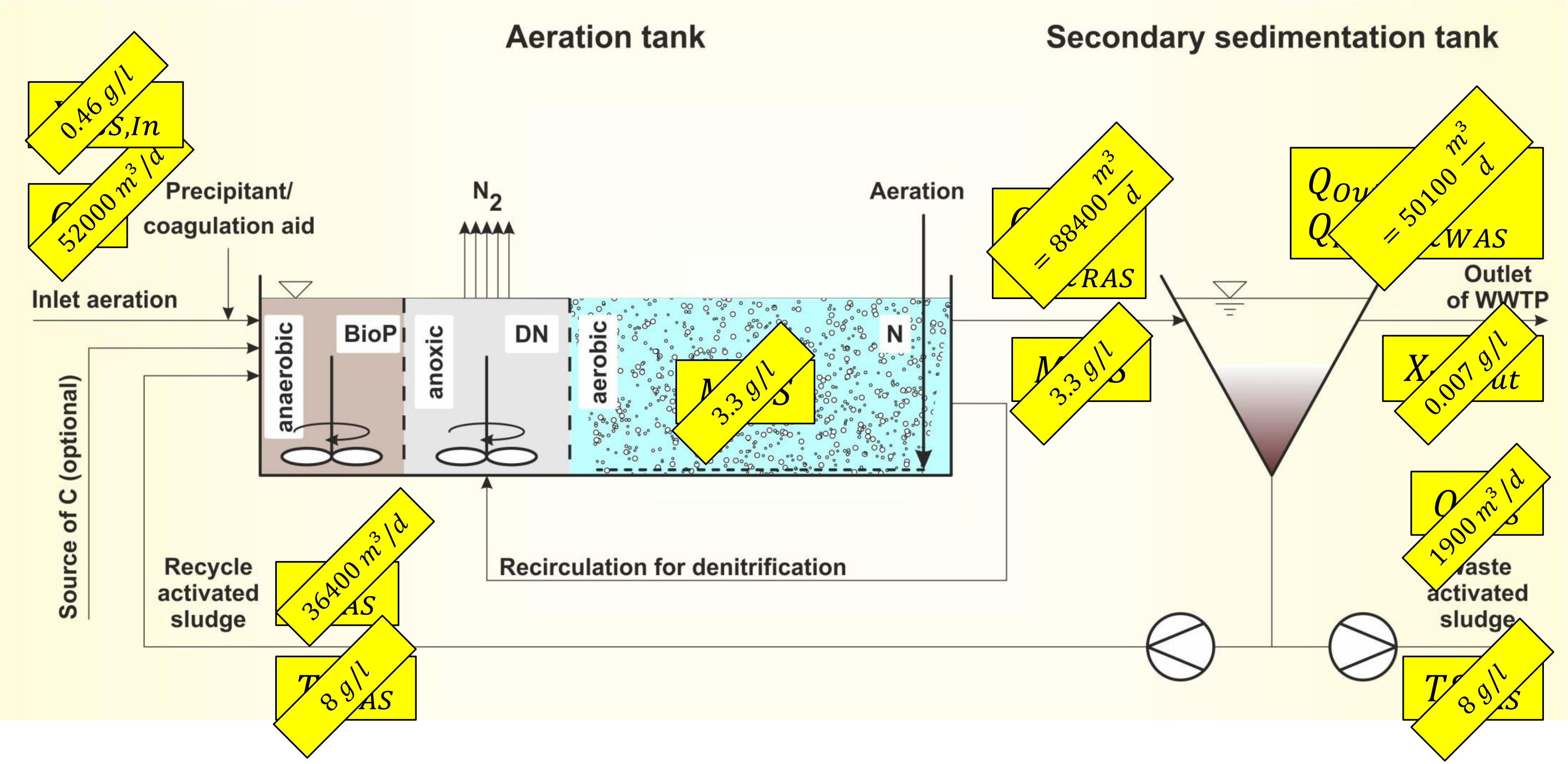
TS_{RAS} - Total

RR – RAS rec

	Current state	Increasing RR		
RR	0.7	1	1.25	1.5
$MLSS$	3.3	4.0	4.4	4.8
TS_{RAS}	8	8	8	8

Repetition: Flow and solids in WWTP Stahnsdorf

Completed flowsheet of WWTP Stahnsdorf:



Calculating mass of solids in WWTP Stahnsdorf

We know the solids concentration in the RAS of WWTP Stahnsdorf and we know the flow of WAS. Therefore we can calculate the total mass of solids which will be removed by WAS:

$$\boxed{M_{TS,WAS} = Q_{WAS} * TS_{RAS}}$$

$M_{TS,WAS}$ – Mass of solids which will be removed by WAS

Q_{WAS} – WAS flow

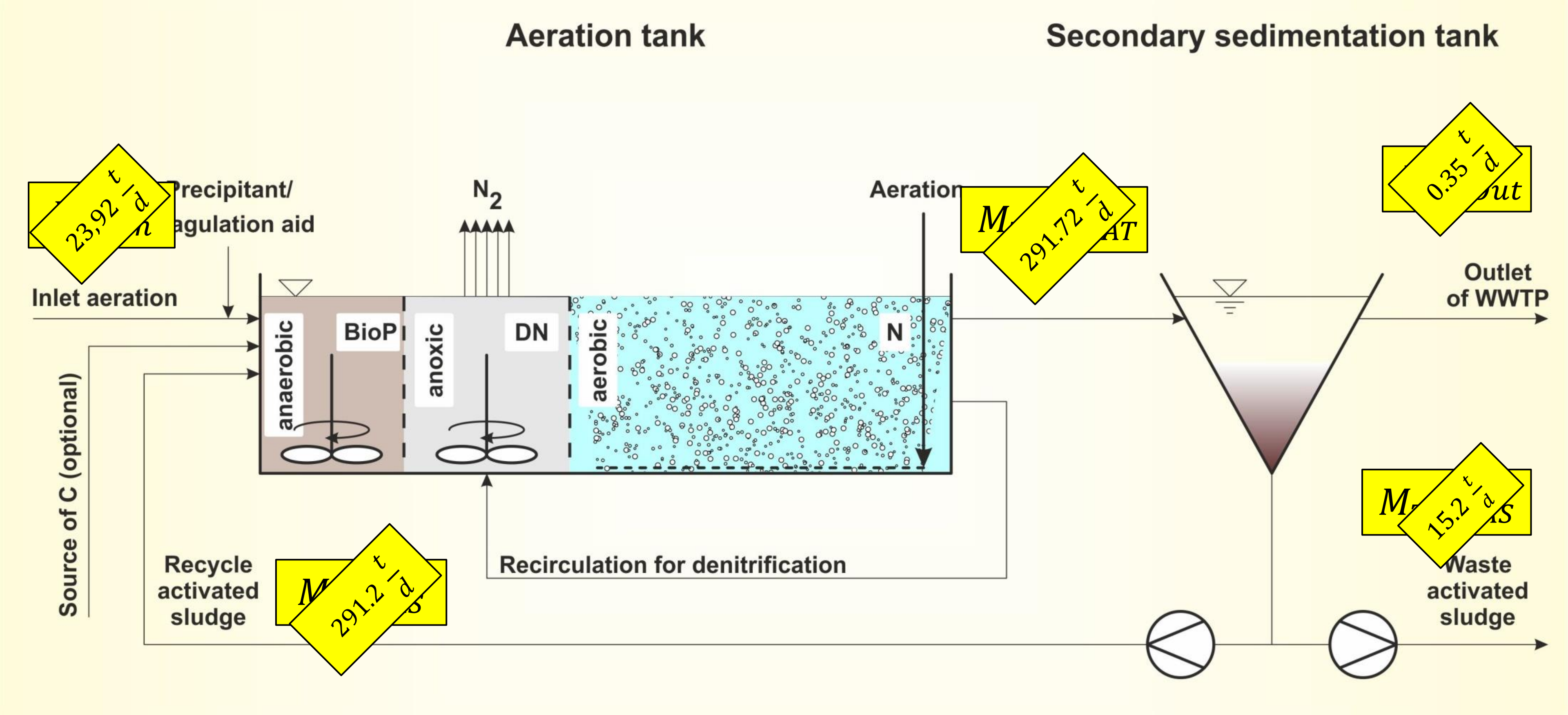
TS_{RAS} –Concentration of Suspended Solids in RAS

$$\boxed{M_{TS,WAS} = 1900 \frac{m^3}{d} * 8 \frac{kg}{m^3} = 15200 \frac{kg}{d}}$$

The same way we can calculate the influent and effluent solids, the RAS solids and the solids, entering the secondary sedimentation tank.

Balance of solids in WWTP Stahnsdorf

It is typical for the solids balance that it is not 100% correct. There are always a few differences, caused by measurement errors. This also applies for WWTP Stahnsdorf:



For instance we did not take into account the effluent solids. Please note that they are ridiculous compared to RAS solids.

Calculation of $M_{TS,WAS}$ without data from existing plants

For planning a new plant "on the green field“ or planning a biological step for an existing WWTP you don’t have data like we had from WWTP Stahnsdorf. Therefore you have to go other ways.

$$M_{TS,WAS} = M_{TS,C} + M_{TS,P}$$

$M_{TS,WAS}$ - Mass of solids which has to be removed by wastage

$M_{TS,C}$ - Mass of solids resulting of biomass growth by removal of organics

$M_{TS,P}$ - Mass of solids resulting from the precipitation of phosphorus

$$M_{TS,C} = L_{BOD,In} * \left(0.75 + 0.6 * \frac{X_{TS,In} * (1-0.2) * 0.17 * 0.75 * SRT_{AT} * F_T}{C_{BOD,In} * (1 + 0.17) * SRT_{AT} * F_T}\right)$$

$L_{BOD,In}$ - Daily influent BOD Load

$X_{TS,In}$ - Influent solids concentration

$C_{BOD,In}$ - Influent BODconcentration

SRT_{AT} - Sludge retention time

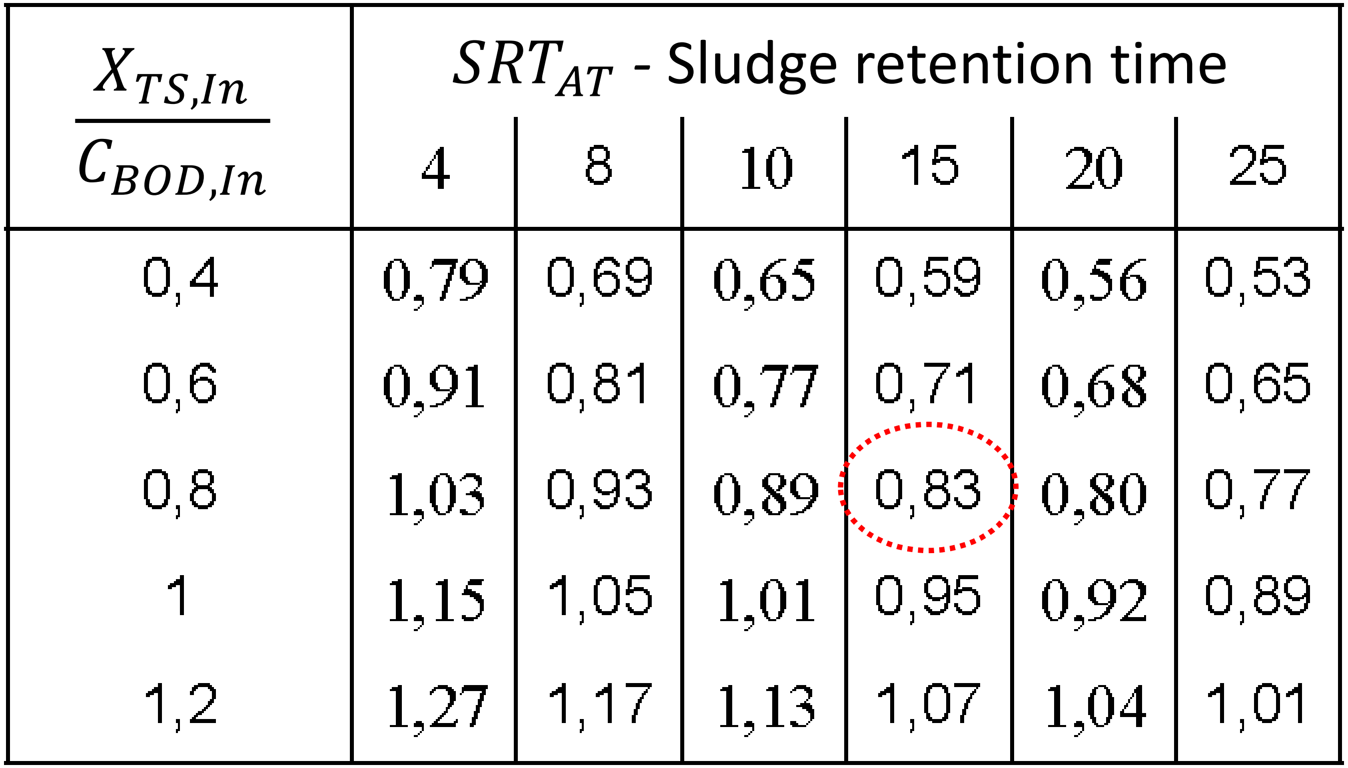
$$F_T = 1.072^{(T-15)}$$

F_T - Correcting factor for temperature

T – Design temperature

Calculation of $M_{TS,WAS}$ without data from existing plants

Basic values resulting of the empiric formula regarding $M_{TS,C}$ are listed in the table below:



$\frac{X_{TS,In}}{C_{BOD,In}}$	SRT_{AT} - Sludge retention time					
	4	8	10	15	20	25
0,4	0,79	0,69	0,65	0,59	0,56	0,53
0,6	0,91	0,81	0,77	0,71	0,68	0,65
0,8	1,03	0,93	0,89	0,83	0,80	0,77
1	1,15	1,05	1,01	0,95	0,92	0,89
1,2	1,27	1,17	1,13	1,07	1,04	1,01

Specific Production of sludge by removal of C at 10…12°C in $\frac{kg\ TS}{kg\ BOD_5}$

Excerpt of table no. 5 in "ATV-DVWK-A 131 Bemessung von einstufigen Belebungsanlagen"

WWTP Stahnsdorf:

$SRT_{AT} = 14.4\ d$

$\frac{X_{TS,In}}{C_{BOD,In}} = \frac{283\ mg/l}{363\ mg/l} = 0.78$

The longer the sludge retention time the smaller WAS solids resulting from C removal. But the bigger the value of $X_{TS,In}$ divided by $C_{BOD,In}$ the more solids are produced by C removal.

Calculation of $M_{TS,WAS}$ without data from existing plants

$M_{TS,C}$ for WWTP Stahnsdorf

$$M_{TS,C} = 18900\ \frac{kg\ BOD_5}{d} * 0.83\ \frac{kg\ TS}{kg\ BOD_5} = 15687\ \frac{kg\ TS}{d}$$

$$M_{TS,P} = Q_d * \left(3 * X_{P,BioP} + 6.8 * X_{P,prec,Fe} + 5.3 * X_{P,prec,Al}\right)$$

$M_{TS,P}$ - Mass of solids resulting from the precipitation of phosphorus	
$X_{P,BioP}$ - Phosphorus bound in biomass by biological removal of P	(4.5 mg/l)
$X_{P,prec,Fe}$ - Phosphorus removed by precipitation with Fe	(1.5 mg/l)
$X_{P,prec,Al}$ - Phosphorus removed by precipitation with Al	(- mg/l)

$M_{TS,P}$ for WWTP Stahnsdorf

$$M_{TS,P} = 52000 * (3 * 4.5 + 6.8 * 1.5) = 1232\ \frac{kg\ TS}{d}$$

WWTP Stahnsdorf solids in summa:

$$M_{TS,WAS} = 15687 + 1232 \approx 16900\ \frac{kg\ TS}{d}$$

Calculation of $M_{TS,WAS}$ without data from existing plants

Compared to the measured $M_{TS,WAS}$ of 15.2 t/d the calculated $M_{TS,WAS}$ of 16.9 t/d seems to be an overestimation.
However, in terms of mud calculation, this is a pretty good match!

Calculation of M_{TS} without data from existing plants

The mass of excess solids removal per day on the one hand and the SRT on the other hand leads to the mass of solids needed in the aeration tank:

$$\boxed{M_{TS} = SRT_{AT} * M_{TS,WAS}}$$

M_{TS} - Mass of solids within the aeration tank

SRT_{AT} - Sludge retention time

$M_{TS,WAS}$ - Mass of solids which has to be removed by wastage

WWTP Stahnsdorf:

$SRT_{AT} = 14.4\ d$

$M_{TS,WAS} = 16900\ kg/d$

$$\boxed{M_{TS} = 14.4\ d * 16900 \frac{kg}{d} = 243360\ kg}$$

Compared to the existing M_{TS} of about 218.5 t the calculated M_{TS} of 243.4 t seems to be an overestimation too.
The oversizing of individual quantities, however, is propagated by the above formula. Also here it is a pretty good match!

Calculation of $Total\ V_{AT}$ without data from existing plants

The mass of solids needed and the solids concentration allow for calculating the needed volume of the aeration tank:

$$\boxed{Total\ V_{AT} = \frac{M_{TS}}{MLSS}}$$

$Total\ V_{AT}$ - Total volume of the aeration tank

M_{TS} - Mass of solids within the aeration tank

$MLSS$ – Mixed Liquor Suspended Solids

WWTP Stahnsdorf:

$M_{TS} = 243360\ kg$

$MLSS = 3.3\ kg/m^3$

$$\boxed{Total\ V_{AT} = \frac{243360\ kg}{3.3\ kg/m^3} = 73745\ m^3}$$

Compared to the existing $Total\ V_{AT}$ of $66200\ m^3$ the calculated $Total\ V_{AT}$ of $73745\ m^3$ seems to be oversized too. But the percentage of oversizing of $Total\ V_{AT}$ is the same as for M_{TS} which is propagated. Again it is a pretty good match!

Overview: $Total\ V_{AT}$, M_{TS}, $MLSS$, $M_{TS,WAS}$ and SRT_{AT}

Volume of the whole aeration tank

$$Total\ V_{AT} \geq \frac{M_{TS,WAS} * SRT_{AT}}{MLSS} = \frac{M_{TS}}{MLSS}\ [m^3]$$

Mass of suspended solids in the aeration tank

$$M_{TS,AT} = SRT_{AT} * M_{TS,WAS} = Total\ V_{AT} * MLSS\ [kg\ TS]$$

Mixed Liquor Suspended Solids

$$MLSS = \frac{RR * TS_{RAS}}{1 + RR}$$

🟥 Way of Calculation without data from existing plant

🟩 Proof of compliance

Overview: $Total\ V_{AT}$, M_{TS}, $M_{TS,WAS}$ and SRT_{AT}

Mass of suspended solids in the excess sludge

$$M_{TS,WAS} = \frac{M_{TS}}{SRT_{AT}} = M_{TS,C} + M_{TS,P} = Q_{WAS} * TS_{RAS} \left[\frac{kg}{d}\right]$$

Sludge retention time

$$SRT_{AT} = \frac{Total\ V_{AT} * MLSS}{M_{TS,WAS}} = \frac{M_{TS}}{M_{TS,WAS}}\ [d]$$

Way of Calculation without data from existing plant

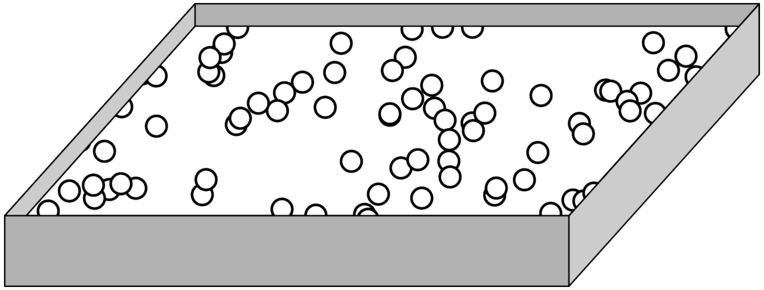
Proof of compliance

WWTP Stahnsdorf: $Total\ V_{AT}$, M_{TS}, $M_{TS,WAS}$ and SRT_{AT}

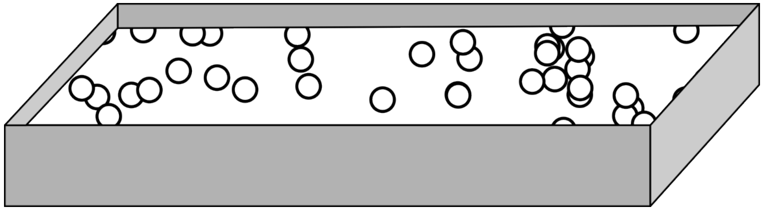
Design Parameter	Target according calculation	Current state according BWB	Remarks
$Total\ V_{AT}$	73,745 m³	= 66,200 m³	- 10%
M_{TS}	243.36 t	= 218.46 t	- 10%
$M_{TS,WAS}$	16.9 t/d	= 15.2 t/d	- 10%
SRT_{AT}	12.4 d	= 14.4 d	+ 17%
$MLSS$	3.3 g/l	= 3.5…5.0 g/l	$RR = 0.7$, $TS_{RAS} = 8\ g/l$

Relationship of $Total\ V_{AT}$, $MLSS$, M_{TS}, $M_{TS,WAS}$ and SRT_{AT}

Comparison of two activated sludge tanks with different volumes (constructed example):



$V_{AT,Length} = 80\ m$
$V_{AT,Width} = 25\ m$
$V_{AT,Depth} = 5\ m$
$\boldsymbol{V_{AT} = 10.000\ m^3}$



$V_{AT,Length} = 80\ m$
$V_{AT,Width} = \boldsymbol{12.5\ m}$
$V_{AT,Depth} = 5\ m$
$\boldsymbol{V_{AT} = 5000\ m^3}$

For both aeration tanks the following applies:

$MLSS = 3.500\ g\ TS/m^3$
$L_{d,BOD} = 5.000\ kg\ O_2/d$
$M_{TS,WAS} = 2.800\ kg\ TS/d$

Design specification :

$\boldsymbol{SRT_{AT} \geq 12\ d}$

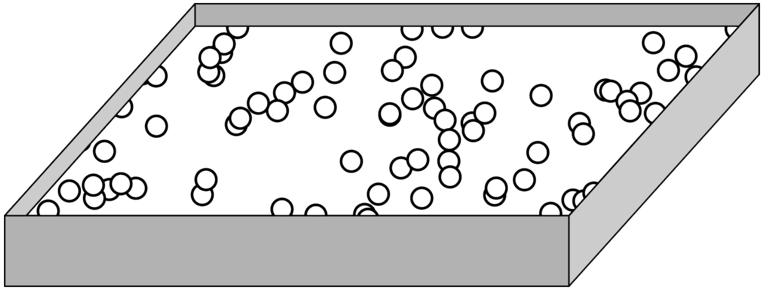
What does $M_{TS,WAS}$ depend on?

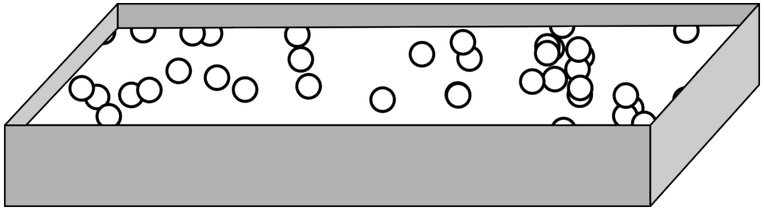
Or, in other words:

Can $M_{TS,WAS}$ be as high in the small aeration tank as in the big one?

Relationship of $Total\ V_{AT}$, $MLSS$, M_{TS}, $M_{TS,WAS}$ and SRT_{AT}

Comparison of two activated sludge tanks with different volumes (constructed example):





$$\boldsymbol{M_{TS}} = 10.000\ m^3 * 3{,}5\ kg\ TS/m^3$$

$$= \boldsymbol{35.000\ kg\ TS}$$

$$\boldsymbol{M_{TS}} = 5.000\ m^3 * 3{,}5\ kg\ TS/m^3$$

$$= \boldsymbol{17.500\ kg\ TS}$$

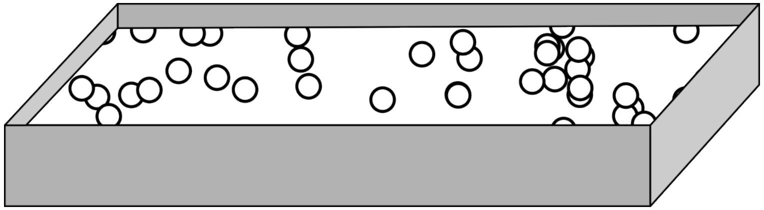
$$\boldsymbol{SRT_{AT}} = \frac{35.000\ kg\ TS}{2.800\ kg\ TS/d} = \boxed{\boldsymbol{12{,}5\ d}}$$

$$\boldsymbol{SRT_{AT}} = \frac{17.500\ kg\ TS}{2.800\ kg\ TS/d} = \boxed{\boldsymbol{6{,}25\ d}}$$

Can $M_{TS,WAS}$ in the small aeration tank for further calculation just be smaller to comply with SRT_{AT} of 12 d? If no, why not? Justify your answer!

Relationship of $Total\ V_{AT}$, $MLSS$, M_{TS}, $M_{TS,WAS}$ and SRT_{AT}

Comparison of two activated sludge tanks with different volumes (constructed example):



Ergo: Dimension of the small BB has to be changed!

Options:

- Increasing of ML
  (but $MLSS \leq 5$

and, if that alone is not enough, to keep SRT_{AT} within the permitted range

- Increasing of V_{AT}

What options are available to bring the sludge age SRT_{AT} in the small tank into the green zone?

$$\boldsymbol{M_{TS}} = 5.000\ m^3 * 5{,}0\ kg\ TS/m^3 = 25.000\ kg\ TS$$

$$SRT_{AT} = \frac{25.000\ kg\ TS}{2.800\ kg\ TS/d} = \mathbf{8{,}9\ d}$$

$$\boldsymbol{min.\ M_{TS}} = SRT_{AT} * M_{TS,WAS}$$

$$= 12\ d * 2.800\ kg\ TS/d = 33.600\ kg\ TS$$

$$= \frac{33.600\ kg\ TS}{5\ kg\ TS/m^3} = 6.720\ m^3$$

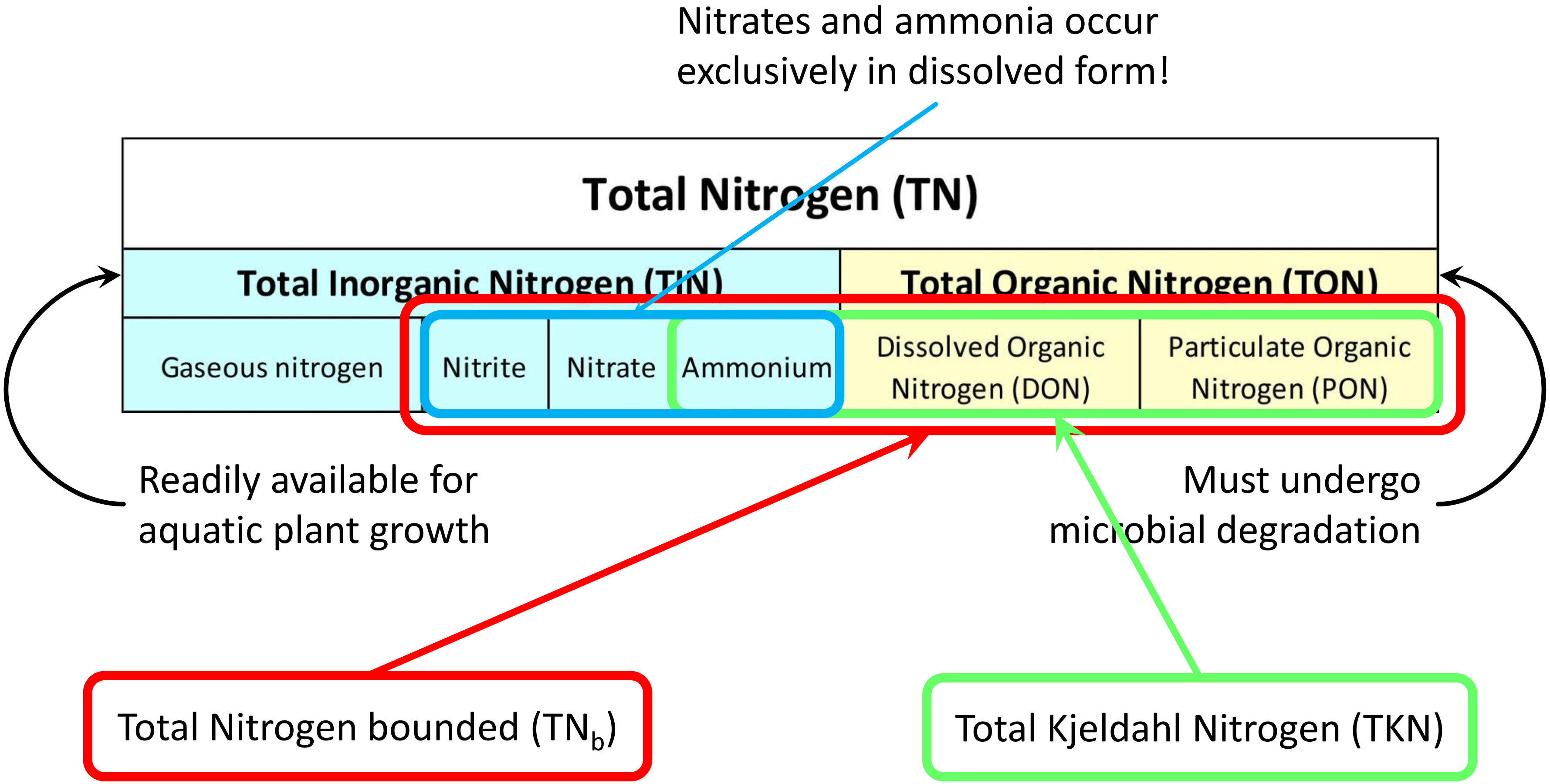
chosen: $V_{AT,Width} = 17{,}0\ m$

$$17\ m * 80\ m * 5\ m = 6.800\ m^3$$

$$SRT_{AT} = \frac{6.800\ m^3 * 5\ kg\ TS/m^3}{2.800\ kg\ TS/d} = \mathbf{12{,}1\ d}$$

Nitrification / Denitrification

Repetition: Fractions of nitrogen in water / wastewater



Nitrates and ammonia occur exclusively in dissolved form!

Total Nitrogen (TN)					
Total Inorganic Nitrogen (TIN)				Total Organic Nitrogen (TON)	
Gaseous nitrogen	Nitrite	Nitrate	Ammonium	Dissolved Organic Nitrogen (DON)	Particulate Organic Nitrogen (PON)

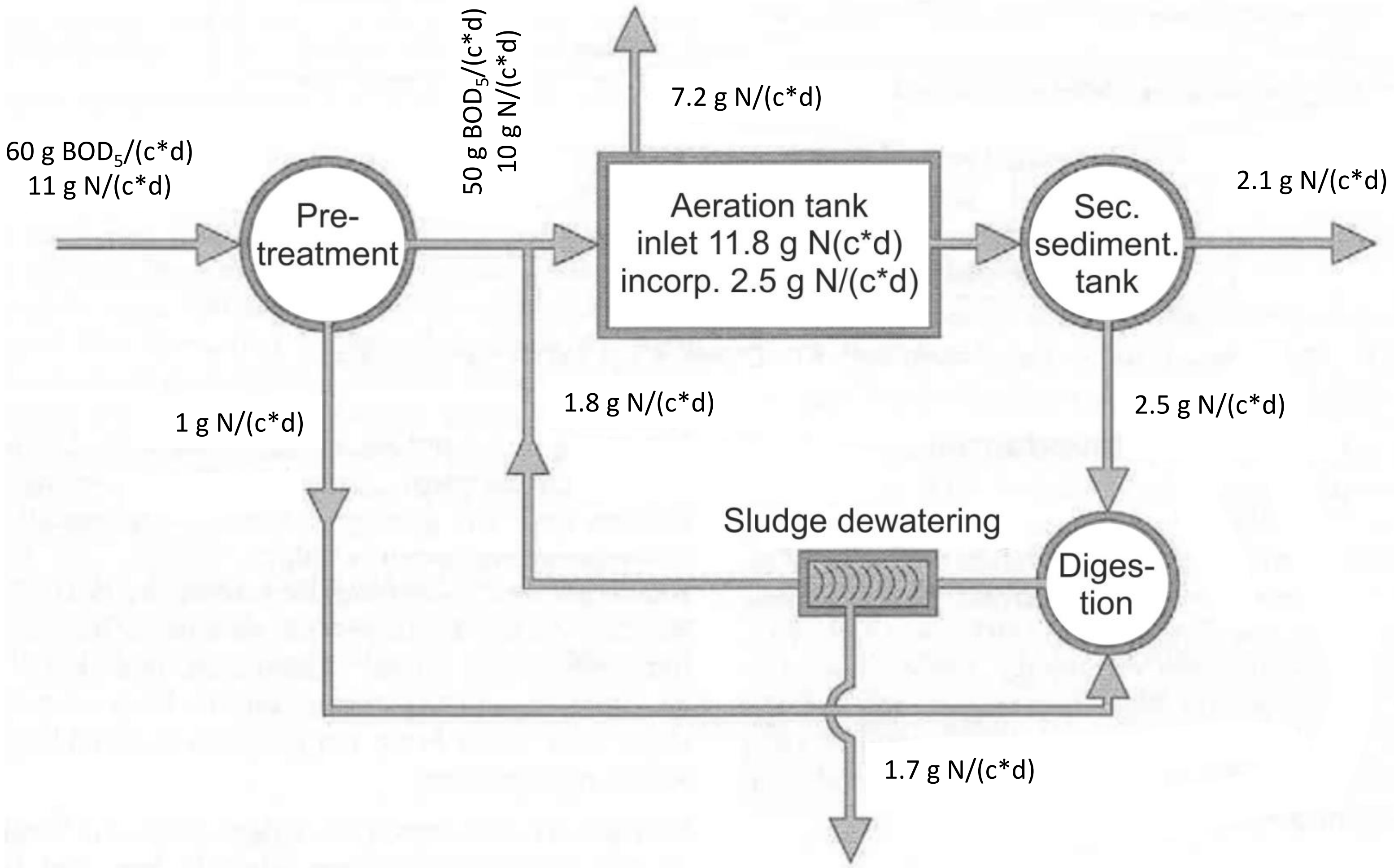
Readily available for aquatic plant growth

Must undergo microbial degradation

Total Nitrogen bounded (TN_b)

Total Kjeldahl Nitrogen (TKN)

Nitrogen balance in sewage treatment plants



60 g BOD_5/(c*d)
11 g N/(c*d)

Pre-treatment

50 g BOD_5/(c*d)
10 g N/(c*d)

7.2 g N/(c*d)

Aeration tank
inlet 11.8 g N(c*d)
incorp. 2.5 g N/(c*d)

Sec. sediment. tank

2.1 g N/(c*d)

1 g N/(c*d)

1.8 g N/(c*d)

2.5 g N/(c*d)

Sludge dewatering

Diges-tion

1.7 g N/(c*d)

Nitrification / Denitrification

How much oxygen is consumed to completely oxidize 1 g of NH_4-N?

Reaction equation :

$$NH_4^+ + 2\ O_2 \rightarrow NO_3 + H_2O + H_2^+$$

Atomic weights : N=14, H = 1, O = 16

Molecular weight of ammonium nitrogen: $\boxed{14\ g\ N}$

Molecular weight of oxygen: $\boxed{16 * 2 = \frac{32g}{mole\ O_2}}$

To oxidize 1 mole of NH_4-N, 2 moles of oxygen are consumed, i. H.:
64 g oxygen per 14 g NH_4-N are required. After that follows:

$$\boxed{\frac{64\ g\ O_2}{14\ g\ NH_4 - N} = \frac{4{,}57\ g\ O_2}{g\ NH_4 - N}}$$

Nitrification / Denitrification

But: The conversion of the ammonium nitrogen by nitrification is not as oxidation in the strictly stoichiometric ratio, because it is a biological metabolism. Part of the nitrogen is incorporated into the cells of the nitrifying bacteria. This cell yield reduces the actually required oxygen demand.
Usually one therefore expects:

$$\boxed{\frac{4{,}3\ g\ O_2}{g\ NH_4 - N}}$$

Nitrification / Denitrification

How much oxygen is recovered during denitrification per g of NO_3-N??

Reaction equation:

$$NO_3^- + ½\ H_2O \rightarrow ½\ N_2 + {}^5/_2\ O + OH^-$$

Molecular weight of nitrate nitrogen:

$$\boxed{14\ g\ N}$$

In other words, 1 mole of nitrate nitrogen weighs 14 g

Recovery of oxygen:

$$\boxed{\frac{5}{2} \cdot 16 = 40\ g\ O_2}$$

In other words: Recovery of oxygen is *40 g*

$$\boxed{\frac{40\ \frac{g\ O_2}{Mol\ NO_3 - N}}{14\ \frac{g}{Mol\ NO_3 - N}} \approx 2{,}9 \frac{g\ O_2}{g\ NO_3 - N}}$$

Nitrification / Denitrification

How is the oxygen balance of nitrification / denitrification?

Oxygen demand for nitrification:

$$4{,}3\,\frac{g\;O_2}{g\;NH_4-N}$$

Recovery of oxygen by denitrification:

$$2{,}9\,\frac{g\;O_2}{g\;NO_3-N}$$

$$\frac{2{,}9\;\dfrac{g\;O_2}{g\;NO_3-N}}{4{,}3\;\dfrac{g}{g\;NH_4-N}}=0{,}67$$

In other words:

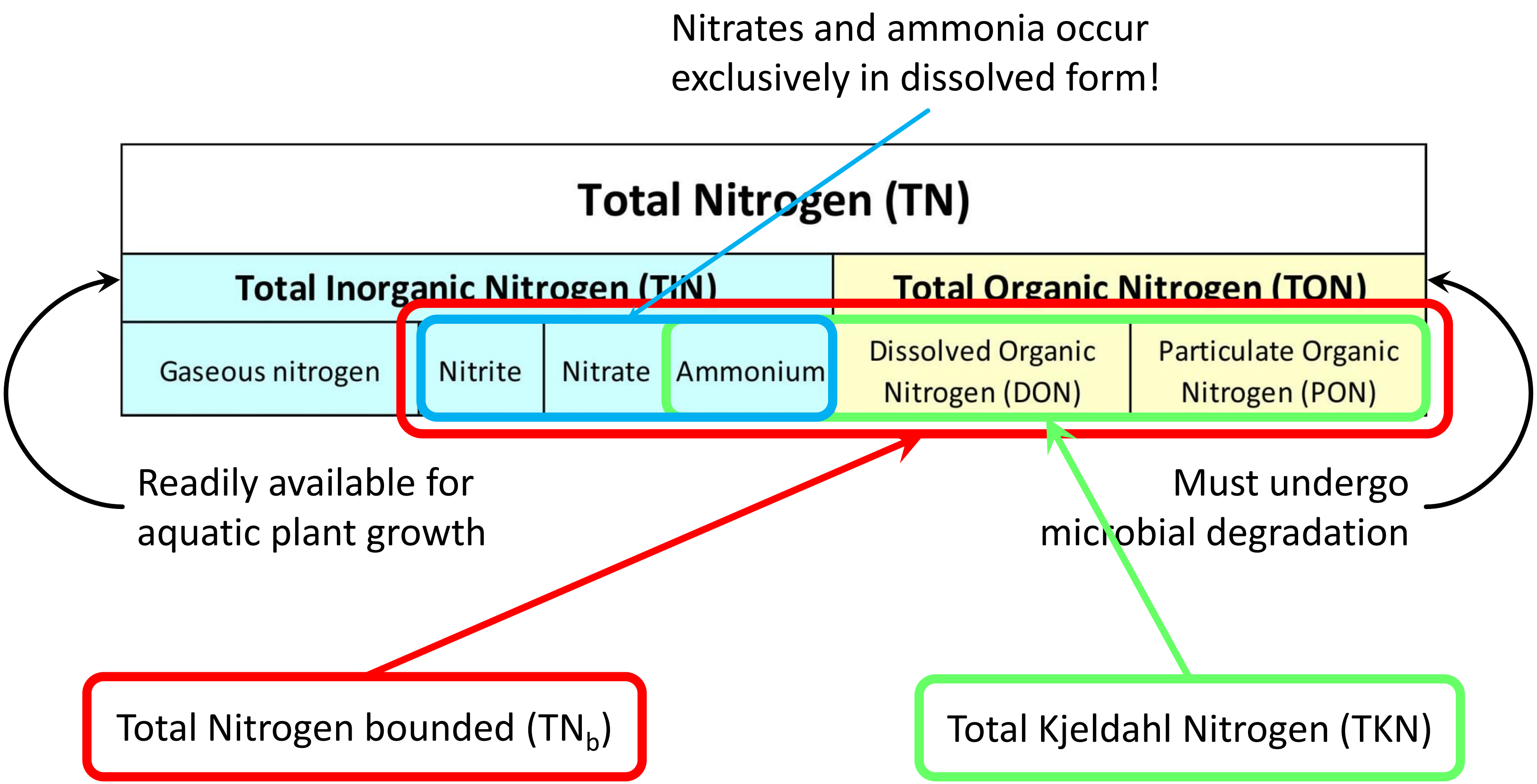
In denitrification, about 2/3 of the oxygen consumption from nitrification can be recovered.

6th Lecture

Biological wastewater treatment:
Design of Nitrification/Denitrification
Oxygen demand / Design of Aeration
Design of secondary sedimentation tanks

Nitrification / Denitrification

Repetition: Fractions of nitrogen in water / wastewater



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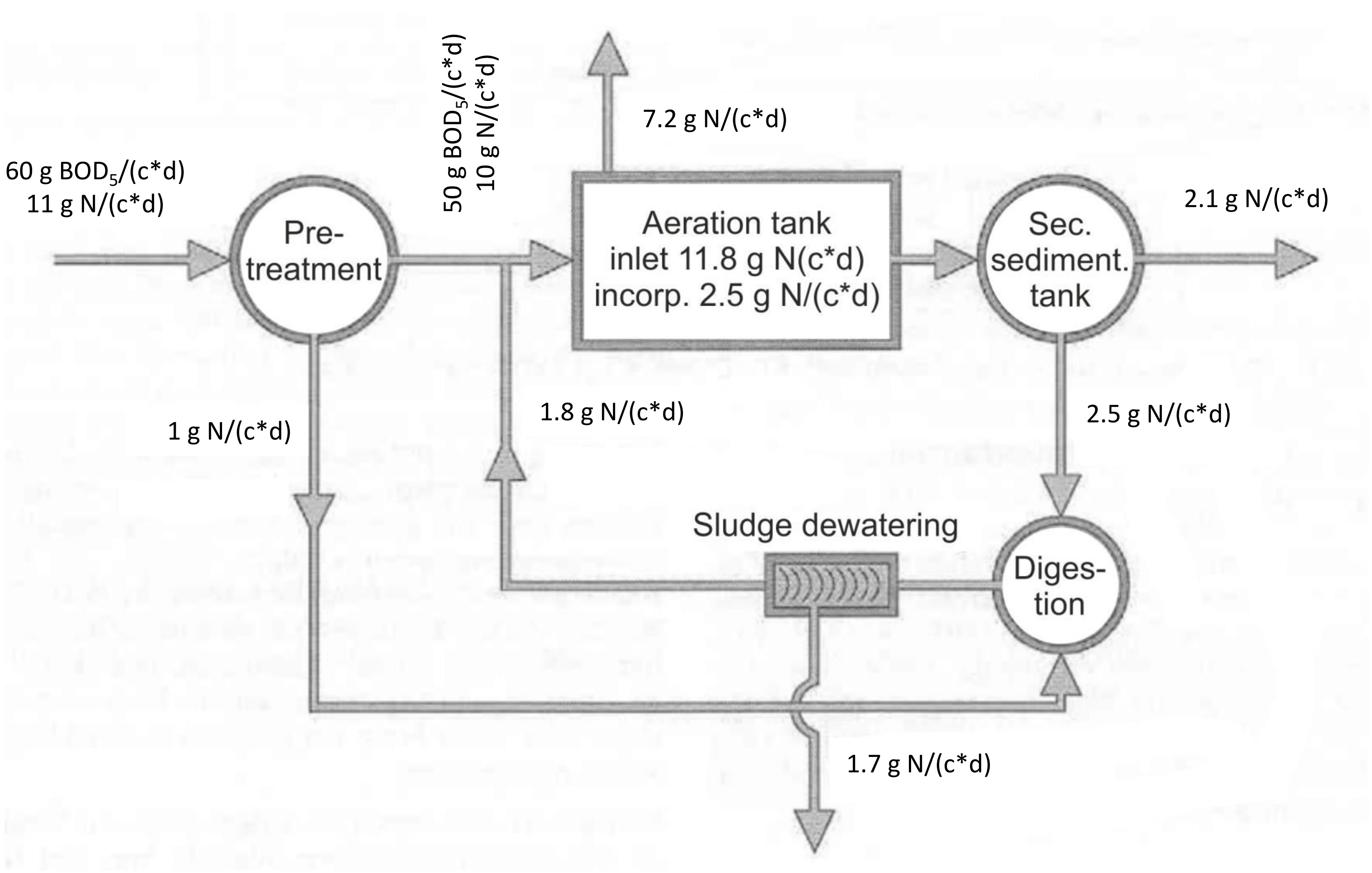

60 g BOD_5/(c*d)
11 g N/(c*d)

50 g BOD_5/(c*d)
10 g N/(c*d)

7.2 g N/(c*d)

2.1 g N/(c*d)

1 g N/(c*d)

1.8 g N/(c*d)

2.5 g N/(c*d)

1.7 g N/(c*d)

Nitrification / Denitrification

How much oxygen is consumed to completely oxidize 1 g of NH_4-N?

Reaction equation :

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Nitrification / Denitrification

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Usually one therefore expects:

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Nitrification / Denitrification

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Nitrification / Denitrification

How is the oxygen balance of nitrification / denitrification?

Oxygen demand for nitrification:

$$4{,}3\,\frac{g\;O_2}{g\;NH_4-N}$$

Recovery of oxygen by denitrification:

$$2{,}9\,\frac{g\;O_2}{g\;NO_3-N}$$

$$\frac{2{,}9\;\frac{g\;O_2}{g\;NO_3-N}}{4{,}3\;\frac{g}{g\;NH_4-N}}=0{,}67$$

In other words:

In denitrification, about 2/3 of the oxygen consumption from nitrification can be recovered.

Nitrification / Denitrification

Reaction equation for nitrification:

$$\mathbf{NH_4^+ + 2\ O_2 \rightarrow NO_3 + H_2O + H_2^+}$$

The nitrification is characterized by high oxygen consumption (1 g NH_4-N requires 4.3 g 0_2) and high acid production (1 mole NH_4-N forms 2 mole H^+).

How does the pH change during nitrification?

Reaction equation for denitrification:

$$\mathbf{NO_3^- + \tfrac{1}{2}\ H_2O \rightarrow \tfrac{1}{2}\ N_2 + {}^{5}/_{2}\ O + OH^-}$$

The denitrification is characterized by a gain in oxygen (1 g NO_3-N provides 2.9 g O_2) and by a base production which half neutralizes the acid formed in the nitrification (1 mole NO_3-N forms 1 mole OH^-).

Calculation of DR and Q_{IRD}

$$DR = \frac{S_{NH4,In}}{S_{NO3,Out}} - 1 = \frac{Q_{RAS}}{Q_{In}} + \frac{Q_{IRD}}{Q_{In}}$$

$$Q_{IRD} = DR * Q_{In} - Q_{RAS} = (DR - RR) * Q_{In}$$

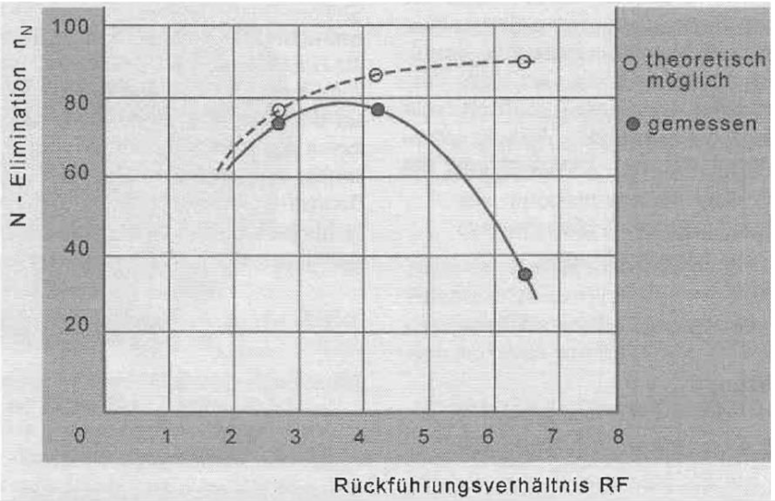
DR	Internal recirculation ratio for denitrification for which the pumps have to be designed
$S_{NH4,In}$	Ammonia nitrogen which has to be oxidized
$S_{NO3,Out}$	Concentration of nitrate N which has to be met in the effluent of the WWTP
Q_{RAS}	Flow of recycle activated sludge
Q_{IRD}	Flow of internal recirculation for denitrification
Q_{In}	Flow inlet aeration tank (maximum dry weather influent)
RR	RAS recycle ratio

Calculation of DR

$$\boxed{\eta_D \leq 1 - \frac{1}{1+DR}}$$

η_D	Maximum possible efficiency of denitrification
DR	Internal recirculation ratio for denitrification for which the pumps have to be designed

The equation on the previous slide only accounts for the resulting efficiency due to the available nitrate. The theoretical values, however, are often inconsistent with the practice values, as negative effects occur due to oxygen transport into the denitrification stage, dilution and decreasing contact time.



aus LONDONG, 2009

WWTP Stahnsdorf: Calculation of DR and Q_{IRD}

$S_{NH4,In}$ Influent concentration of NH_4-N

$$DR = \frac{82{,}2\ mg\ N/l}{9{,}1\ mg\ N/l} - 1 = 8.0$$

The calculated value exceeds the optimum (see previous slide). Therefore, DR is chosen to be 3.

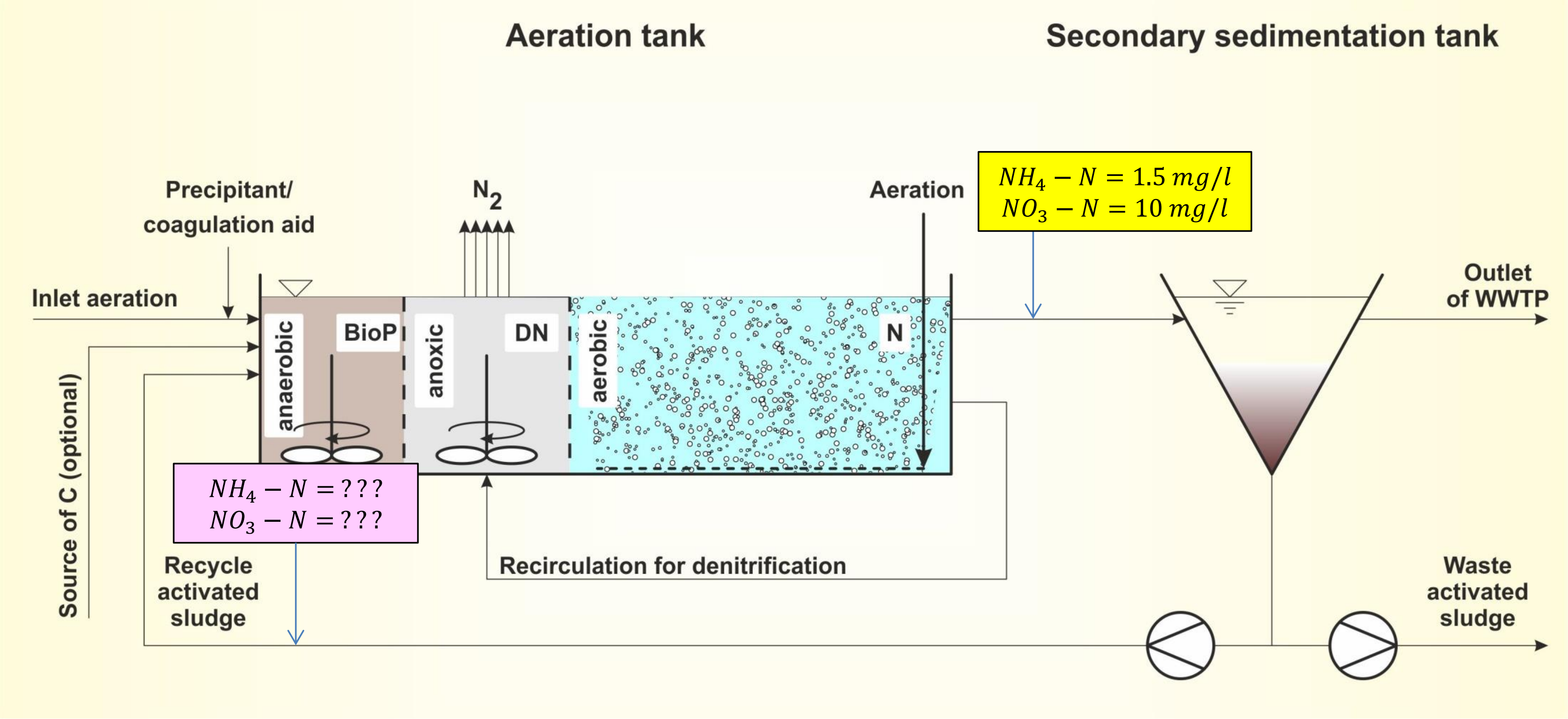
$S_{NO3,AN}$ Concentration of nitrate N which has to be met in the effluent of the WWTP

$$Q_{IRD} = DR * Q_{In} - RR * Q_{In} = (DR - RR) * Q_{In}$$

$$Q_{IRD} = (3 - 0{,}7) * 2167 m^3/h = 4983 \approx 5.000\ m^3/h$$

Why should the volumetric flow of recycled activated sludge be taken into account when calculating the volume flow of nitrate-containing wastewater from the nitrification to be recycled for denitrification?

Calculation of DR and Q_{IRD}



$NH_4 - N = 1.5\,mg/l$
$NO_3 - N = 10\,mg/l$

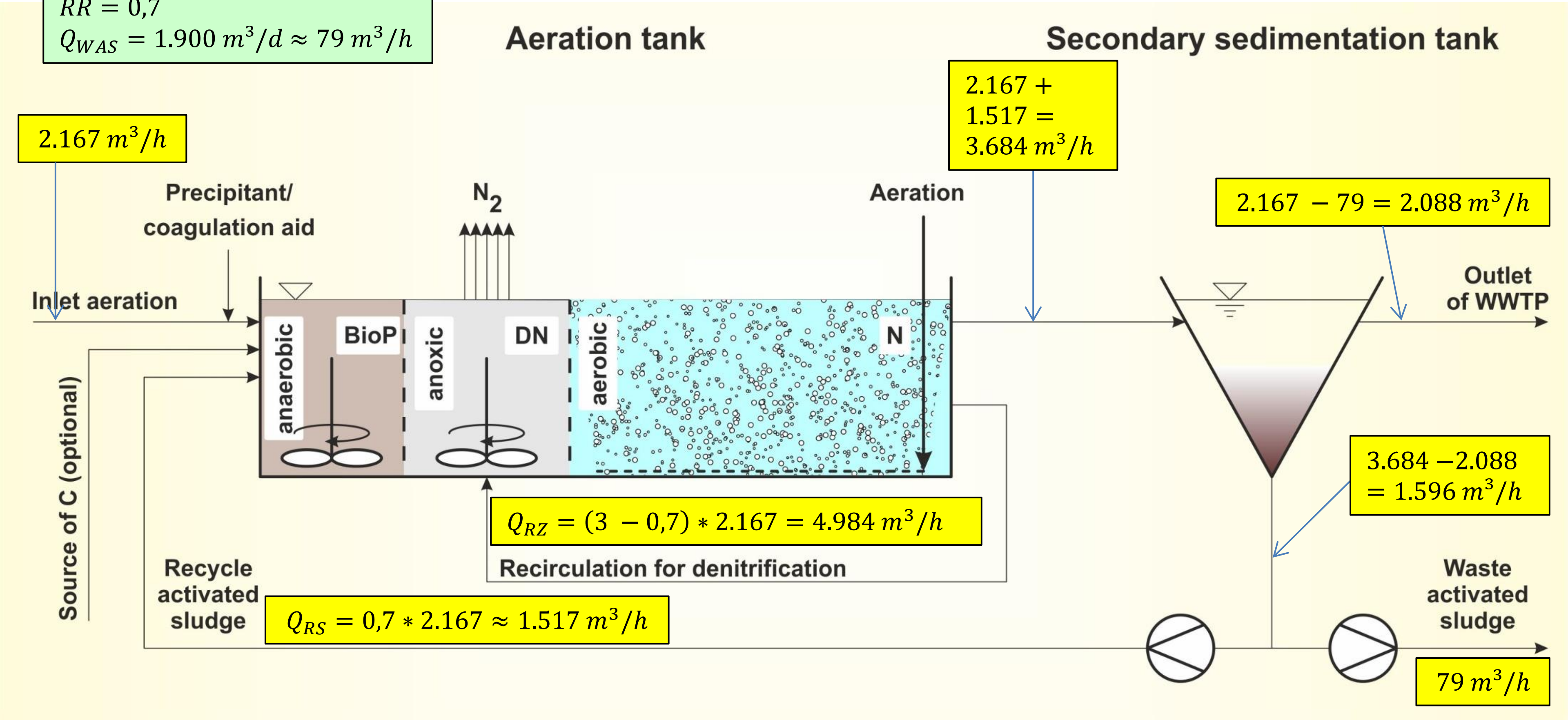
$NH_4 - N = ???$
$NO_3 - N = ???$

What is the concentration of nitrate and ammonia in RAS? Give reasons for your opinion!

WWTP Stahnsdorf: Flow balance completed

$Q_{In} = 2.167\ m^3/h$
$DR = 3$
$RR = 0,7$
$Q_{WAS} = 1.900\ m^3/d \approx 79\ m^3/h$

(dry weather conditions)



$2.167\ m^3/h$

$2.167 + 1.517 = 3.684\ m^3/h$

$2.167 - 79 = 2.088\ m^3/h$

$3.684 - 2.088 = 1.596\ m^3/h$

$Q_{RZ} = (3 - 0,7) * 2.167 = 4.984\ m^3/h$

$Q_{RS} = 0,7 * 2.167 \approx 1.517\ m^3/h$

$79\ m^3/h$

Aeration

Which influencing factors determine the oxygen requirement of the aeration?

Aeration

Which influencing factors determine the oxygen requirement of the aeration?

Inlet concentration of BOD in the aeration tank	$C_{BOD,In}$
COD removed by WAS	$X_{COD,WAS}$
Inert soluble COD which leaves the secondary settlement tank	$S_{COD,inert,Out}$
Oxygen demand for nitrification	$OD_{d,N}$
Oxygen recovery from denitrification	$OR_{d,D}$
Impact factor of oxygen consumption for carbon elimination	f_C
Impact factor of oxygen consumption for nitrification	f_N

Aeration

Flashback oxygen balance N/DN:

Oxygen consumption for nitrification:

$$\boxed{4{,}3\,\frac{g\ O_2}{g\ NH_4-N}}$$

Oxygen recovery by denitrification:

$$\boxed{2{,}9\,\frac{g\ O_2}{g\ NO_3-N}}$$

$$\boxed{\frac{2{,}9\ \dfrac{g\ O_2}{g\ NO_3-N}}{4{,}3\ \dfrac{g}{g\ NH_4-N}}=0{,}67}$$

In other words:

In denitrification, about 2/3 of the oxygen consumption from nitrification is recovered.

Oxygen consumption for elimination of C

Determination according to empirical formula by HARTWIG (only valid for $\frac{C_{COD,In}}{C_{BOD,In}} \leq 2,2$):

$$\boxed{OD_{d,C} = L_{d,BOD,In} * \left(0{,}56 + \frac{0{,}15 * SRT_{AT} * F_T}{1 + 0{,}17 * SRT_{AT} * F_T}\right)}$$

$OD_{d,C}$ – Daily oxygen demand for elimination of carbonaceous substances

$L_{BOD,In}$ – Daily influent BOD Load

SRT_{AT} – Sludge retention time

F_T – Correcting factor for temperature

T – Design temperature

$$\boxed{F_T = 1.072^{(T-15)}}$$

Which temperature should be chosen here for design to be on the safe side? Highest? Deepest? Average? Justify your decision!

Oxygen consumption for elimination of C

Determination via oxygen balance (always valid, is binding for $\frac{C_{COD,In}}{C_{BOD,In}} > 2,2$):

$$OD_{d,C} = \frac{Q_d * \left(C_{COD,In} - S_{COD,inert,Out} - X_{CSB,ÜS}\right)}{1.000}$$

$OD_{d,C}$ – Daily oxygen demand for elimination of carbonaceous substances

Q_d – Daily flow for dry weather (inlet aeration tank)

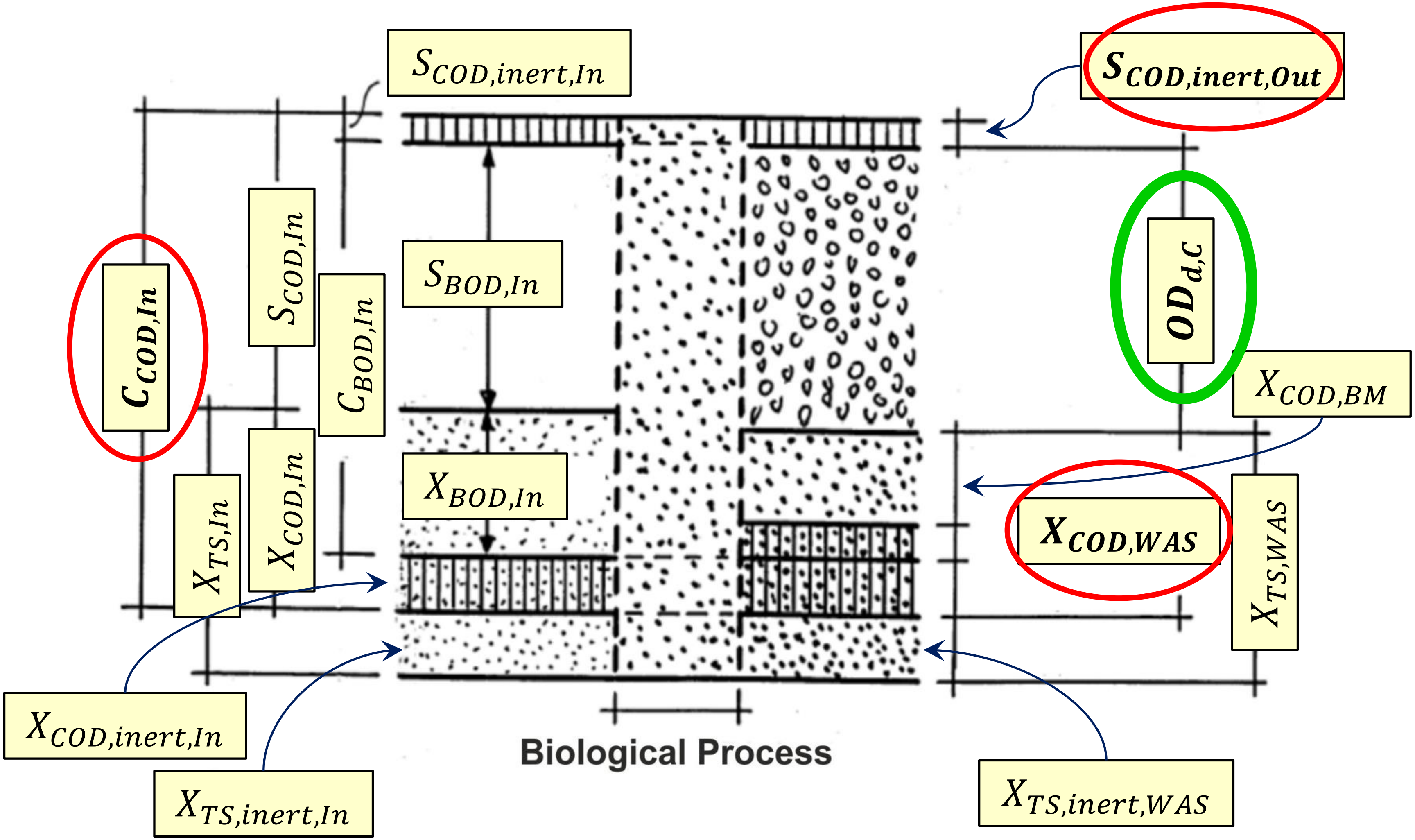
$C_{COD,In}$ – Inlet concentration of COD in the aeration tank

$S_{COD,inert,Out}$ – Inert soluble COD which leaves the secondary settlement tank

$X_{COD,WAS}$ – COD removed by WAS

Let’s use the following graph of change of COD and solids during the biological treatment for explaining the above calculation formula!

COD elimination by activated sludge process



Metabolism of COD and solids in the biological treatment step

ATV-DVWK-A 131, 2000

Oxygen consumption for nitrification

Determination via nitrate oxygen balance:

$$OD_{d,N} = \frac{Q_d \ * 4{,}3 \ * \left(S_{NO3,D} - S_{NO3,In} + S_{NO3,Out}\right)}{1.000}$$

Daily oxygen consumption for nitrification	$OD_{d,N}$
Daily wastewater flow at dry weather conditions (inlet aeration tank)	Q_d
Concentration of nitrates which are to be denitrificated	$S_{NO3,D}$
Influent concentration of nitrates	$S_{NO3,In}$
Effluent concentration of nitrates	$S_{NO3,Out}$

Recovery of oxygen by denitrification

$$OR_{d,D} = \frac{Q_d * 2{,}9 * S_{NO3,D}}{1.000}$$

Daily recovery of oxygen by denitrification (= Oxygen consumption for the C-elimination, which is covered by the denitrification)	$OR_{d,D}$
Daily wastewater flow at dry weather conditions (inlet aeration tank)	Q_d
Concentration of nitrates which are to be denitrificated	$S_{NO3,D}$

Oxygen consumption - peak value OD_h

The peak oxygen consumption is calculated as follows :

$$OD_h = \frac{f_C \ * \ (OD_{d,C} \ - \ OD_{d,D}) + \ f_N \ * \ OV_{d,N}}{24}$$

Hourly oxygen consumption - peak value	OD_h
Impact factor of oxygen consumption for carbon elimination	f_C
Daily oxygen demand for elimination of carbonaceous substances	$OD_{d,C}$
Daily oxygen demand for elimination of carbonaceous substances which is covered by oxygen recovery from denitrification	$OR_{d,D}$
Impact factor of oxygen consumption for nitrification	f_N
Daily oxygen consumption for nitrification	$OD_{d,N}$

Oxygen consumption - peak value OD_h

f_C and f_N can be taken from the following table:

(from A 131)

	Sludge retention time in d					
	4	**6**	**8**	**10**	**15**	**25**
f_C	1.3	1.25	1.2	1.2	1.15	1.1
$f_N, L_{BOD,In} \leq 1200\ kg/d$	-	-	-	2.5	2.0	1.5
$f_N, L_{BOD,In} > 6000\ kg/d$	-	-	2.0	1.8	1.5	-

Values that apply for WWTP Stahnsdorf

Oxygen consumption - peak value OD_h

Because the oxygen peak for nitrification usually does not coincide in time with the oxygen peak for carbon elimination, the oxygen consumption peak must be calculated twice using the formula on the previous slide:

1. once with the appropriate value for the impact factor for the removal of carbonaceous substances f_C, whereby the impact factor for the ammonium oxidation f_N is set to be 1
2. vice versa, with the appropriate value for the impact factor for ammonium oxidation f_N, whereby the impact factor for the removal of carbonaceous substances f_C is set to be 1

The higher value of OV_h is decisive.

Required oxygen supply $erf.\alpha * OC$

For continuously aerated basins, the required oxygen supply is calculated as follows :

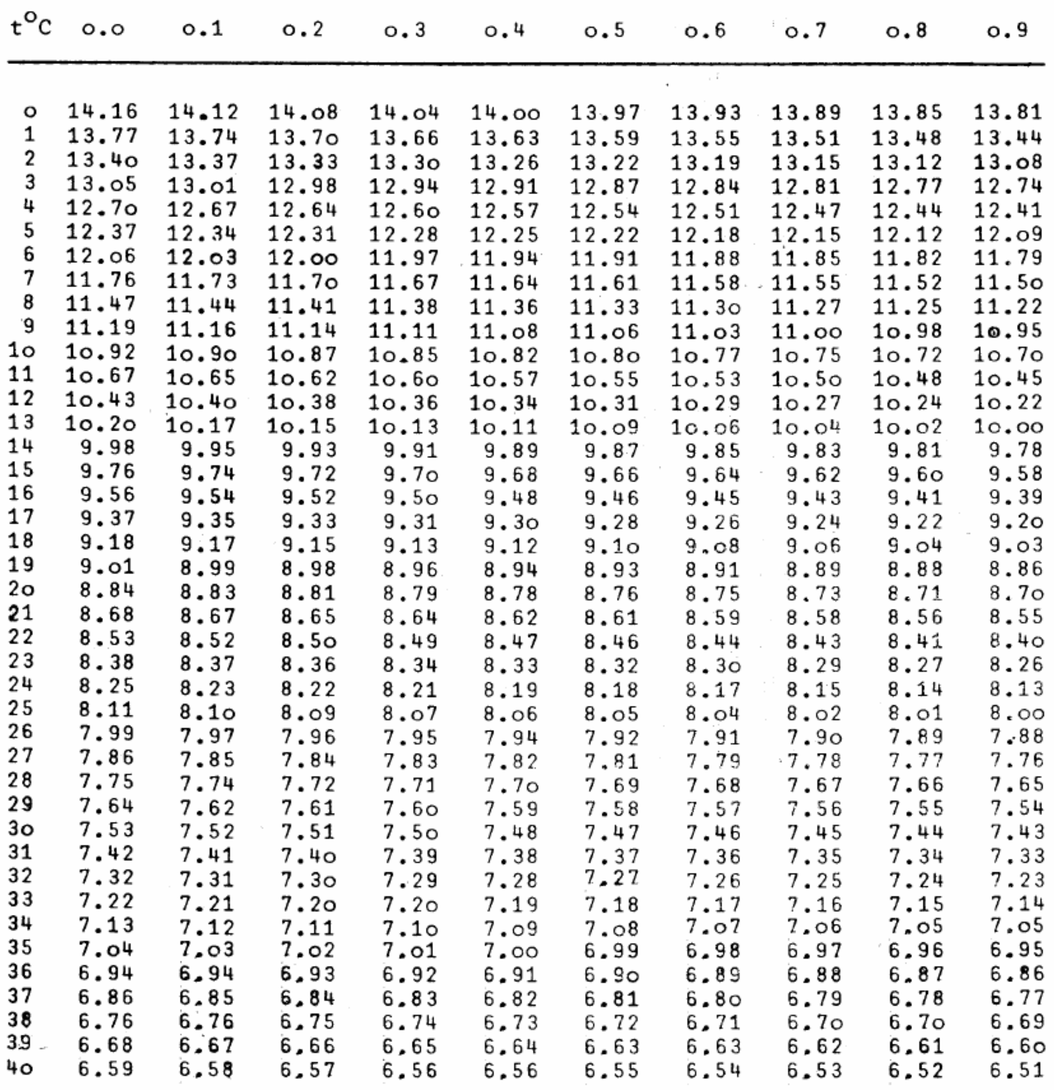
$$\boxed{req.\alpha * OC = \frac{c_S \; * \; OD_h}{c_S \; - c_x}}$$

Required oxygen capacity (oxygen supply)	$req.\alpha * OC$
Oxygen saturation concentration (must be determined separately)	c_S
Hourly oxygen consumption - significant peak value	OV_h
Set point of oxygen concentration in the aeration tank	c_x

The calculation of the required oxygen supply should be calculated for all relevant load cases (summer operation, winter operation, high BOD load, high N load, etc.).

Oxygen saturation concentration

The oxygen saturation concentration can be taken from tables …



$t\ ^{\circ}C$	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	14.16	14.12	14.08	14.04	14.00	13.97	13.93	13.89	13.85	13.81
1	13.77	13.74	13.70	13.66	13.63	13.59	13.55	13.51	13.48	13.44
2	13.40	13.37	13.33	13.30	13.26	13.22	13.19	13.15	13.12	13.08
3	13.05	13.01	12.98	12.94	12.91	12.87	12.84	12.81	12.77	12.74
4	12.70	12.67	12.64	12.60	12.57	12.54	12.51	12.47	12.44	12.41
5	12.37	12.34	12.31	12.28	12.25	12.22	12.18	12.15	12.12	12.09
6	12.06	12.03	12.00	11.97	11.94	11.91	11.88	11.85	11.82	11.79
7	11.76	11.73	11.70	11.67	11.64	11.61	11.58	11.55	11.52	11.50
8	11.47	11.44	11.41	11.38	11.36	11.33	11.30	11.27	11.25	11.22
9	11.19	11.16	11.14	11.11	11.08	11.06	11.03	11.00	10.98	10.95
10	10.92	10.90	10.87	10.85	10.82	10.80	10.77	10.75	10.72	10.70
11	10.67	10.65	10.62	10.60	10.57	10.55	10.53	10.50	10.48	10.45
12	10.43	10.40	10.38	10.36	10.34	10.31	10.29	10.27	10.24	10.22
13	10.20	10.17	10.15	10.13	10.11	10.09	10.06	10.04	10.02	10.00
14	9.98	9.95	9.93	9.91	9.89	9.87	9.85	9.83	9.81	9.78
15	9.76	9.74	9.72	9.70	9.68	9.66	9.64	9.62	9.60	9.58
16	9.56	9.54	9.52	9.50	9.48	9.46	9.45	9.43	9.41	9.39
17	9.37	9.35	9.33	9.31	9.30	9.28	9.26	9.24	9.22	9.20
18	9.18	9.17	9.15	9.13	9.12	9.10	9.08	9.06	9.04	9.03
19	9.01	8.99	8.98	8.96	8.94	8.93	8.91	8.89	8.88	8.86
20	8.84	8.83	8.81	8.79	8.78	8.76	8.75	8.73	8.71	8.70
21	8.68	8.67	8.65	8.64	8.62	8.61	8.59	8.58	8.56	8.55
22	8.53	8.52	8.50	8.49	8.47	8.46	8.44	8.43	8.41	8.40
23	8.38	8.37	8.36	8.34	8.33	8.32	8.30	8.29	8.27	8.26
24	8.25	8.23	8.22	8.21	8.19	8.18	8.17	8.15	8.14	8.13
25	8.11	8.10	8.09	8.07	8.06	8.05	8.04	8.02	8.01	8.00
26	7.99	7.97	7.96	7.95	7.94	7.92	7.91	7.90	7.89	7.88
27	7.86	7.85	7.84	7.83	7.82	7.81	7.79	7.78	7.77	7.76
28	7.75	7.74	7.72	7.71	7.70	7.69	7.68	7.67	7.66	7.65
29	7.64	7.62	7.61	7.60	7.59	7.58	7.57	7.56	7.55	7.54
30	7.53	7.52	7.51	7.50	7.48	7.47	7.46	7.45	7.44	7.43
31	7.42	7.41	7.40	7.39	7.38	7.37	7.36	7.35	7.34	7.33
32	7.32	7.31	7.30	7.29	7.28	7.27	7.26	7.25	7.24	7.23
33	7.22	7.21	7.20	7.20	7.19	7.18	7.17	7.16	7.15	7.14
34	7.13	7.12	7.11	7.10	7.09	7.08	7.07	7.06	7.05	7.05
35	7.04	7.03	7.02	7.01	7.00	6.99	6.98	6.97	6.96	6.95
36	6.94	6.94	6.93	6.92	6.91	6.90	6.89	6.88	6.87	6.86
37	6.86	6.85	6.84	6.83	6.82	6.81	6.80	6.79	6.78	6.77
38	6.76	6.76	6.75	6.74	6.73	6.72	6.71	6.70	6.70	6.69
39	6.68	6.67	6.66	6.65	6.64	6.63	6.63	6.62	6.61	6.60
40	6.59	6.58	6.57	6.56	6.56	6.55	6.54	6.53	6.52	6.51

Oxygen saturation concentration

… or calculate. Various formulas have been published for this purpose.

Calculation proposal of the U.S. American Public Health Association, 1995:

$$c_S = e^{\left(-139{,}3441 + \frac{1{,}57570 * 10^{5}}{T} - \frac{6{,}64231 * 10^{7}}{T^{2}} + \frac{1{,}2438 * 10^{10}}{T^{3}} - \frac{8{,}62195 * 10^{11}}{T^{4}}\right)}$$

where

c_S	Oxygen saturation concentration under normal pressure (1 bar) and negligible low salt level of the water
T	Temperature of the water in °K (= 273,15 + Temperature in °C)

APHA 1995, cited by U.S. EPA, 2008

Oxygen saturation concentration

Calculation proposal of PÖPEL, 1985:

$$\boxed{c_S = \frac{2.234,34}{(T + 45,93)^{1,31403}}}$$

Where

c_S	Oxygen saturation concentration under normal pressure (1 bar) and negligible low salt level of the water
T	Temperature of the water in °C

Cited by WAGNER, 1992

The direct calculation according to a formula is the method of choice as soon as the water temperature enters the calculation as a variable (eg if a scenario analysis is to be performed)!

Calculation of $OD_{d,C}$ for WWTP Stahnsdorf

Determination according to empirical formula of HARTWIG:

$$OD_{d,C} = L_{d,BOD} * \left(0{,}56 + \frac{0{,}15 * SRT_{AT} * F_T}{1 + 0{,}17 * SRT_{AT} * F_T}\right)$$

$OD_{d,C}$	Daily oxygen demand for elimination of carbonaceous substances	
$L_{d,BOD}$	Daily influent BOD Load (Value chosen, because in measurement apparently too low)	$18.900\ kg/d$
SRT_{AT}	Sludge retention time (rounded)	$15{,}4\ d$
F_T	Correcting factor for temperature	
$T_{des.,high}$	Design temperature (highest value)	$20°\ C$

$$F_T = 1{,}072^{(20-15)} = 1{,}4157\ldots$$

$$OD_{d,C} = 18.900 * \left(0{,}56 + \frac{0{,}15 * 15{,}4 * 1{,}41\ldots}{1 + 0{,}17 * 15{,}4 * 1{,}41\ldots}\right) = 23.714\ kg\ O_2/d$$

Calculation of $OD_{d,C}$ for WWTP Stahnsdorf

Determination via balance of oxygen :

$$OD_{d,C} = \frac{Q_d \,*\, \left(C_{COD,In} - S_{COD,inert,Out} - X_{COD,WAS}\right)}{1.000}$$

Q_d	Daily wastewater flow under dry weather conditions (inlet aeration tank)	$52.000\ m^3/d$
$C_{COD,In}$	Influent COD-Concentration	$789\ mg\ O_2/l$
$S_{COD,inert,Out}$	Effluent concentration of the soluble non-degradable COD fraction (effluent of sec. sedimentation tank)	$39\ mg\ O_2/l$
$X_{CSB,ÜS}$	COD removed by WAS	$249\ mg\ O_2/l$

$$OD_{d,C} = \frac{52.000 * \ (789 \ - 39 \ - 249)}{1.000} = 26.022\ kg\ O_2/d$$

$23.714\ kg\ O_2/d$
(according emp. formula)

The results of both calculation ways differ. The reason for this is that, despite the choice of a higher feed-in value than the operators of WWTP Stahnsdorf told us, it appears that the BOD for calculating by empirical formula is still too low.

Calculation of $OR_{d,D}$ for WWTP Stahnsdorf

Daily recovery of oxygen by denitrification: $OR_{d,D} = \frac{Q_d \, * 2{,}9 \, * \, S_{NO3,D}}{1.000}$

Daily wastewater flow at dry weather conditions (inlet aeration tank) $52.000 \, m^3/d$

Concentration of nitrates which are to be denitrificated $58{,}8 \, mg/l$

$$OR_{d,D} = \frac{52000 * 2{,}9 \, * 58{,}8}{1.000} = 8.869 \, kg \, O_2/d$$

Calculation of $OD_{d,N}$ for WWTP Stahnsdorf

Determination by balancing of oxygen bounded in nitrate:

$$OD_{d,N} = \frac{Q_d \ * 4{,}3 \ * \left(S_{NO3,D} \ - \ S_{NO3,ZB} + \ S_{NO3,AN}\right)}{1.000}$$

Daily wastewater flow at dry weather conditions (inlet aeration tank)	$52.000 \; m^3/d$
Concentration of nitrates which are to be denitrificated	$58{,}8 \; mg/l$
Influent concentration of nitrates	$0 \; mg/l$
Effluent concentration of nitrates	$9{,}1 \; mg/l$

$$OV_{d,N} = \frac{52.000 * 4{,}3 \ * \ (58{,}8 \ - 0 + 9{,}1)}{1.000} = 15.185 \; kg \; O_2/d$$

Calculation of OD_h for WWTP Stahnsdorf

Impact factor of oxygen consumption for carbon elimination	1,15
Daily oxygen demand for elimination of carbonaceous substances (Here, the higher of the two calculated values is selected)	$26.022\ kg\ O_2/d$
Daily oxygen demand for elimination of carbonaceous substances which is covered by oxygen recovery from denitrification	$8.869\ kg\ O_2/d$
Impact factor of oxygen consumption for nitrification	1,5
Daily oxygen consumption for nitrification	$15.185\ kg\ O_2/d$

1. calculation process:

$$OD_h = \frac{1{,}0 \ast (26.022 - 8.869) + 1{,}5 \ast 15.185}{24} \approx 1.664\ kg\ O_2/h$$

Relevant value!

2. calculation process:

$$OD_h = \frac{1{,}15 \ast (26.022 - 8.869) + 1{,}0 \ast 15.185}{24} \approx 1.455\ kg\ O_2/h$$

Calculation of $req.\alpha * OC$ for WWTP Stahnsdorf

Calculation for summer operation, e.g. relevant is the highest wastewater temperature, $\boldsymbol{T_{design,high} = 20°C}$

Oxygen saturation concentration (read from table)	$8{,}8\ mg/l$
Hourly oxygen consumption - significant peak value	$1.664\ kg\ O_2/h$
Set point of oxygen concentration in the aeration tank	$2{,}0\ mg/l$

$$\boxed{erf.\alpha * OC = \frac{8{,}8\ * 1.664\ kg\ O_2/h}{8{,}8\ - 2} \approx 2.153\ kg\ O_2/h}$$

Calculation of $V_{Air,OC}$ for WWTP Stahnsdorf

1 standard cubic meter of air weighs 1,293 kg, ambient air contains about 23,16 mass% O_2
Ergo: 1 standard m^3 of air contains approx. 300 g of oxygen

Standard m^3 (Sm^3) means that it is measured at 0°C and air pressure = 1.013 mbar)

Required oxygen capacity ($req.\alpha * OC$)	$2.153\ kg\ O_2/h$
Average of oxygen uptake by microorganisms	33 %
Quotient of oxygen supply in activated sludge and in pure water (α-value)	0,7

$$V_{Air,OC} = \frac{2.153\ kg\ O_2/h}{1{,}293\,\frac{kg\ Air}{Sm^3 Air} * 0{,}2316\ \frac{kg\ O_2}{kgAir} * 0{,}33\ * 0{,}7} \approx 31.124\, m^3 Air/h$$

Alternative calculation method:

$$V_{Air,OC} = \frac{2.153\ kg\ O_2/h}{0{,}3\ \frac{kg\ O_2}{Sm^3 Air} * 0{,}33\ * 0{,}7} \approx 31.068\, m^3 Air/h$$

Design of secondary sedimentation tanks

Which factors influence the design of secondary sedimentation tanks?

Maximum flow for stormy weather (in case of combined sewer system)	Q_m
Mixed Liquor Suspended Solids	$MLSS$
Sludge volume index	ISV

In addition to note or to choose:

Thickening time	t_T
Sludge load	q_{SV}
Clear water zone (depth)	h_1
Total solids of waste activated sludge	TS_{WAS}
Total solids at the bottom of secondary sedimentation tank	$TS_{SST,bott.}$
Flow of recycle activated sludge	Q_{RAS}

Design of secondary sedimentation tanks

Sludge index (ISV), dry matter content in the bottom sludge of the secondary sedimentation tank ($TS_{STT,bottom}$) and thickening time (t_T) are interdependent variables. Similar to the determination of dry matter content in the aeration tank ($MLSS$), RAS recycle ratio (RR) and dry matter content of the recycle sludge (TS_{RAS}), one value must first be estimated to iteratively determine the other values.

$$ISV = \frac{1000}{TS_{SST,bott.}} * \sqrt[3]{t_T}$$

$$TS_{SST,bott.} = \frac{1000}{ISV} * \sqrt[3]{t_E}$$

$$t_T = \left(\frac{TS_{SST,bott.} * ISV}{1000}\right)^3$$

Decisive for the area of NKB (A_{SST}) is the so-called surface charge (q_A), which in turn depends on the volume of sludge, which enters the secondary sedimentation tank (q_{SV}) and on the comparative sludge volume (CSV):

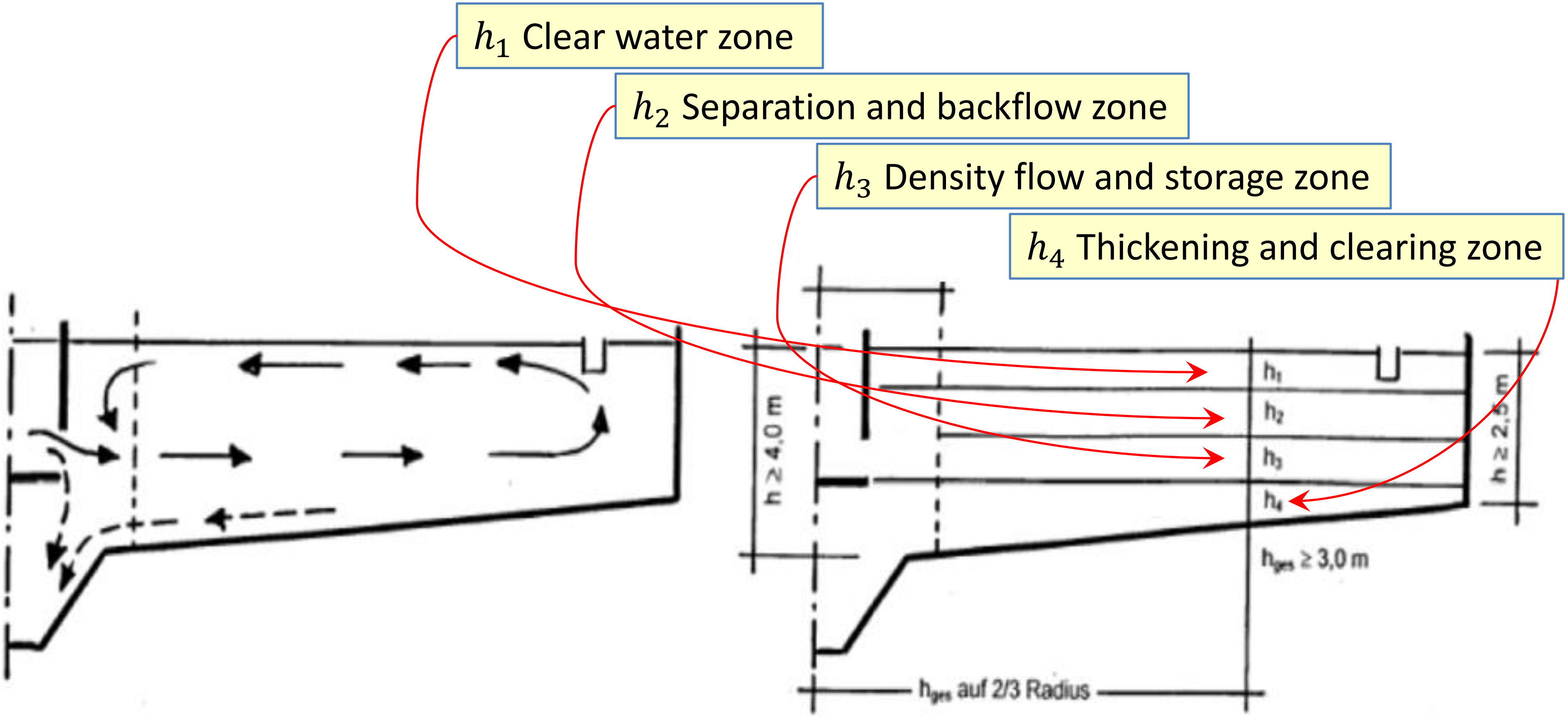
$$A_{SST} = \frac{Q_m}{q_A}$$

$$q_A = \frac{q_{SV}}{CSV}$$

$$CSV = MLSS * ISV$$

q_{SV} is to be selected according to instructions in papers like ATV-DVWK-A 131.

Design of secondary sedimentation tanks



h_1 Clear water zone

h_2 Separation and backflow zone

h_3 Density flow and storage zone

h_4 Thickening and clearing zone

Main flow directions and functional zones of horizontally flowed round secondary sedimentation tanks

(ATV-DVWK-A 131)

Design of secondary sedimentation tanks

The clear water zone (h_1) is a safety zone with a minimum depth of 0.50 m. The depth of the remaining three functional zones is determined from previously calculated values according to empirical formulas:

$$h_2 = \frac{0{,}5 * q_A * (1 + RR)}{1 - CSV/1.000}$$

$$h_3 = \frac{1{,}5 * 0{,}3 * q_{SV} * (1 + RR)}{500}$$

$$h_4 = \frac{MLSS * q_A * (1 + RR) * t_T}{TS_{SST,bott.}}$$

Finally, check whether the following conditions are met:

- h_{sum} at 2/3 of flow path ≥ 3,00 m
- Slope of the tank bottom ≥ 1 : 15

Design of sec. sedimentation tank WWTP Stahnsdorf

Sludge volume index (ISV) chosen $100\ l/kg$

Total solids at the bottom of secondary sedimentation tank ($TS_{SST,bott.}$) $11.5\ kg/m^3$

$$t_T = \left(\frac{11.5 * 100}{1000}\right)^3 \approx 1.5\ h, chosen\ 2\ h$$

$$CSV = 3.3\ kg/m^3 * 100\ l/kg = 330\ l/m^3$$

Sludge load (q_{SV}) chosen $450\ l/m^2 * h$

$$q_A = \frac{450 \frac{l}{m^2 * h}}{330\ l/m^3} \approx 1.37\ m/h$$

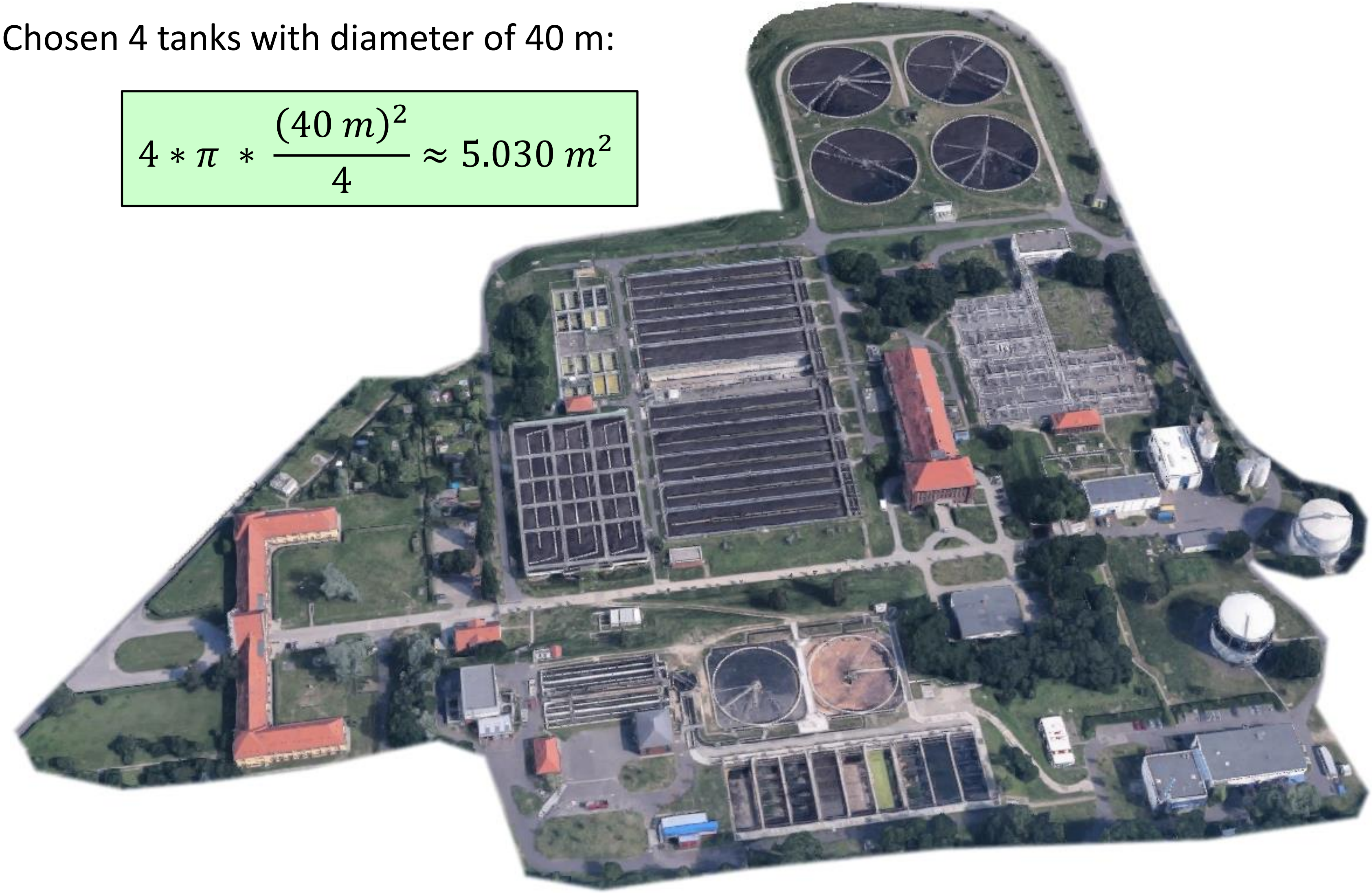
Maximum flow for stormy weather (combined sewer system - Q_m) $6480\ m^3/h$

$$A_{SST} = \frac{6480\ m^3/h}{1.37\ m/h} \approx 4.730\ m^2$$

Design of sec. sedimentation tank WWTP Stahnsdorf

Chosen 4 tanks with diameter of 40 m:

$$4 * \pi \ * \frac{(40\ m)^2}{4} \approx 5.030\ m^2$$



Design of sec. sedimentation tank WWTP Stahnsdorf

Clear water zone (h_1) chosen $0.50\ m$

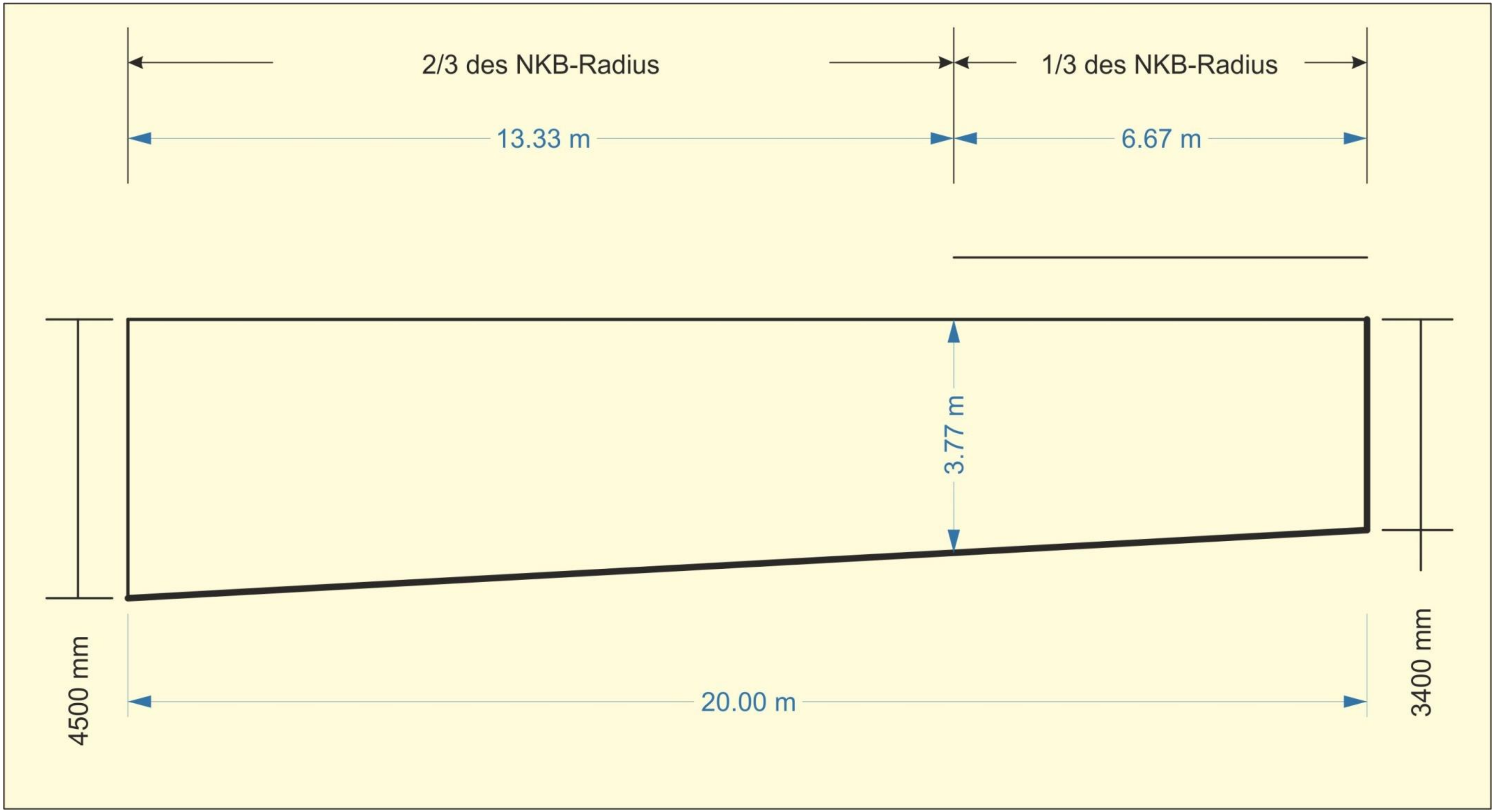
$$\boxed{h_2 = \frac{0.5\ * 1.36 * (1 + 0.7)}{1\ - 330/1000} = 1.72\ m}$$

$$\boxed{h_3 = \frac{1.5\ * 0.3\ * 450\ * (1 + 0.7)}{500} = 0{,}69\ m}$$

$$\boxed{h_4 = \frac{3\ * 1.36 * (1 + 0{,}7)\ * 2}{11.5} = 1.21\ m\ - gewählt: 1.59\ m}$$

$$\boxed{h_{sum} = 4.50\ m}$$

Design of sec. sedimentation tank WWTP Stahnsdorf



Proof of h_{sum} at 2/3 of flow path ≥ 3,00 m

Basic requirements for C, N, DN

Requirements for removal of organic pollution (C):

- Dissolved oxygen ≥ **1,5 mg/l** → **aerob**
- Enough **COD/BOD**
- Enough **Heterotrophs**

Requirements for Nitrification (N):

- Dissolved oxygen ≥ **1,5 mg/l** → **aerob**
- Enough **Ammonia nitrogen**
- Enough **Autotrophs**
- Enough **buffering capacity**

Requirements for Denitrification (DN):

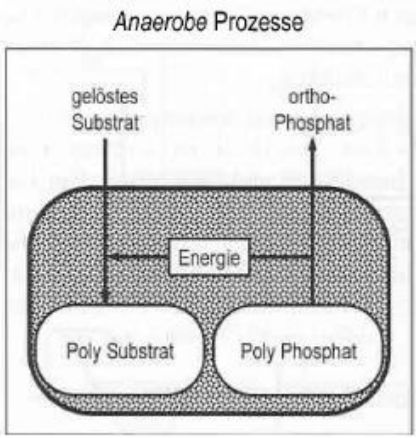
- Dissolved oxygen ≈ **0**
- Enough **Nitrate**

} → **anoxisch**

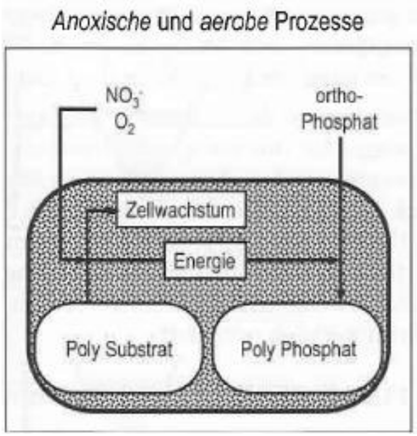
- Enough **readily degradable organic matter** (BOD)
- Enough **Heterotrophs**

Biochemical Reactions for BioP

Biological Removal of Phosphorus (BioP):



In the anaerobic stage, the PAOs absorb readily degradable organic matter with consumption of polyphosphate and store it as organic storage material (polysubstrate) within the cells. Polyphosphate is degraded inside the cells and released into the wastewater as phosphate. This reaction provides the required energy.



In the anoxic and in the aerobic stage, the organic storage materials are degraded (respired), the energy gained from it is used to increase the biomass and rebuild more polyphosphates. In the process, significantly more phosphate is removed from the wastewater than is needed to build up the biomass. The phosphorus content of the PAOs can be up to 15% (normal is about 1-2%).

anaerob

anoxisch

aerob

The excess phosphorus-loaded PAOs are either removed from the excess sludge or returned to the anaerobic stage with the return sludge, where the cycle begins again.

Acc. GUJER, 2007

7th Lecture

Introduction into the
dynamic sewage treatment simulation
with the program system STOAT

Preliminary remarks

Sewer network and sewage treatment plants always form one unit. They must not be considered or operated independently! Nevertheless, because of didactic reasons my courses are focused on the wastewater treatment in sewage treatment plants.

There are many different methods of wastewater treatment. Permanently new processes are developed and tested. Processes which prove to be efficient will be introduced into praxis. Therefore dynamic wastewater simulation also has to be up to date.

The most common biological technology for sewage treatment in Germany and also on an international scale is upstream denitrification. WWTP Stahnsdorf is one example. We will try to simulate it by STOAT.

Dynamic wastewater simulation using STOAT

STOAT *Sewage **T**reatment **O**peration and **A**nalysis over **T**ime*

Developed by Water Research centre plc, Swindon/Großbritannien
http://www.wrcplc.co.uk/

Proven worldwide, freeware since 2010 (previously: licence fee 10,000 pounds sterling)

For free download of STOAT go to registration

http://www.wrcplc.co.uk/freeware/STOAT/downloadform.aspx

WRc will then send you an unlock code to download the software by e-mail.

Dynamic wastewater simulation using STOAT

Numerous software solutions are available worldwide, most of them with costs such as

BioWin™	http://envirosim.com/products/biowin
EFOR™	http://www.mpassociates.gr/software/environment/efor.html
GPS-X™	http://www.hydromantis.com/GPS-X.html
Matlab/Simulink™	http://www.mathworks.de/
SIMBA®	https://simba.ifak.eu/content/simba-sharp-water
ASIM	http://www.asim.eawag.ch/
WEST®	http://www.mikepoweredbydhi.com/products/west

However, there also software for free exists as STOAT™ or

City Drain	http://www.hydro-it.com/extern/IUT/citydrain/

In a large-scale software benchmark within the COST projects of the EU, BioWin™, EFOR™, GPS-X™, Matlab / Simulink™, Simba®, STOAT™ and WEST® have been compared.

http://apps.ensic.inpl-nancy.fr/benchmarkWWTP/Pdf/Simulator_manual.pdf

All candidates had to simulate a given system under a specific operating situation. The results of all programs were nearly identical (COPP, 2000 - see link above).

Dynamic wastewater simulation using STOAT

All common wastewater treatment processes can be imaged:

Upstream denitrification
Cascading denitrification
Simultaneous denitrification
Alternating denitrification
Intermittent denitrification
Downstream denitrification
SBR plant (Sequencing Batch Reactor)
Trickling filter
Biofilter

Besides these core processes a lot of upstream and downstream processes can be simulated by STOAT (eg rain overflow basin, equalization basin, wastewater filtration / disinfection, sludge treatment)
Control (PID controller, PLC and fuzzy logic controller).

Dynamic wastewater simulation using STOAT

STOAT only works properly if the usual English dot is used as a decimal separator.
Before STOAT is started, it should be ensured that the regional setting of the operating system is "English (United Kingdom)".
Otherwise STOAT calculates foolish results.

Dynamic wastewater simulation using STOAT

Static (stationary) approach:

Time does not matter in the static calculation. Only a representative system state is considered.

For example, the design of sewage treatment plants in accordance with DWA-A 131 refers to "... the BOD_5 load, which has fallen below 85% of dry days in the inflow to the sewage treatment plant plus a planned spare capacity ..." - the design is therefore static.

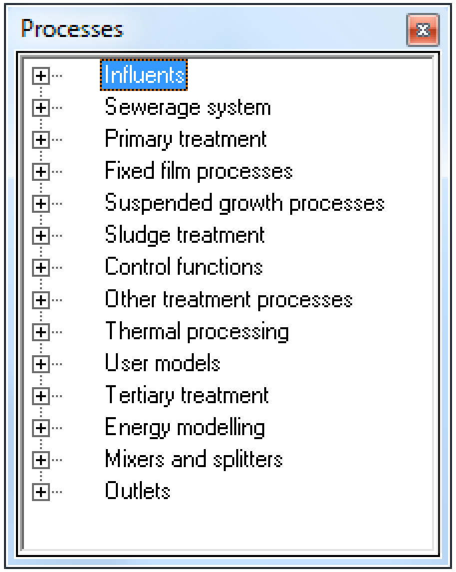
Dynamic simulation:

In the dynamic simulation, all system states that occur during the period of time examined are considered. Thus, all load peaks and other extreme conditions are taken into account (eg critical load change situations).

Wastewater treatment simulates the main transport and conversion processes along the effluents of sewage and sewage sludge, and calculates loads and concentrations of all relevant material parameters (e.g., COD, BOD, NH_4-N, org. N, NO_x-N, P) throughout the process.

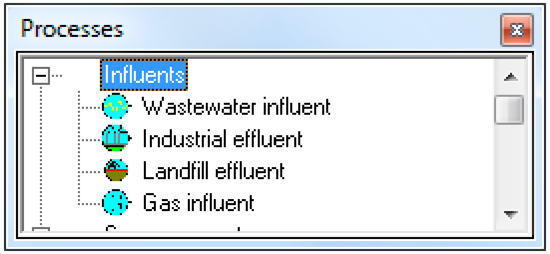
STOAT bits

→ Window → Processes toolbox



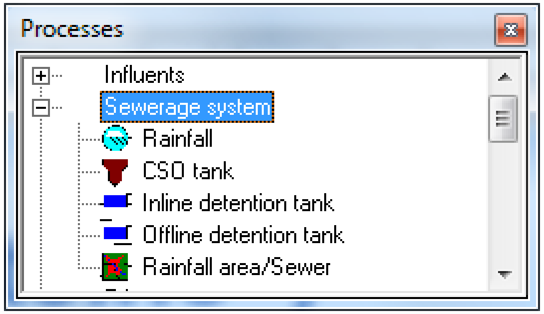
Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
- Thermal processing
- User models
- Tertiary treatment
- Energy modelling
- Mixers and splitters
- Outlets



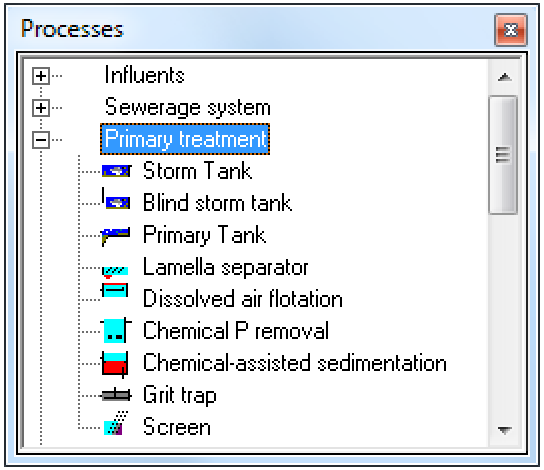
Processes

- Influents
  - Wastewater influent
  - Industrial effluent
  - Landfill effluent
  - Gas influent



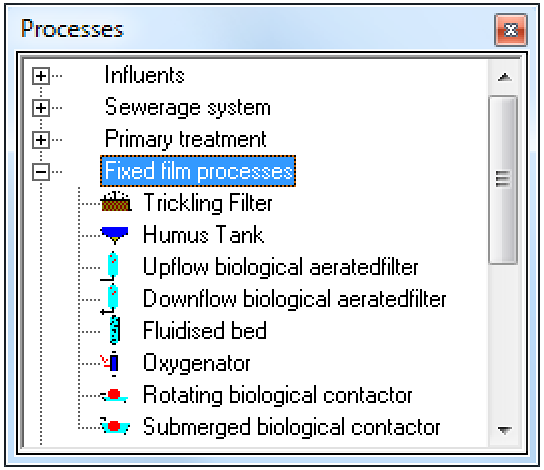
Processes

- Influents
- Sewerage system
  - Rainfall
  - CSO tank
  - Inline detention tank
  - Offline detention tank
  - Rainfall area/Sewer



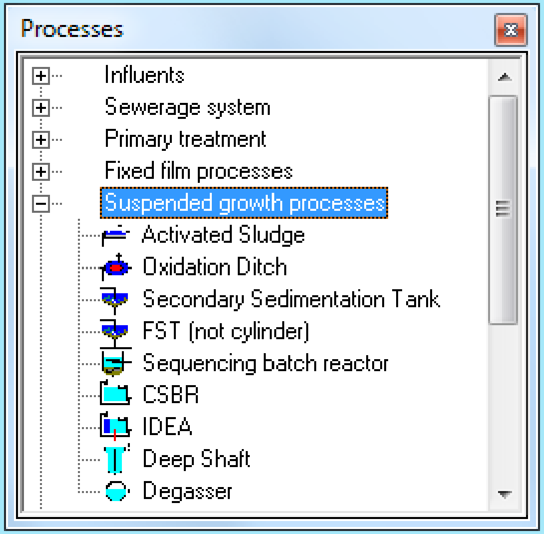
Processes

- Influents
- Sewerage system
- Primary treatment
  - Storm Tank
  - Blind storm tank
  - Primary Tank
  - Lamella separator
  - Dissolved air flotation
  - Chemical P removal
  - Chemical-assisted sedimentation
  - Grit trap
  - Screen



Processes

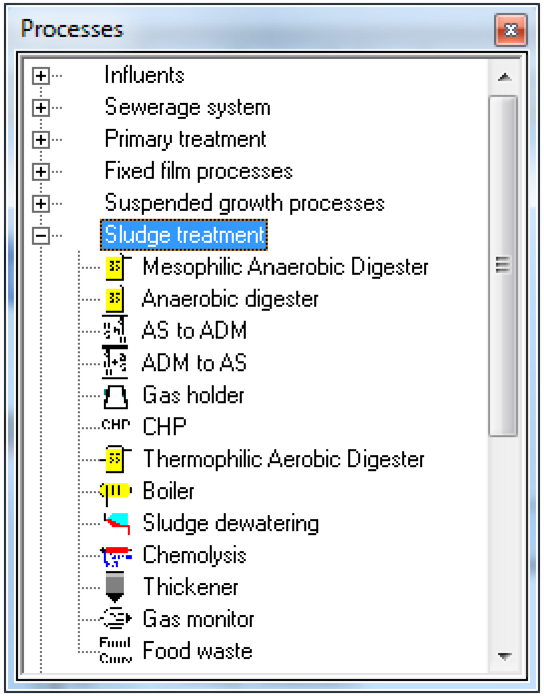
- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
  - Trickling Filter
  - Humus Tank
  - Upflow biological aeratedfilter
  - Downflow biological aeratedfilter
  - Fluidised bed
  - Oxygenator
  - Rotating biological contactor
  - Submerged biological contactor



Processes

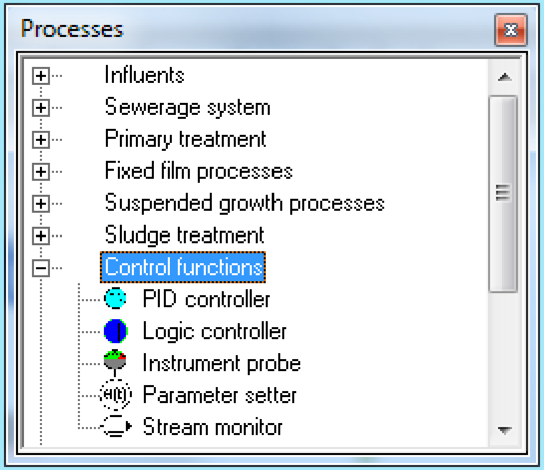
- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
  - Activated Sludge
  - Oxidation Ditch
  - Secondary Sedimentation Tank
  - FST (not cylinder)
  - Sequencing batch reactor
  - CSBR
  - IDEA
  - Deep Shaft
  - Degasser

STOAT bits



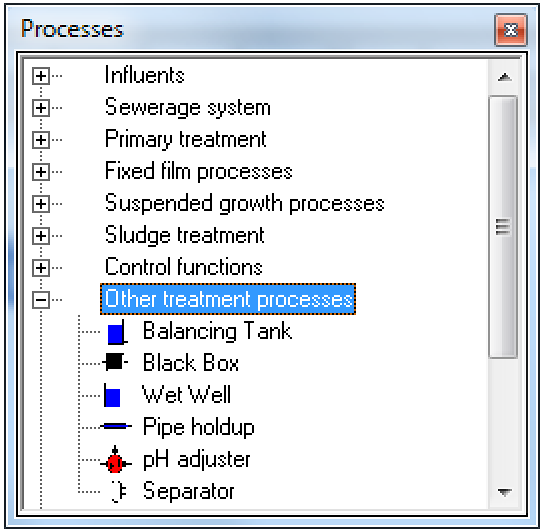
Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
  - Mesophilic Anaerobic Digester
  - Anaerobic digester
  - AS to ADM
  - ADM to AS
  - Gas holder
  - CHP
  - Thermophilic Aerobic Digester
  - Boiler
  - Sludge dewatering
  - Chemolysis
  - Thickener
  - Gas monitor
  - Food waste



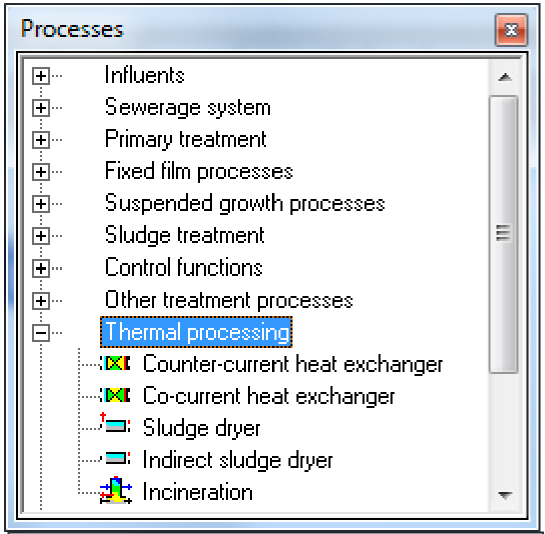
Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
  - PID controller
  - Logic controller
  - Instrument probe
  - Parameter setter
  - Stream monitor



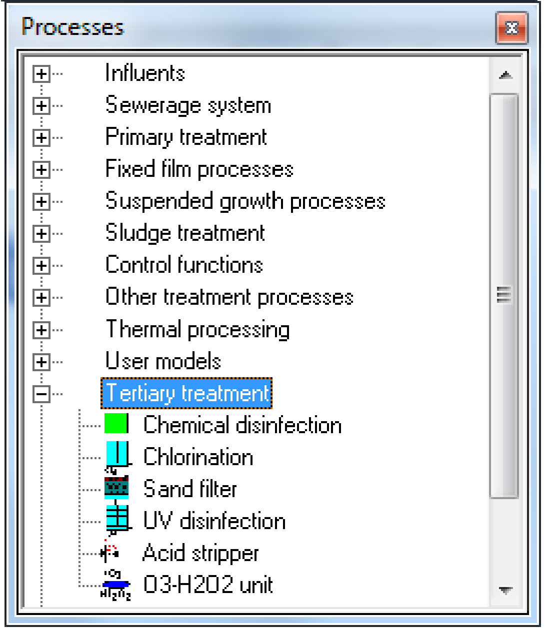
Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
  - Balancing Tank
  - Black Box
  - Wet Well
  - Pipe holdup
  - pH adjuster
  - Separator



Processes

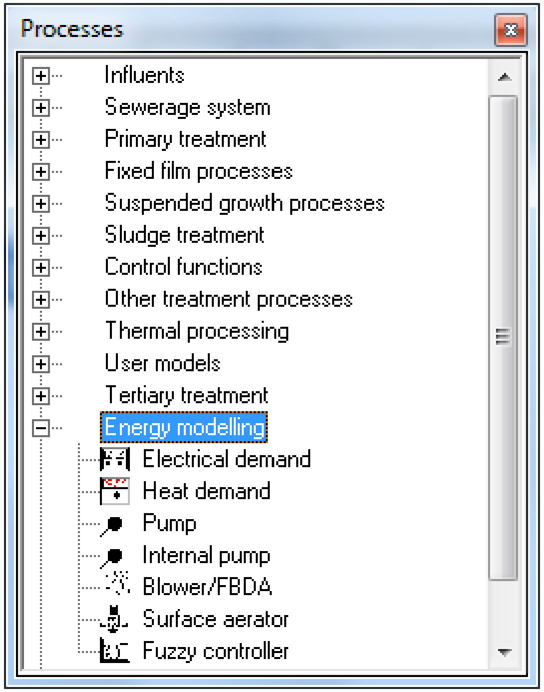
- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
- Thermal processing
  - Counter-current heat exchanger
  - Co-current heat exchanger
  - Sludge dryer
  - Indirect sludge dryer
  - Incineration



Processes

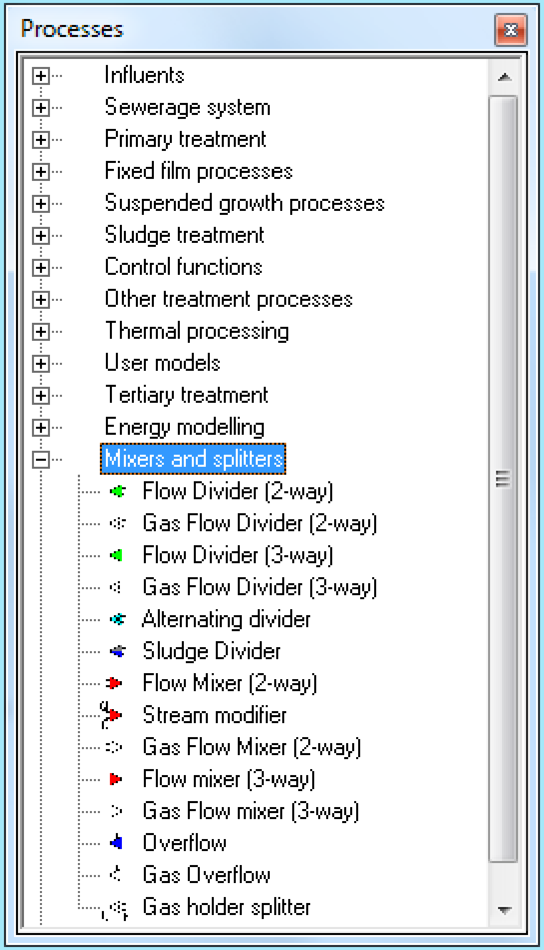
- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
- Thermal processing
- User models
- Tertiary treatment
  - Chemical disinfection
  - Chlorination
  - Sand filter
  - UV disinfection
  - Acid stripper
  - O3-H2O2 unit

STOAT bits



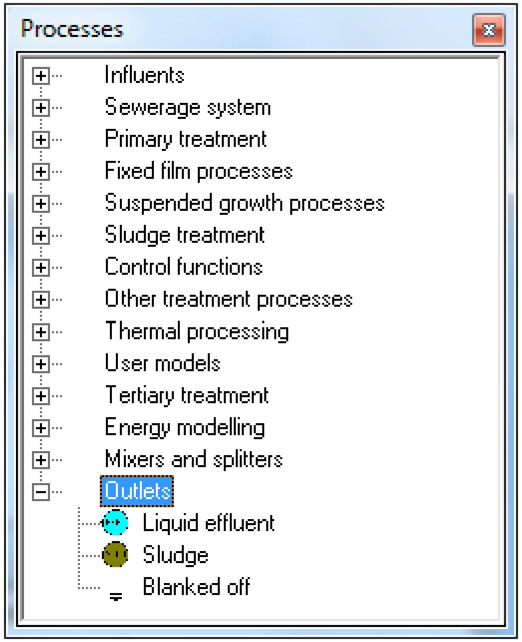
Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
- Thermal processing
- User models
- Tertiary treatment
- Energy modelling
  - Electrical demand
  - Heat demand
  - Pump
  - Internal pump
  - Blower/FBDA
  - Surface aerator
  - Fuzzy controller



Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
- Thermal processing
- User models
- Tertiary treatment
- Energy modelling
- Mixers and splitters
  - Flow Divider (2-way)
  - Gas Flow Divider (2-way)
  - Flow Divider (3-way)
  - Gas Flow Divider (3-way)
  - Alternating divider
  - Sludge Divider
  - Flow Mixer (2-way)
  - Stream modifier
  - Gas Flow Mixer (2-way)
  - Flow mixer (3-way)
  - Gas Flow mixer (3-way)
  - Overflow
  - Gas Overflow
  - Gas holder splitter



Processes

- Influents
- Sewerage system
- Primary treatment
- Fixed film processes
- Suspended growth processes
- Sludge treatment
- Control functions
- Other treatment processes
- Thermal processing
- User models
- Tertiary treatment
- Energy modelling
- Mixers and splitters
- Outlets
  - Liquid effluent
  - Sludge
  - Blanked off

STOAT levels

Report level

Inspection of the results of the computer run

(**All results are set to read only, Model and Run can not be changed!**)

Every flow stream and every bit can be inspected!

Run level

Illustration of the mode of operation of a plant (quantity and nature of the wastewater intake, chemicals dosed, aeration, return sludge production, excess sludge removal, internal recirculation etc.

Model can not be changed!)

File → New run / Open run → name of run

Up to 256 Runs per model

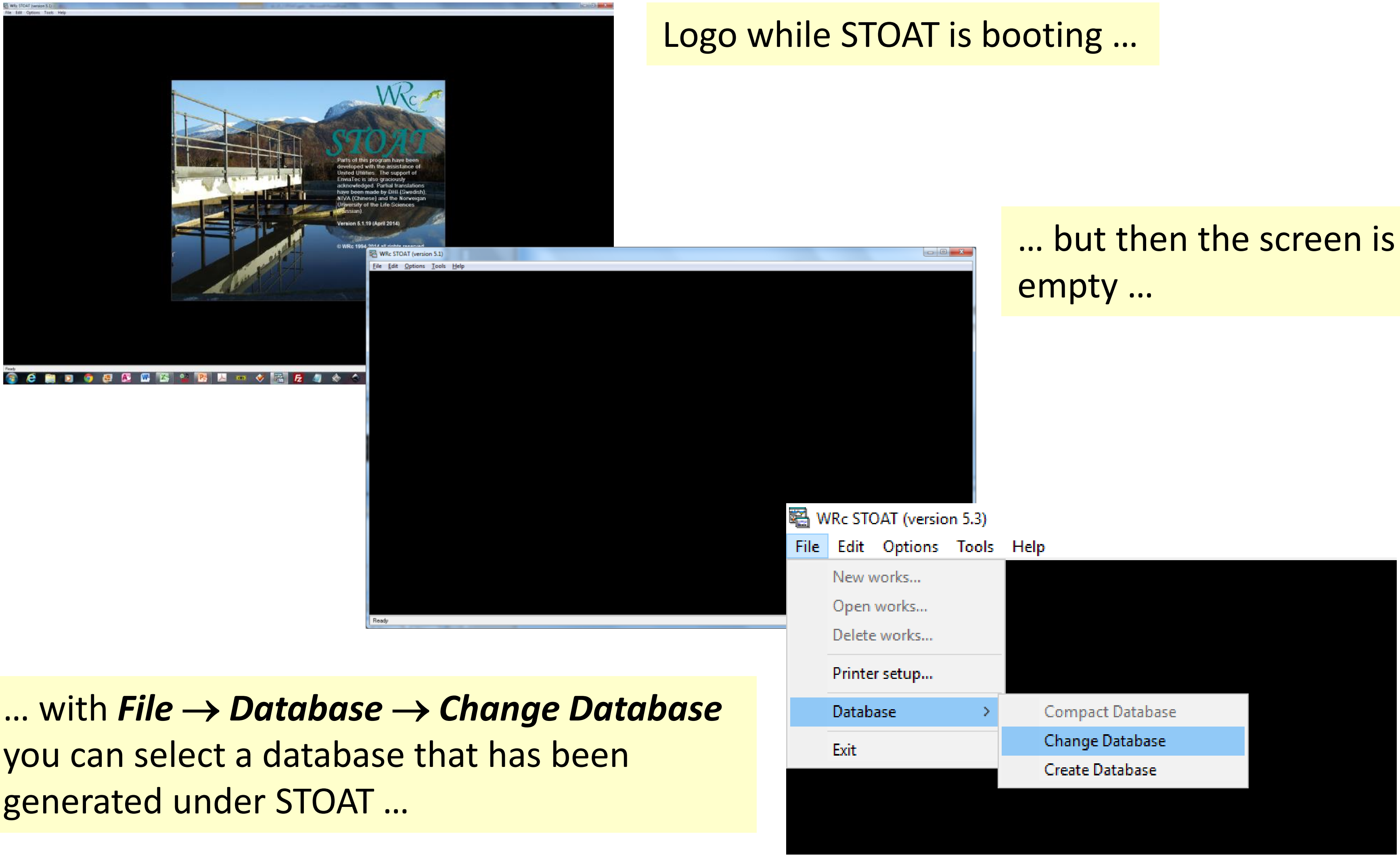
Works level

Illustration of the existing or planned design of a plant (flow of sewage, number and volumes of reactors, mathematical models to be used, etc.)

File → New works / Open works → name of work)

Up to 4.096 STOAT bits per model

Dynamic wastewater simulation using STOAT



Parts of this program have been developed with the assistance of United Utilities. The support of EnviaTec is also graciously acknowledged. Partial translations have been made by DHI (Swedish), NIVA (Chinese) and the Norwegian University of the Life Sciences (Russian).

Version 5.1.19 (April 2014)

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Logo while STOAT is booting …

… but then the screen is empty …

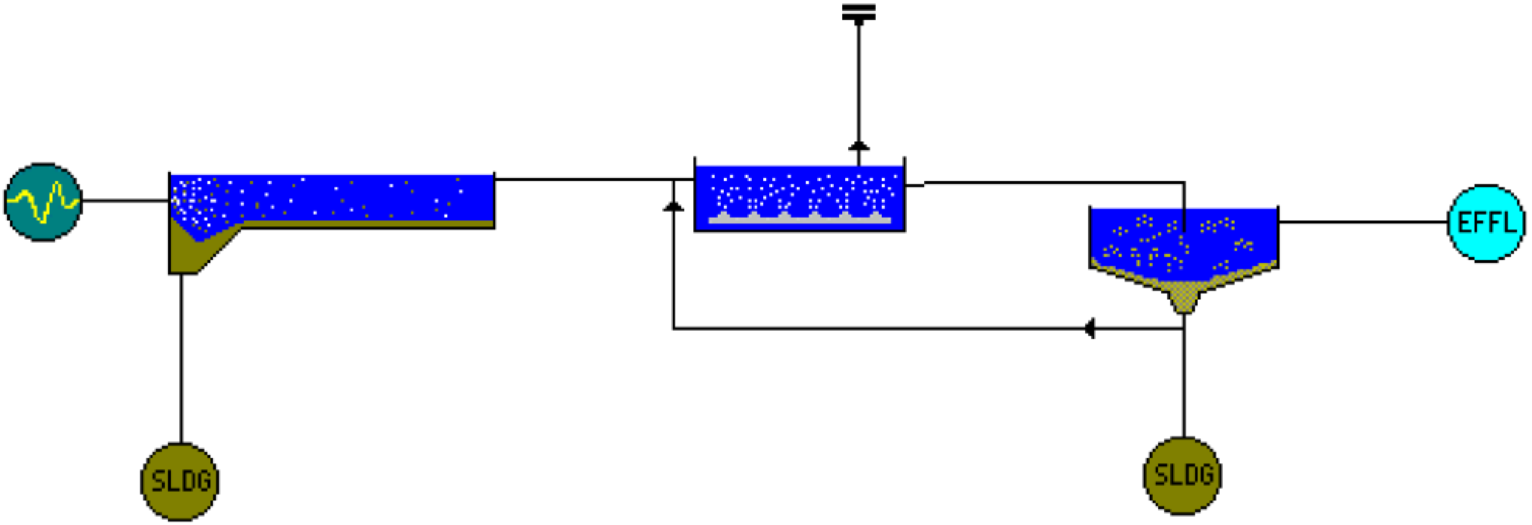
… with ***File → Database → Change Database*** you can select a database that has been generated under STOAT …

Our very first STOAT model

For warming up we will build a very simple model according to the STOAT tutorials guide.

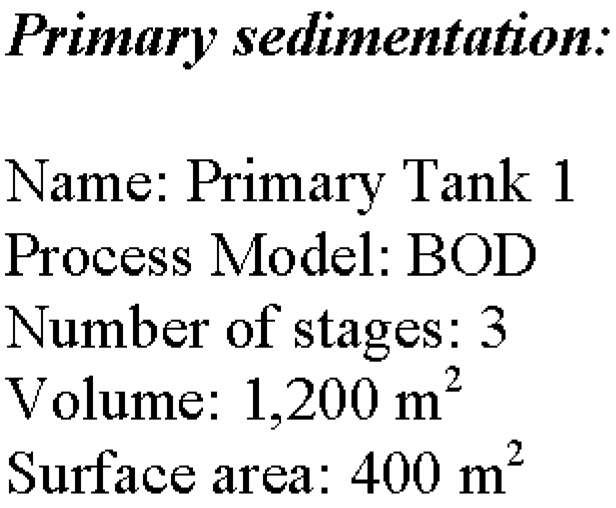
Start by creating a new works. From the 'File' menu select 'New works’.

When you have all the processes on the drawing board connect them together to create the flowsheet shown below.



Our very first STOAT model

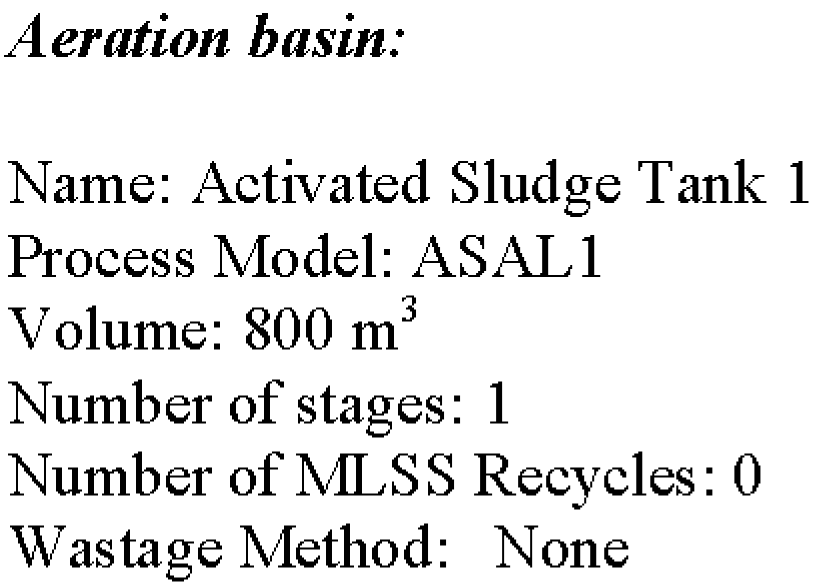
Having completed the works geometry we now define the physical dimensions. For each process – primary sedimentation, aeration basin and settling tank – right-click on the process, select 'Input data' and then select 'Name and dimensions'. Set the processes dimensions as:



Primary sedimentation:

Name: Primary Tank 1
Process Model: BOD
Number of stages: 3
Volume: 1,200 m^2
Surface area: 400 m^2

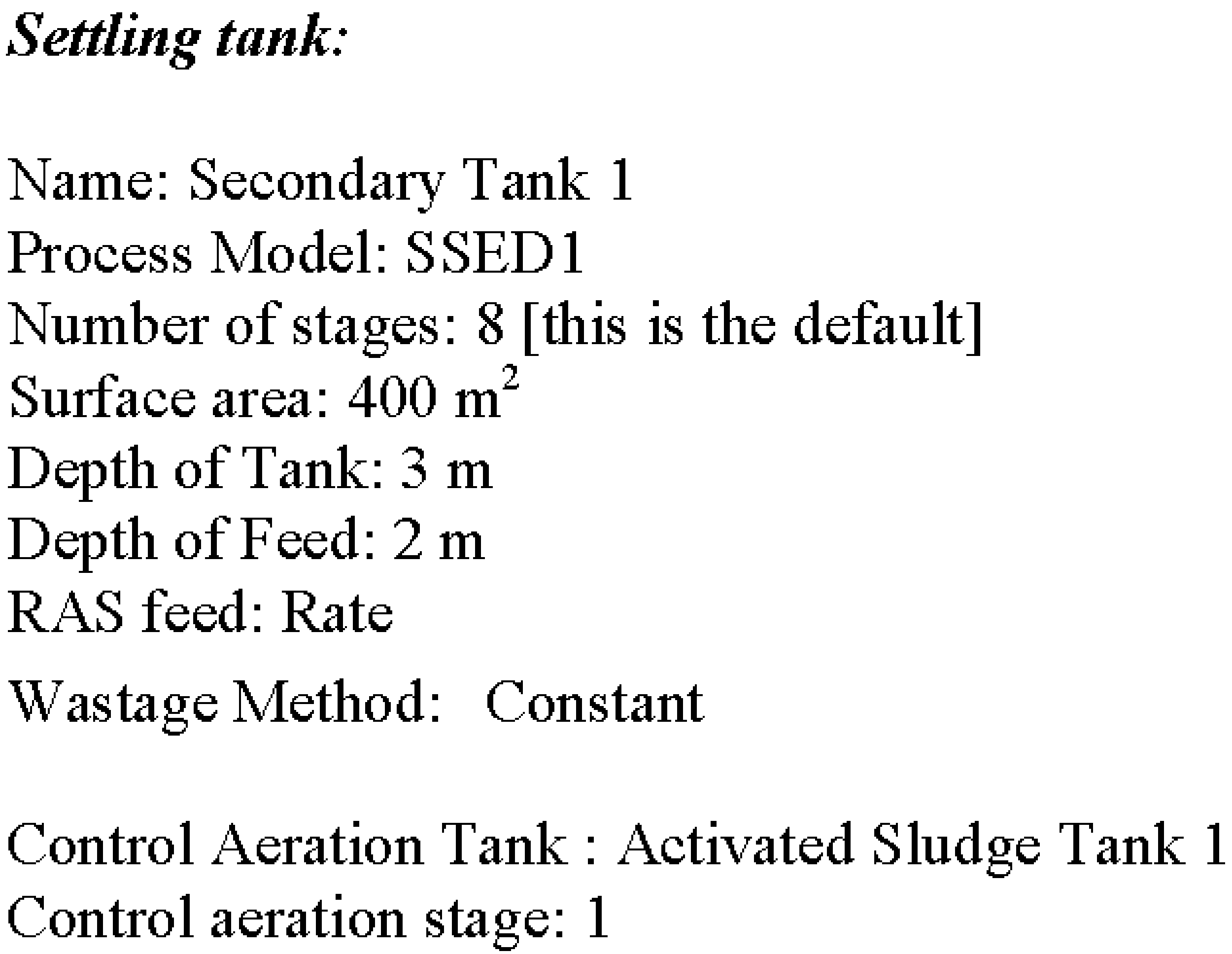
Our very first STOAT model



Aeration basin:

Name: Activated Sludge Tank 1
Process Model: ASAL1
Volume: 800 m^3
Number of stages: 1
Number of MLSS Recycles: 0
Wastage Method: None

Our very first STOAT model



Settling tank:

Name: Secondary Tank 1
Process Model: SSED1
Number of stages: 8 [this is the default]
Surface area: 400 m^2
Depth of Tank: 3 m
Depth of Feed: 2 m
RAS feed: Rate
Wastage Method: Constant

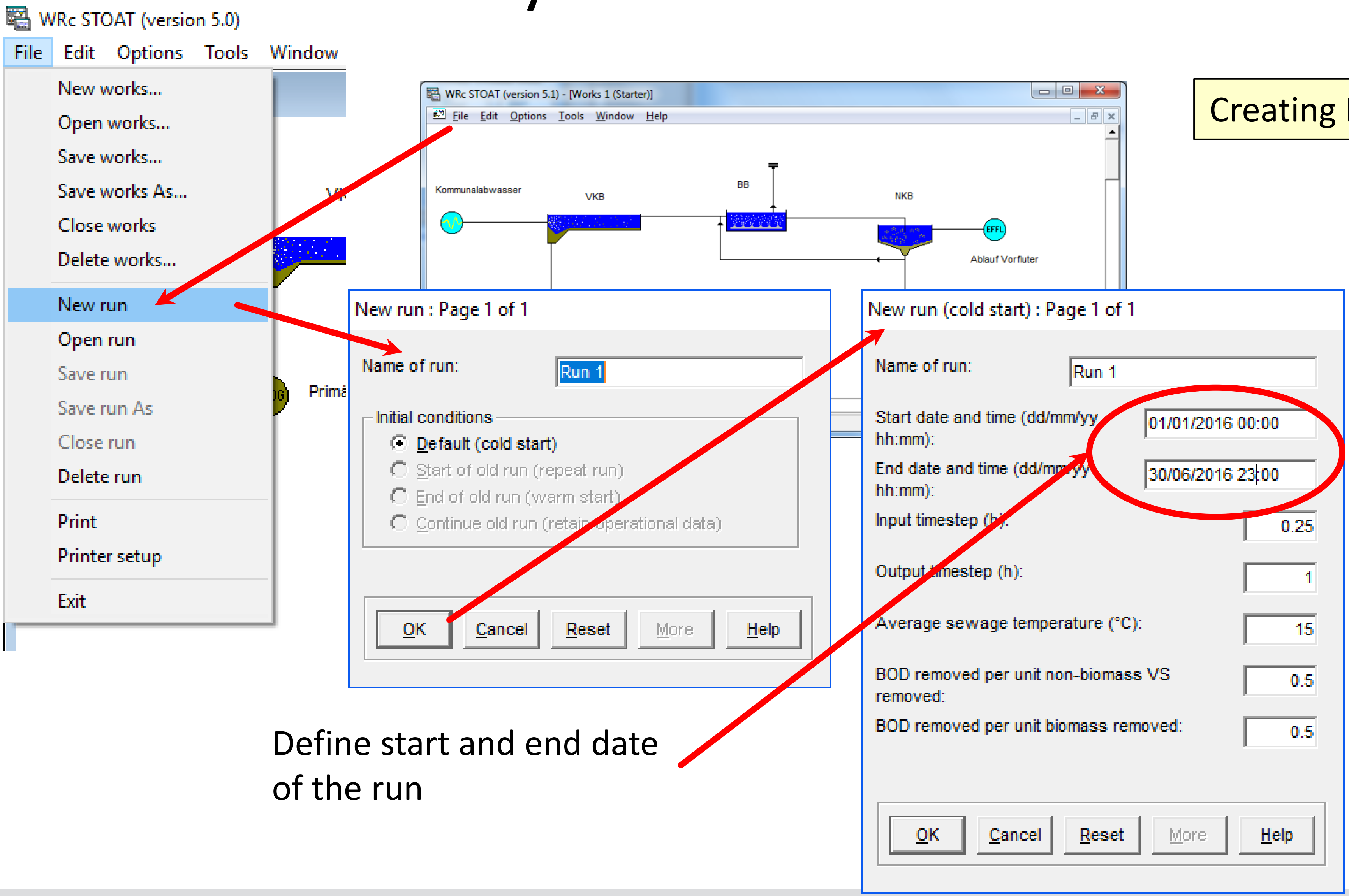
Control Aeration Tank : Activated Sludge Tank 1
Control aeration stage: 1

Our very first STOAT model

Now that the works has been defined and saved we can begin to carry out simulations for the works.
Select 'File/New run'.

Our very first STOAT model

Creating Run



New run : Page 1 of 1

Name of run: Run 1

Initial conditions
- ● Default (cold start)
- ○ Start of old run (repeat run)
- ○ End of old run (warm start)
- ○ Continue old run (retain operational data)

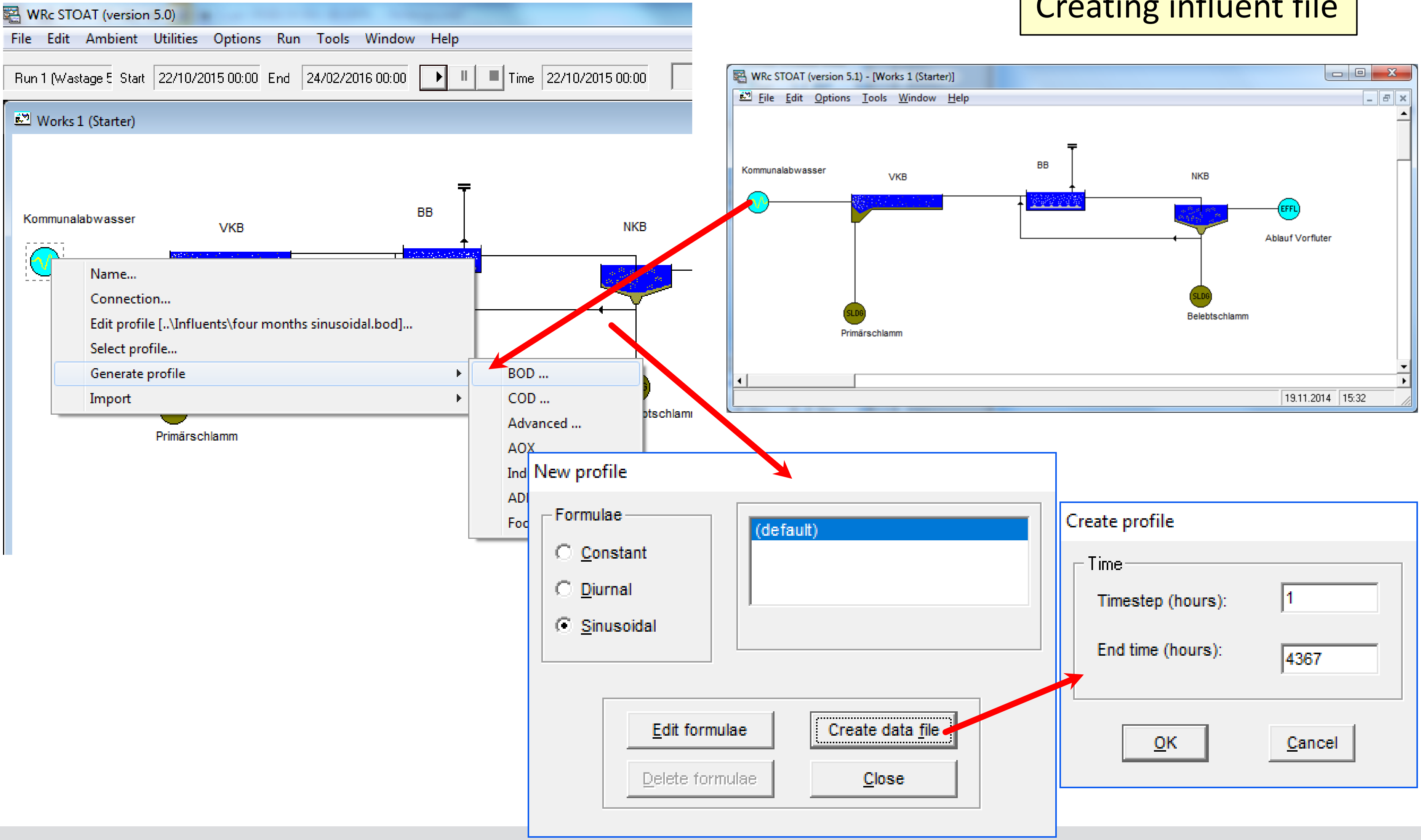
New run (cold start) : Page 1 of 1

Name of run:	Run 1
Start date and time (dd/mm/yy hh:mm):	01/01/2016 00:00
End date and time (dd/mm/yy hh:mm):	30/06/2016 23:00
Input timestep (h):	0.25
Output timestep (h):	1
Average sewage temperature (°C):	15
BOD removed per unit non-biomass VS removed:	0.5
BOD removed per unit biomass removed:	0.5

Define start and end date of the run

Our very first STOAT model

Creating influent file



Run 1 (Wastage 5 Start 22/10/2015 00:00 End 24/02/2016 00:00 Time 22/10/2015 00:00

Edit profile [..\Influents\four months sinusoidal.bod]...

New profile

Formulae

○ Constant
○ Diurnal
● Sinusoidal

(default)

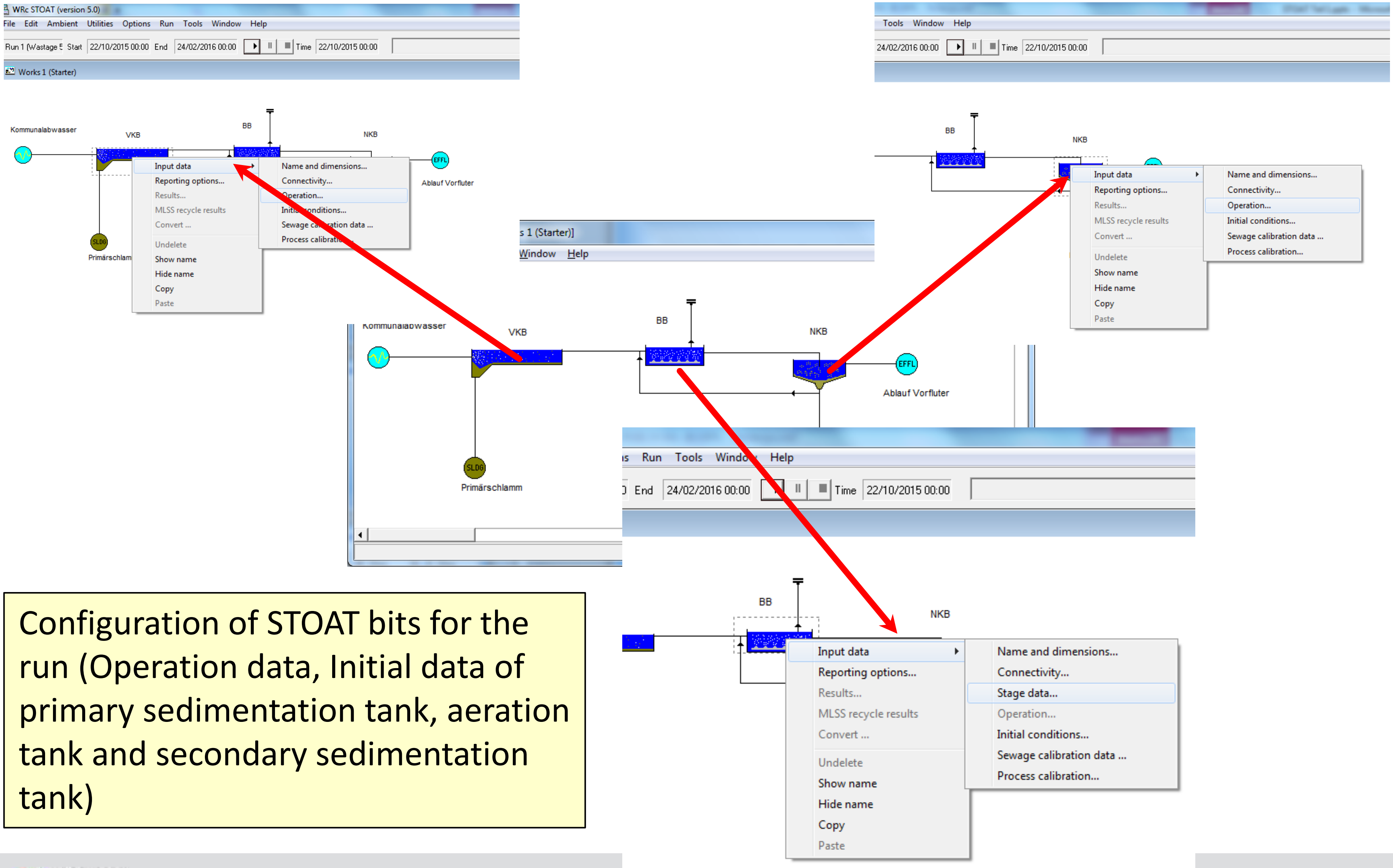
Create profile

Time

Timestep (hours): 1

End time (hours): 4367

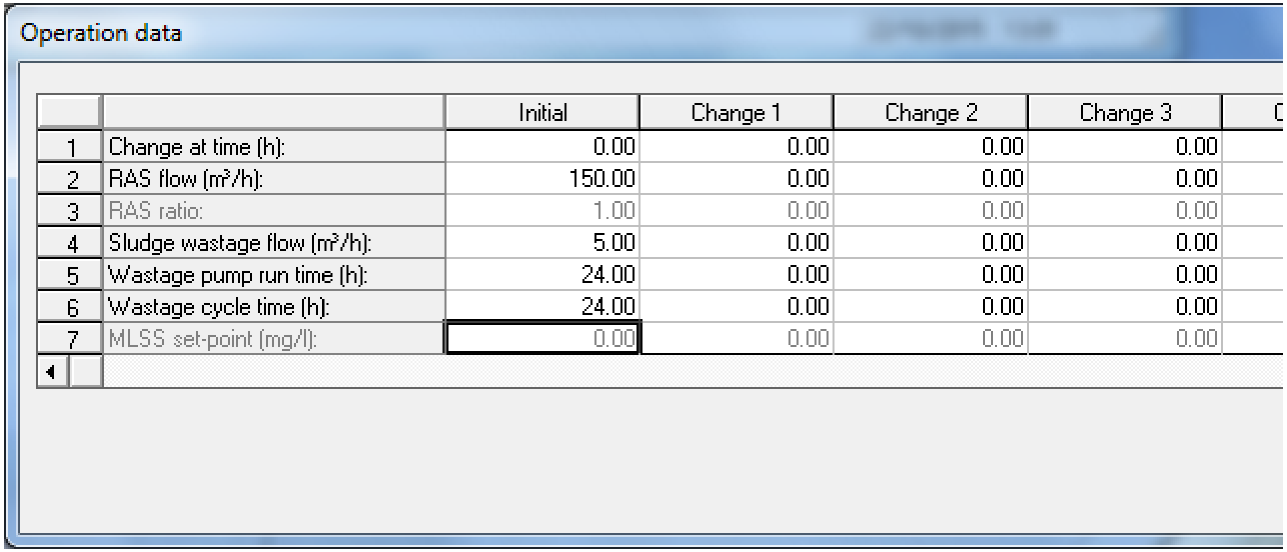
Our very first STOAT model



Configuration of STOAT bits for the run (Operation data, Initial data of primary sedimentation tank, aeration tank and secondary sedimentation tank)

Our very first STOAT model

Operational data of secondary sedimentation tank

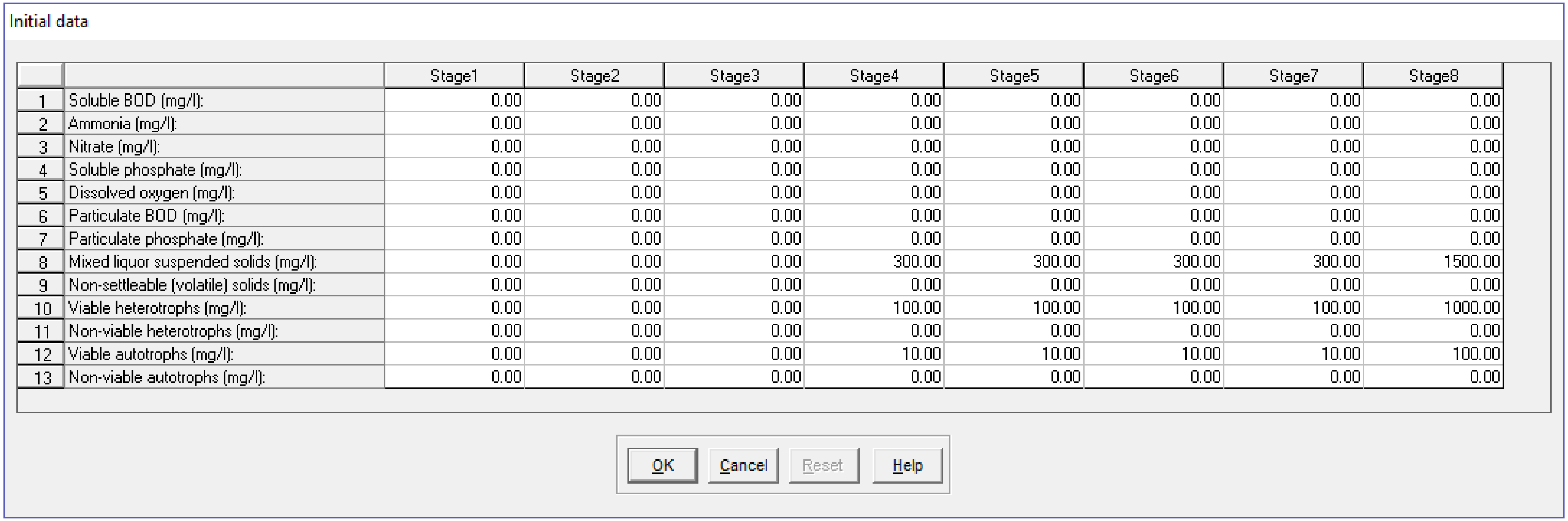


Operation data

		Initial	Change 1	Change 2	Change 3
1	Change at time (h):	0.00	0.00	0.00	0.00
2	RAS flow (m^3/h):	150.00	0.00	0.00	0.00
3	RAS ratio:	1.00	0.00	0.00	0.00
4	Sludge wastage flow (m^3/h):	5.00	0.00	0.00	0.00
5	Wastage pump run time (h):	24.00	0.00	0.00	0.00
6	Wastage cycle time (h):	24.00	0.00	0.00	0.00
7	MLSS set-point (mg/l):	0.00	0.00	0.00	0.00

Our very first STOAT model

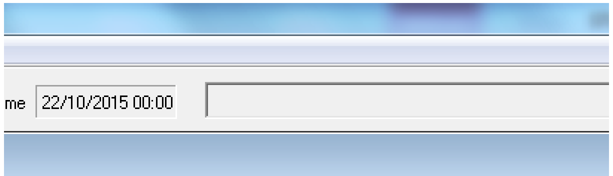
Initial data of secondary sedimentation tank



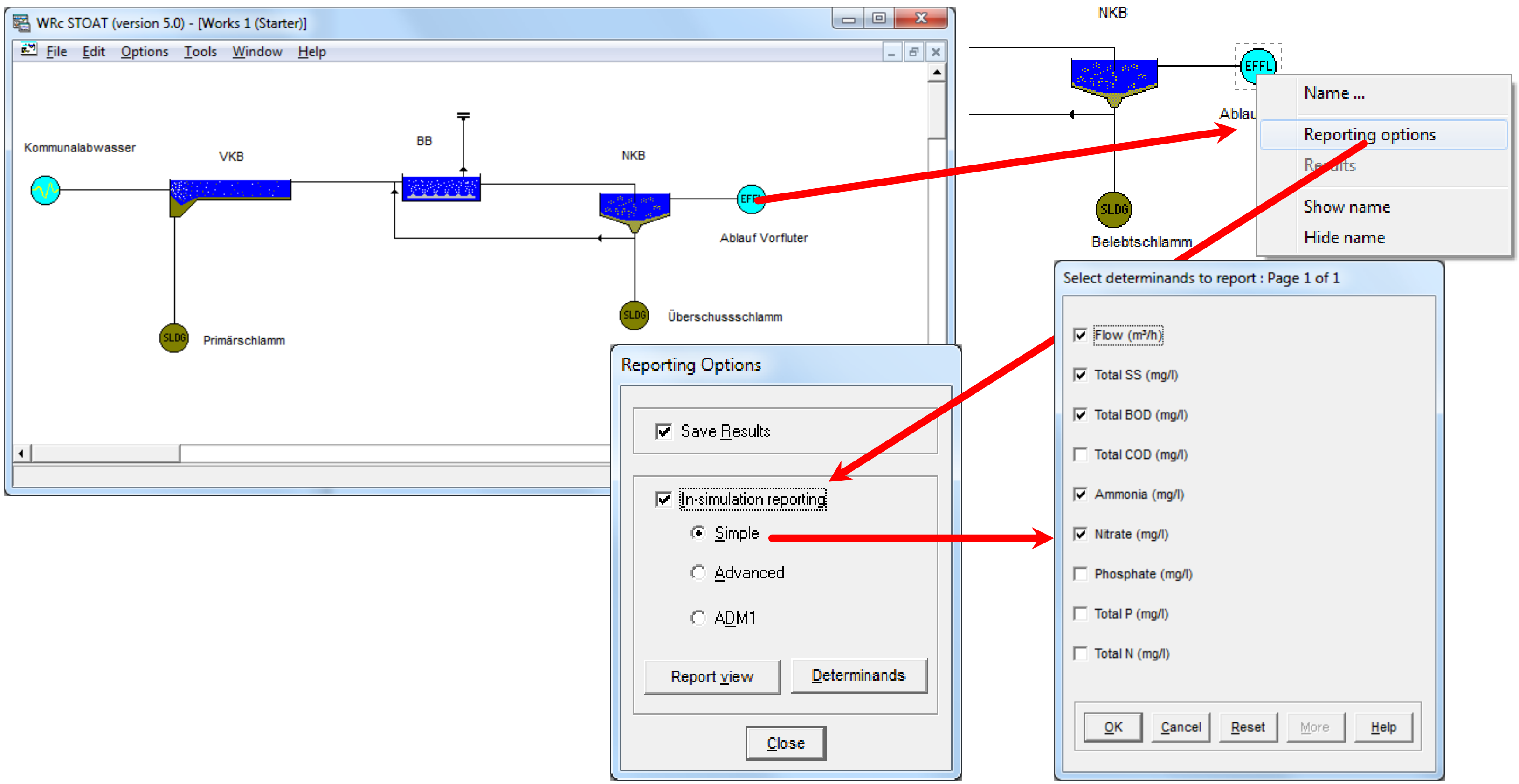
Initial data

		Stage1	Stage2	Stage3	Stage4	Stage5	Stage6	Stage7	Stage8
1	Soluble BOD (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	Ammonia (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	Nitrate (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Soluble phosphate (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Dissolved oxygen (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Particulate BOD (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	Particulate phosphate (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Mixed liquor suspended solids (mg/l):	0.00	0.00	0.00	300.00	300.00	300.00	300.00	1500.00
9	Non-settleable (volatile) solids (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	Viable heterotrophs (mg/l):	0.00	0.00	0.00	100.00	100.00	100.00	100.00	1000.00
11	Non-viable heterotrophs (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	Viable autotrophs (mg/l):	0.00	0.00	0.00	10.00	10.00	10.00	10.00	100.00
13	Non-viable autotrophs (mg/l):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Our very first STOAT model



me 22/10/2015 00:00



Reporting Options

☑ Save Results

☑ In-simulation reporting

● Simple

○ Advanced

○ ADM1

Report view | Determinands | Close

Select determinands to report : Page 1 of 1

☑ Flow (m^3/h)

☑ Total SS (mg/l)

☑ Total BOD (mg/l)

☐ Total COD (mg/l)

☑ Ammonia (mg/l)

☑ Nitrate (mg/l)

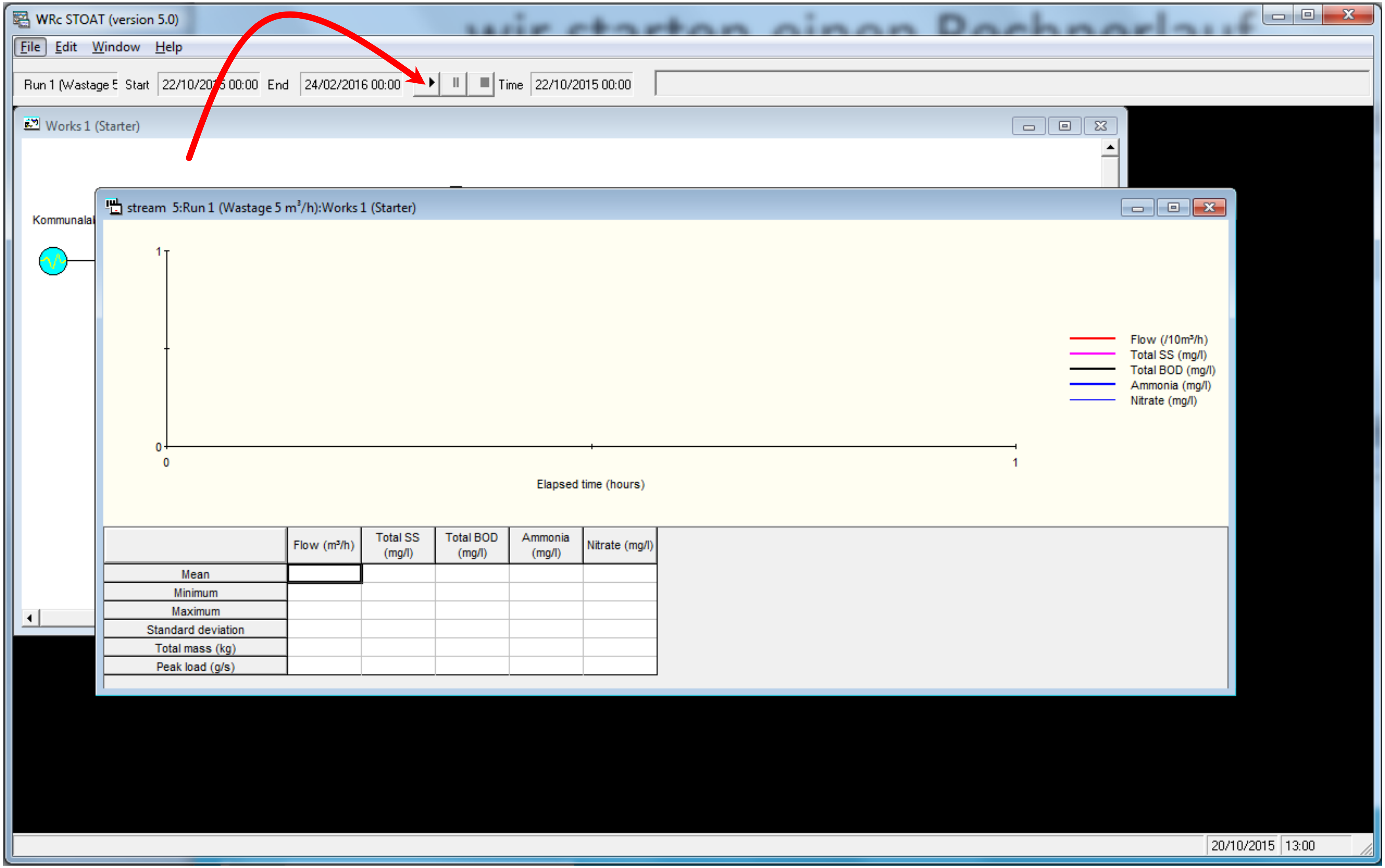
☐ Phosphate (mg/l)

☐ Total P (mg/l)

☐ Total N (mg/l)

OK | Cancel | Reset | More | Help

Our very first STOAT model



Run 1 (Wastage 5 Start 22/10/2015 00:00 End 24/02/2016 00:00 Time 22/10/2015 00:00

	Flow (m³/h)	Total SS (mg/l)	Total BOD (mg/l)	Ammonia (mg/l)	Nitrate (mg/l)
Mean					
Minimum					
Maximum					
Standard deviation					
Total mass (kg)					
Peak load (g/s)					

20/10/2015 13:00

Our very first STOAT model

Which results does a computer run provide?

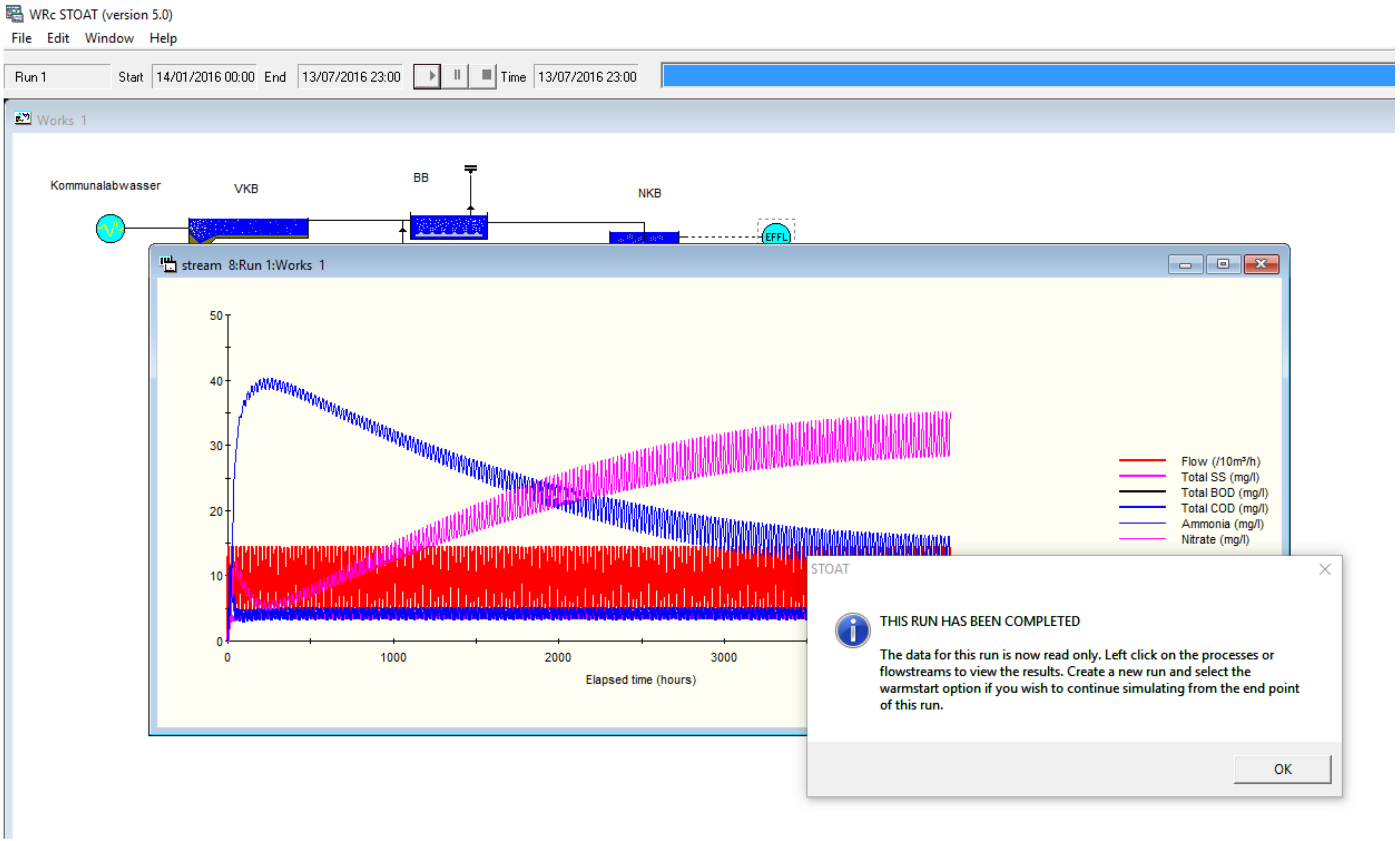
How can I illustrate this?

What conclusions can be drawn from this?

Do I have to change the computer run and / or rebuild the model (change, expand)?

And if so, how?

Our very first STOAT model



Run 1 Start 14/01/2016 00:00 End 13/07/2016 23:00 Time 13/07/2016 23:00

THIS RUN HAS BEEN COMPLETED

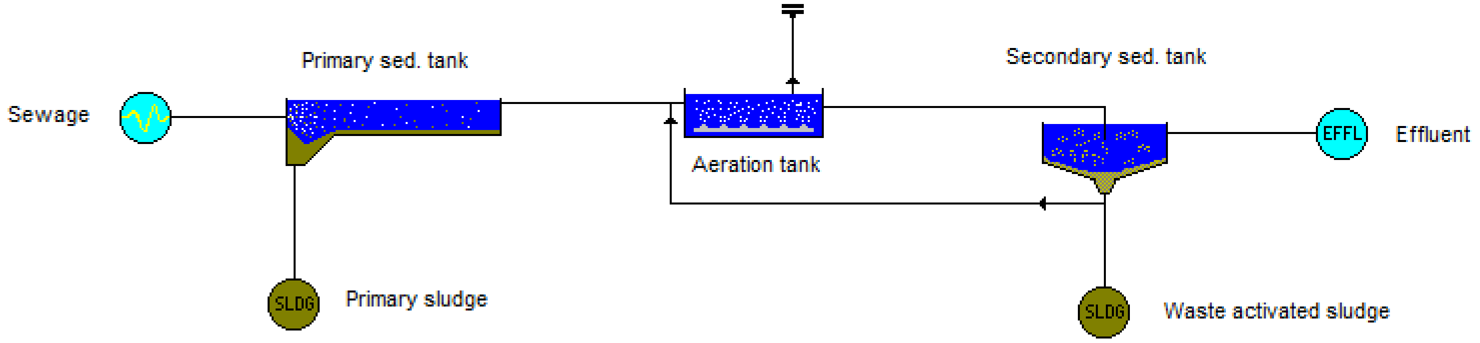
The data for this run is now read only. Left click on the processes or flowstreams to view the results. Create a new run and select the warmstart option if you wish to continue simulating from the end point of this run.

8th Lecture

STOAT simulation of WWTP Stahnsdorf

Supplement to lecture #7

Starter model:



Runs:

Run	Remarks	Results
Run 1	Cold start, WAS = 5 m³/h	Nitrification works
Run 2	Warm start, WAS = 7.5 m³/h	Nitrification breaks down
Run 3	Warm start, WAS = 2.5 m³/h	Nitrification better than Run 1

Supplement to lecture #7

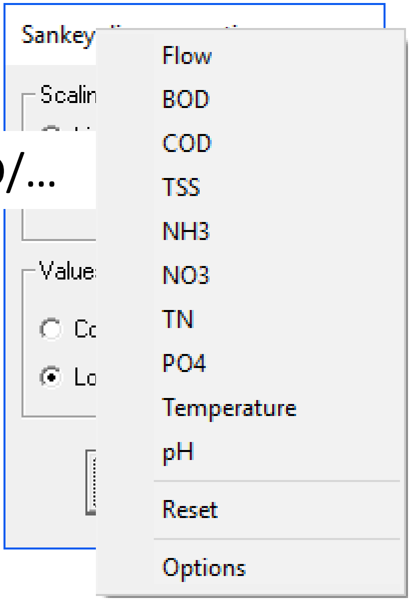
Have a look behind the scene

Bit Aeration tanks → Results → Viable autotrophs → Graph and summary statistics

So you may better understand why nitrification behaves this way…

Menu Tools → Stream reports → **Sankey diagram** → Options

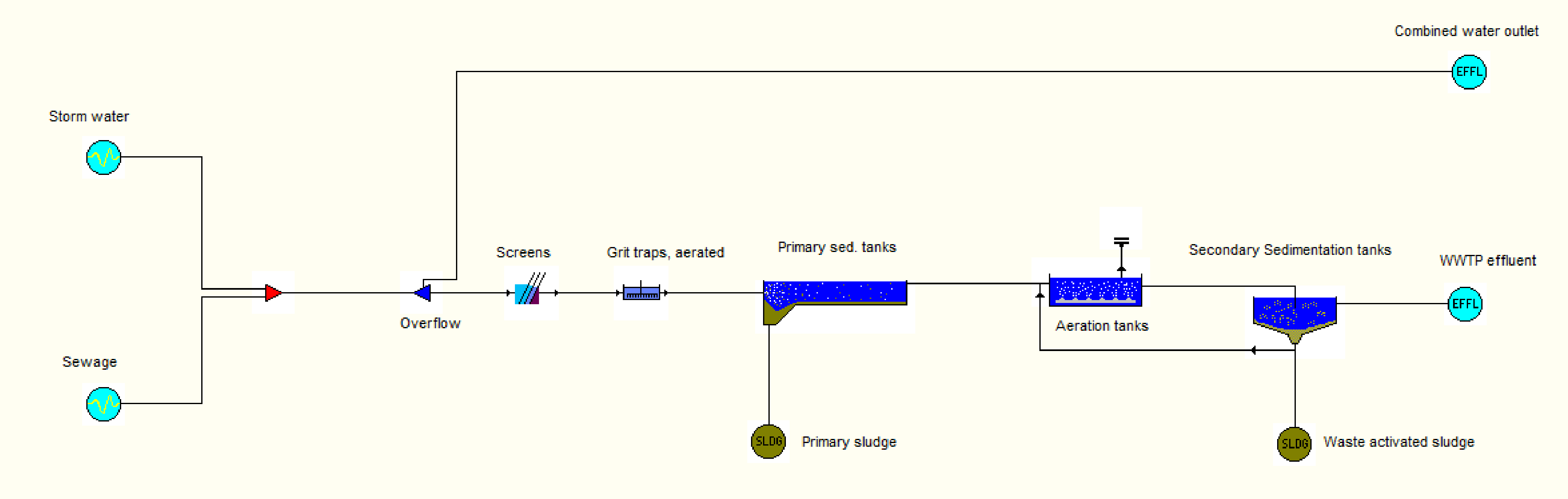
Menu Tools → Stream reports → **Sankey diagram** → Flow/BOD/…



Menu Tools → Stream reports → **Mass balance**

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #1:



Simplification: Only one train, volume of every STOAT bit represents all single installations; No modeling of sludge treatment

Changes: Mixed water influent of WWTP splitted into sewage and storm water (for better investigation of storm water events)

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #1, Runs:

Run	Remarks	Results
Run 1	Cold start, dry weather	Solids and BOD/COD fine, Ammonia with some peaks (nitrification works not good enough), Nitrate fine, Phosphate with some peaks (BioP)
Run 2	Repeat run 1, calib. autotrophs	Now nitrification fine, other results as previous run
Run 3	Repeat run 2, stormy weather	Solids, BOD/COD break through of SST, other results as previous run
Run 4	Repeat run 3, calib. SST	Solids and BOD/COD fine again, other results as previous run

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #1, Results of run 4:

What about the outlet of mixed water?
Check the flow by Sankey diagram and investigate the function of overflow!

What about the behaviour of ammonia, nitrate and Total N?
Check it by Sankey diagram!

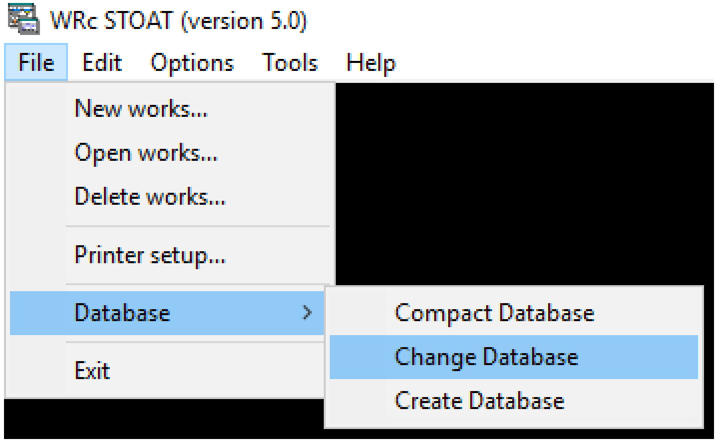
9th Lecture

STOAT simulation of WWTP Stahnsdorf

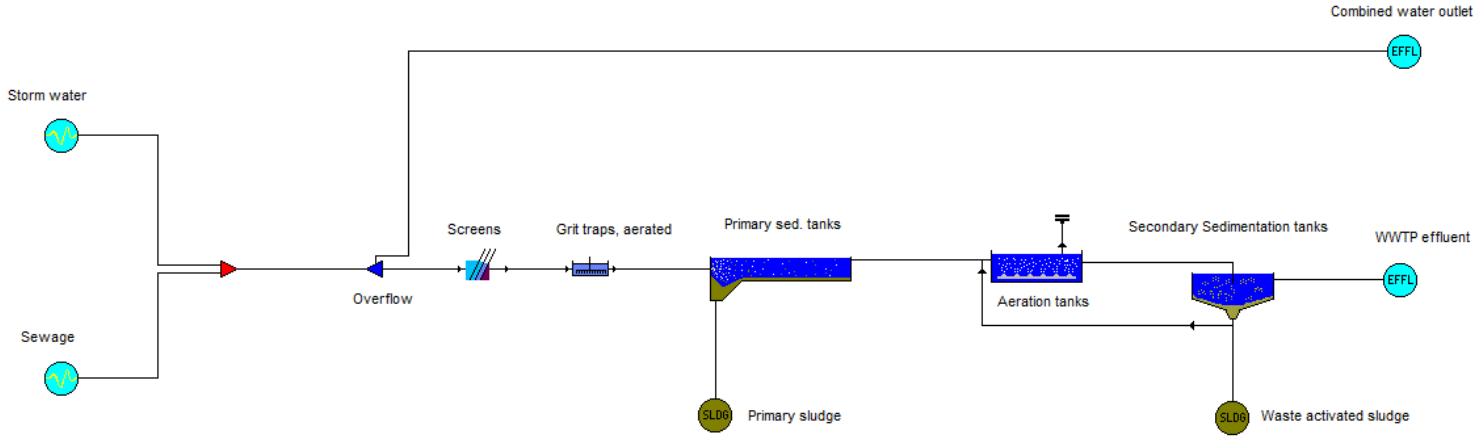
Supplement to lecture #8

Start STOAT, then change database to

...\Stahnsdorf\Runs\Stahnsdorf.mdb



Open work
WWTP Stahnsdorf #1 (basic model)



Supplement to lecture #8

Runs of WWTP Stahnsdorf #1 (basic model):

Runs	Remarks	Results
Run 1 (cold start, dry weather)	RAS = 70%, WAS controls MLSS (3.3 g/l), default calibration	Nitrification not good enough

Last lecture ended with doing Run 1

You’ll find additional runs which I prepared:

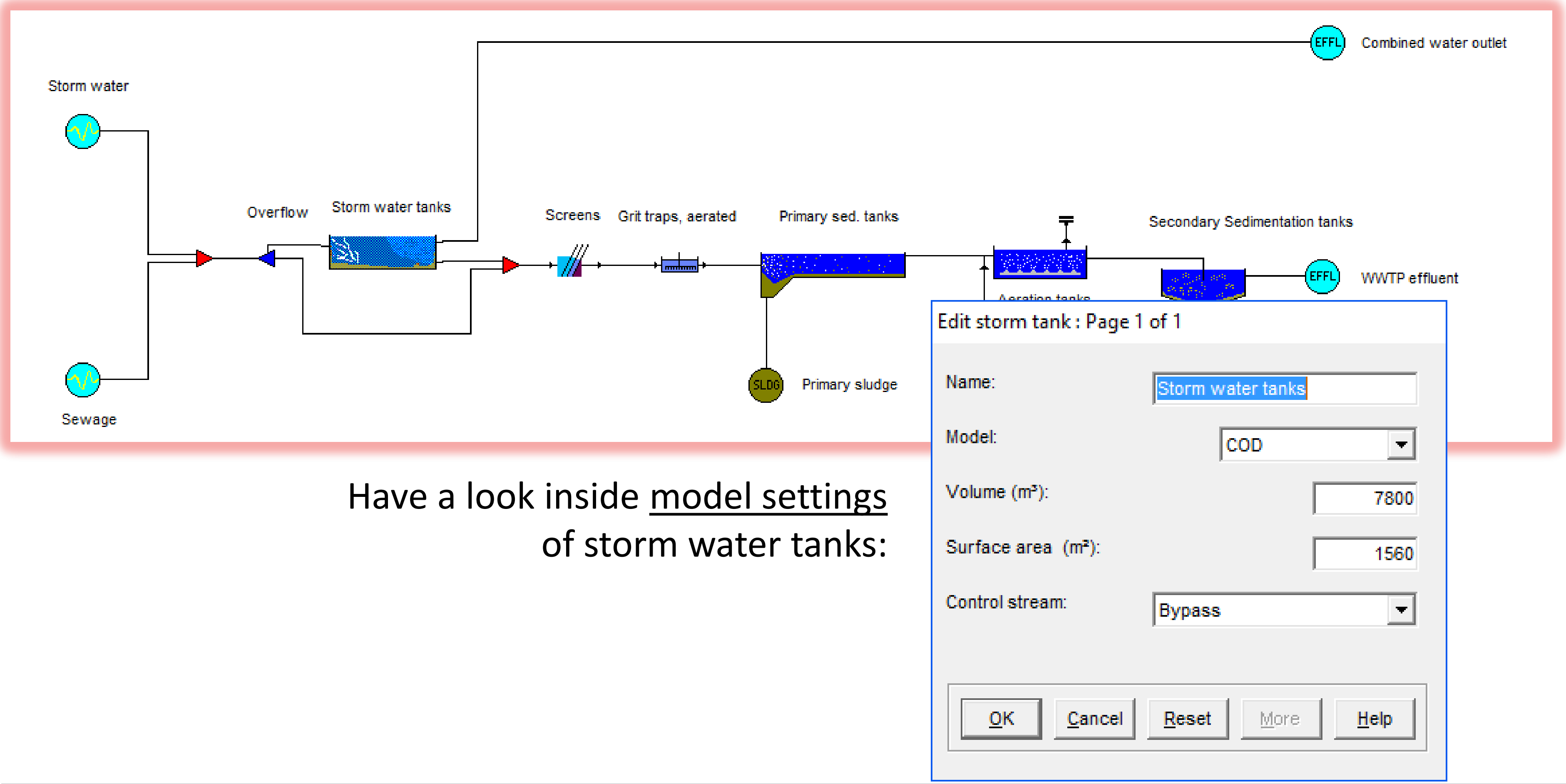
Run 2 (repeat run 1, calib. autotrophs)	RAS/WAS as before, calibration of autotrophs changed to better growth	Nitrification works fine
Run 3 (repeat run 2, stormy weather)	RAS/WAS/calibration as before	Breakthrough of solids after heavy rains
Run 4 (repeat run 3, calib. SST)	RAS/WAS/calibration of autotrophs as before, calibration of SST changed to better working	No more breakthrough of solids

Please do these runs in exercise #10!

STOAT simulation of WWTP Stahnsdorf

Today open work

WWTP Stahnsdorf #2 (#1 + storm water tanks)



Have a look inside <u>model settings</u>
of storm water tanks:

Edit storm tank : Page 1 of 1

Name: Storm water tanks

Model: COD

Volume (m^3): 7800

Surface area (m^2): 1560

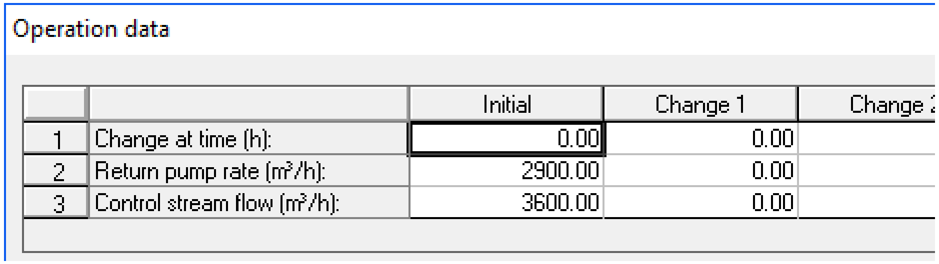
Control stream: Bypass

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #2 (#1 + storm water tanks)

Open run
Run 1 (stormy weather)

Have a look inside <u>operation</u>
of storm water tanks:



Operation data

		Initial	Change 1	Change
1	Change at time (h):	0.00	0.00	
2	Return pump rate (m^3/h):	2900.00	0.00	
3	Control stream flow (m^3/h):	3600.00	0.00	

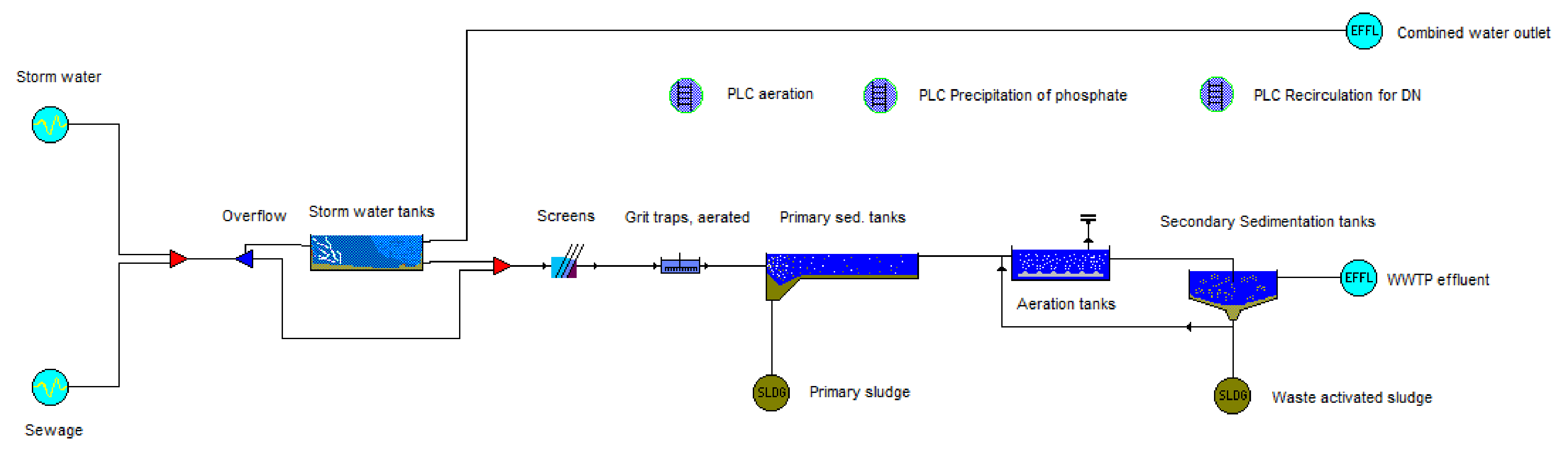
What these settings are good for?

Do **Run 1 (stormy weather)** and inspect the results!

STOAT simulation of WWTP Stahnsdorf

Open work

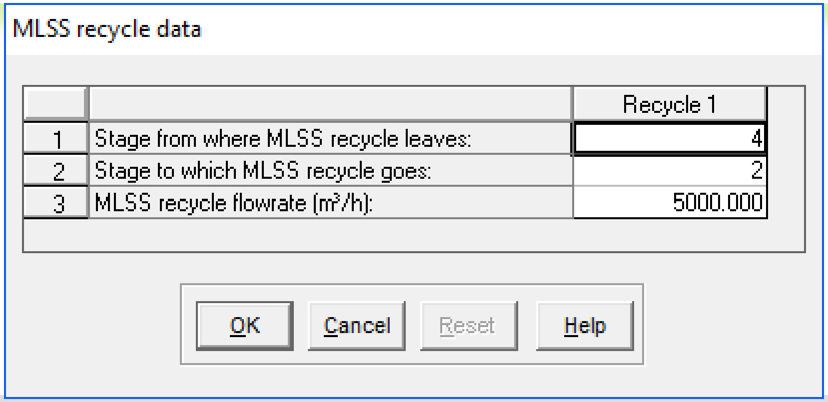
WWTP Stahnsdorf #3 (#2 + PLCs)



Open run

Run 1 (stormy weather)

Have a look inside MLSS recycle data of Aeration tank:



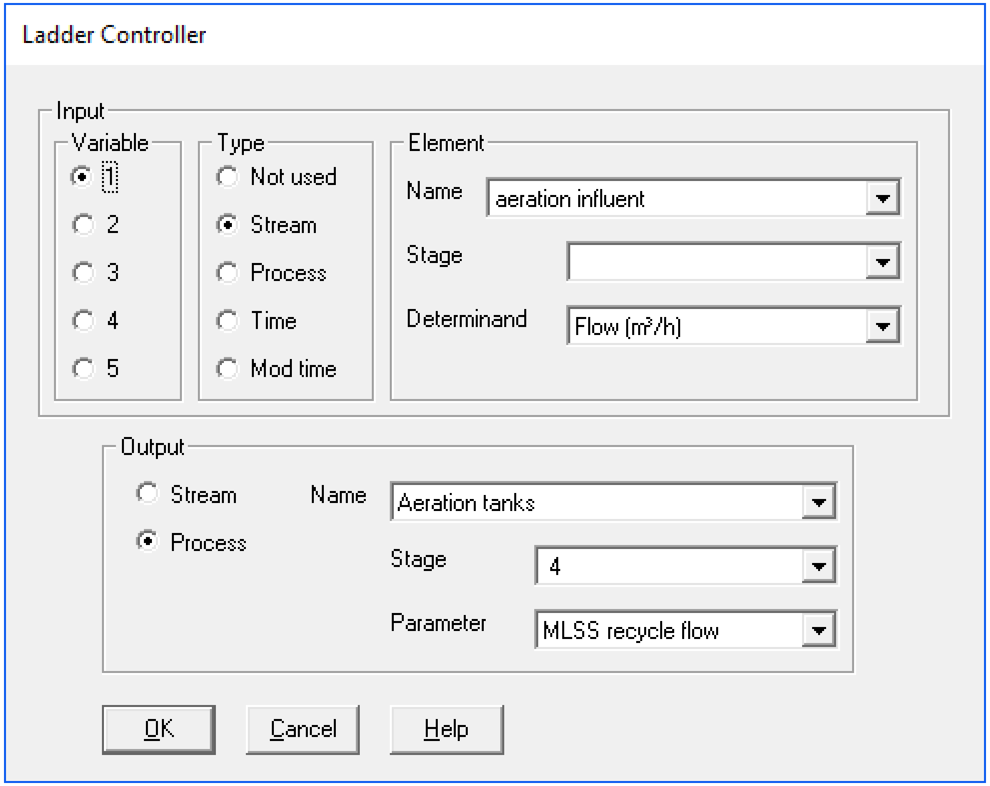
MLSS recycle data

		Recycle 1
1	Stage from where MLSS recycle leaves:	4
2	Stage to which MLSS recycle goes:	2
3	MLSS recycle flowrate (m^3/h):	5000.000

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #3 (#2 + PLCs), Run 1 (stormy weather)

Have a look inside <u>connectivity</u> of PLC Recirculation for DN:



Ladder Controller

Input

Variable: ● 1 ○ 2 ○ 3 ○ 4 ○ 5

Type: ○ Not used ● Stream ○ Process ○ Time ○ Mod time

Element

Name: aeration influent

Stage:

Determinand: Flow (m^3/h)

Output

○ Stream ● Process

Name: Aeration tanks

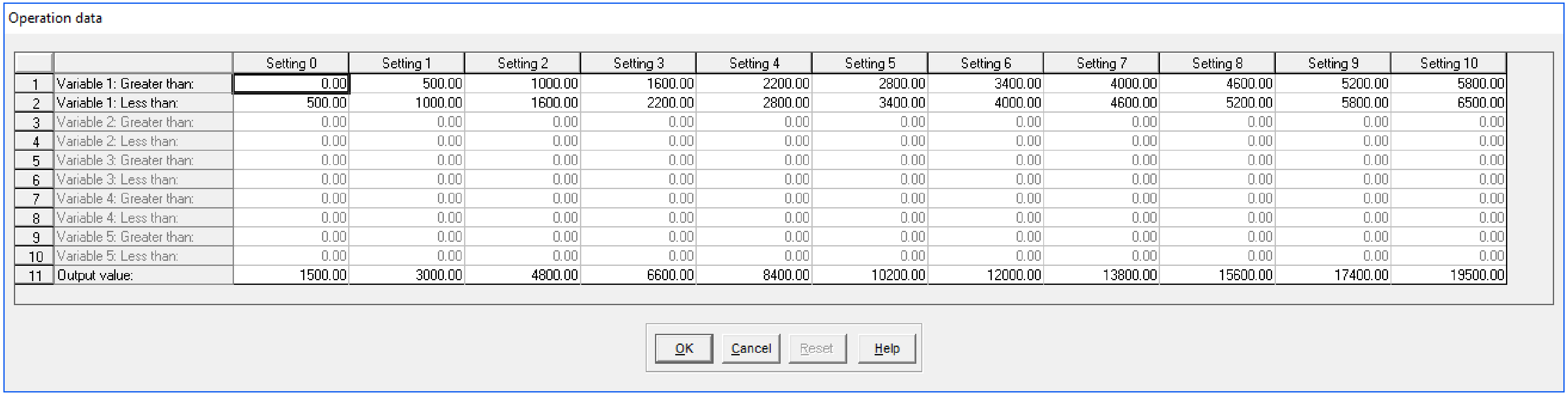
Stage: 4

Parameter: MLSS recycle flow

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #3 (#2 + PLCs), Run 1 (stormy weather)

Have a look inside <u>operation data</u>
of PLC Recirculation for DN:



Operation data

		Setting 0	Setting 1	Setting 2	Setting 3	Setting 4	Setting 5	Setting 6	Setting 7	Setting 8	Setting 9	Setting 10
1	Variable 1: Greater than:	0.00	500.00	1000.00	1600.00	2200.00	2800.00	3400.00	4000.00	4600.00	5200.00	5800.00
2	Variable 1: Less than:	500.00	1000.00	1600.00	2200.00	2800.00	3400.00	4000.00	4600.00	5200.00	5800.00	6500.00
3	Variable 2: Greater than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Variable 2: Less than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Variable 3: Greater than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Variable 3: Less than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	Variable 4: Greater than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Variable 4: Less than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	Variable 5: Greater than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	Variable 5: Less than:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	Output value:	1500.00	3000.00	4800.00	6600.00	8400.00	10200.00	12000.00	13800.00	15600.00	17400.00	19500.00

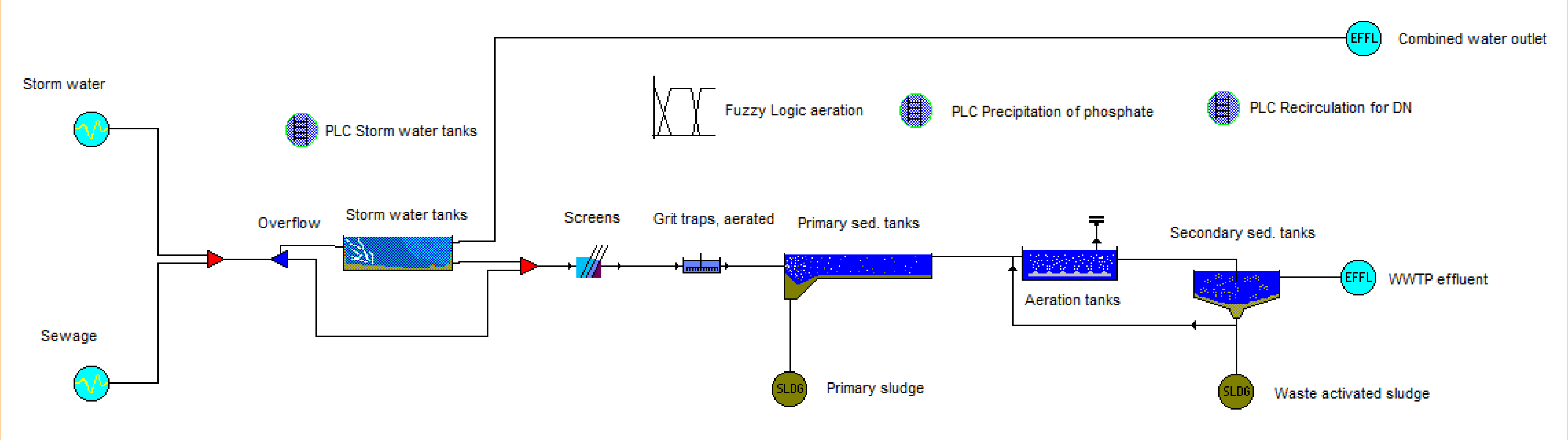
What these settings are good for?

Do **Run 1 (stormy weather)** and inspect the results!

STOAT simulation of WWTP Stahnsdorf

Open work

WWTP Stahnsdorf #4 (#3 + Fuzzy Logic)



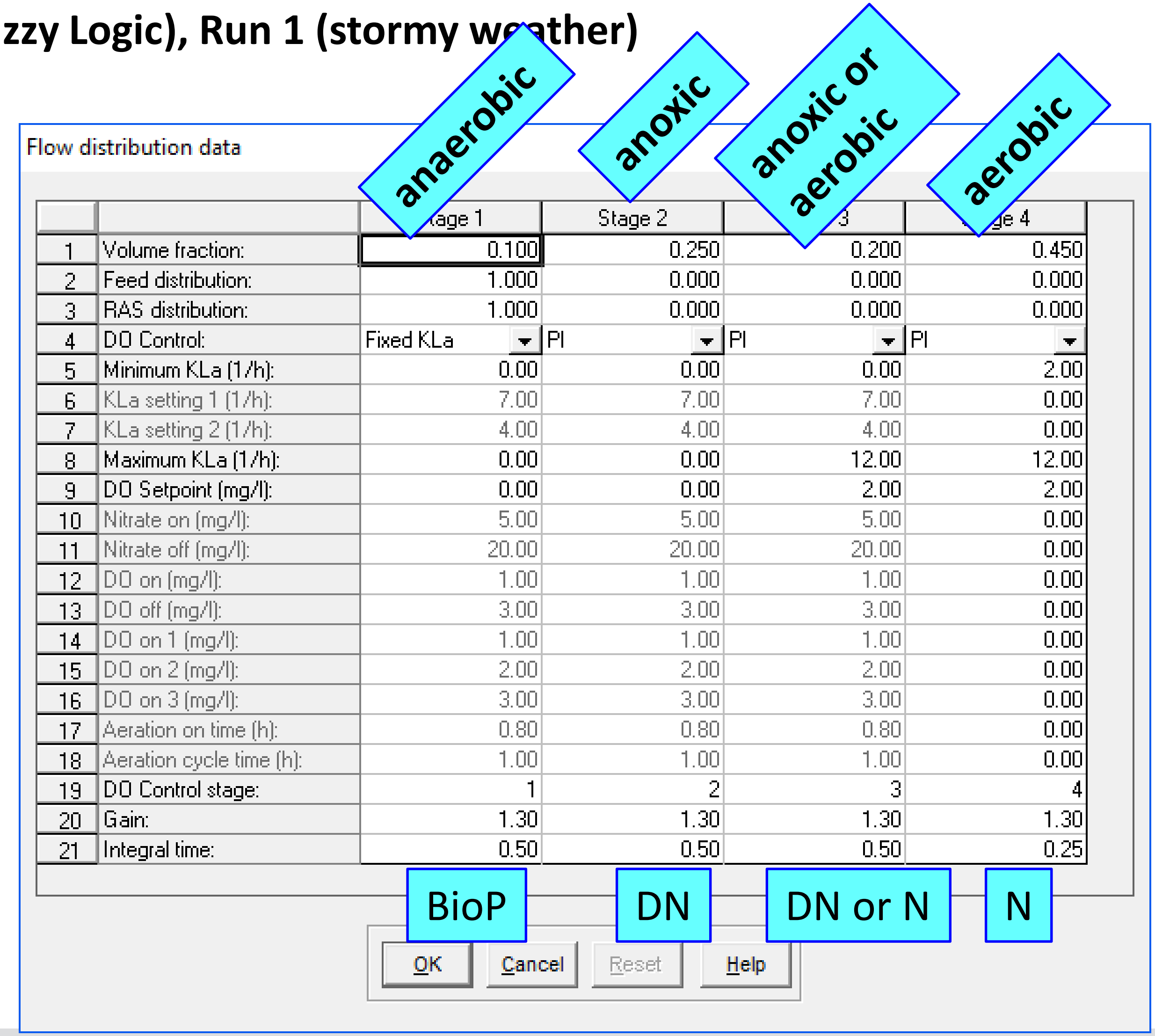
Open run

Run 1 (stormy weather)

STOAT simulation of WWTP Stahnsdorf

WWTP Stahnsdorf #4 (#3 + Fuzzy Logic), Run 1 (stormy weather)

Have a look inside stage data of aeration tanks:



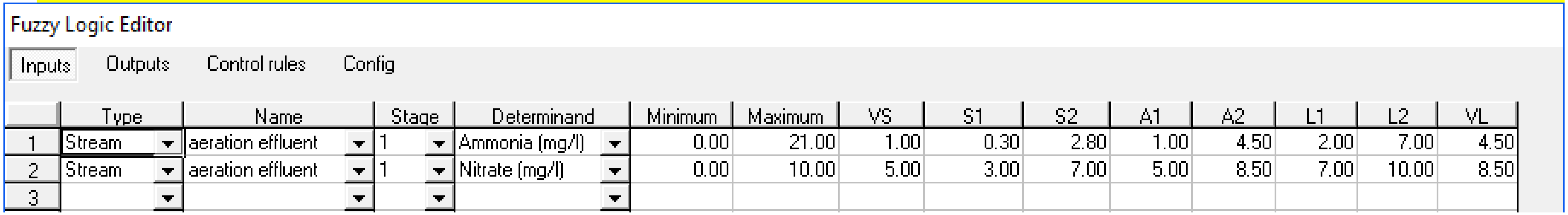
Flow distribution data

		tage 1	Stage 2	3	ge 4
1	Volume fraction:	0.100	0.250	0.200	0.450
2	Feed distribution:	1.000	0.000	0.000	0.000
3	RAS distribution:	1.000	0.000	0.000	0.000
4	DO Control:	Fixed KLa	PI	PI	PI
5	Minimum KLa (1/h):	0.00	0.00	0.00	2.00
6	KLa setting 1 (1/h):	7.00	7.00	7.00	0.00
7	KLa setting 2 (1/h):	4.00	4.00	4.00	0.00
8	Maximum KLa (1/h):	0.00	0.00	12.00	12.00
9	DO Setpoint (mg/l):	0.00	0.00	2.00	2.00
10	Nitrate on (mg/l):	5.00	5.00	5.00	0.00
11	Nitrate off (mg/l):	20.00	20.00	20.00	0.00
12	DO on (mg/l):	1.00	1.00	1.00	0.00
13	DO off (mg/l):	3.00	3.00	3.00	0.00
14	DO on 1 (mg/l):	1.00	1.00	1.00	0.00
15	DO on 2 (mg/l):	2.00	2.00	2.00	0.00
16	DO on 3 (mg/l):	3.00	3.00	3.00	0.00
17	Aeration on time (h):	0.80	0.80	0.80	0.00
18	Aeration cycle time (h):	1.00	1.00	1.00	0.00
19	DO Control stage:	1	2	3	4
20	Gain:	1.30	1.30	1.30	1.30
21	Integral time:	0.50	0.50	0.50	0.25

STOAT simulation of WWTP Stahnsdorf

Have a look inside the <u>inputs</u> of Fuzzy Logic Controller for aeration tank, step 3:

Fuzzy Logic aeration → Input data → Operation → reg. Inputs



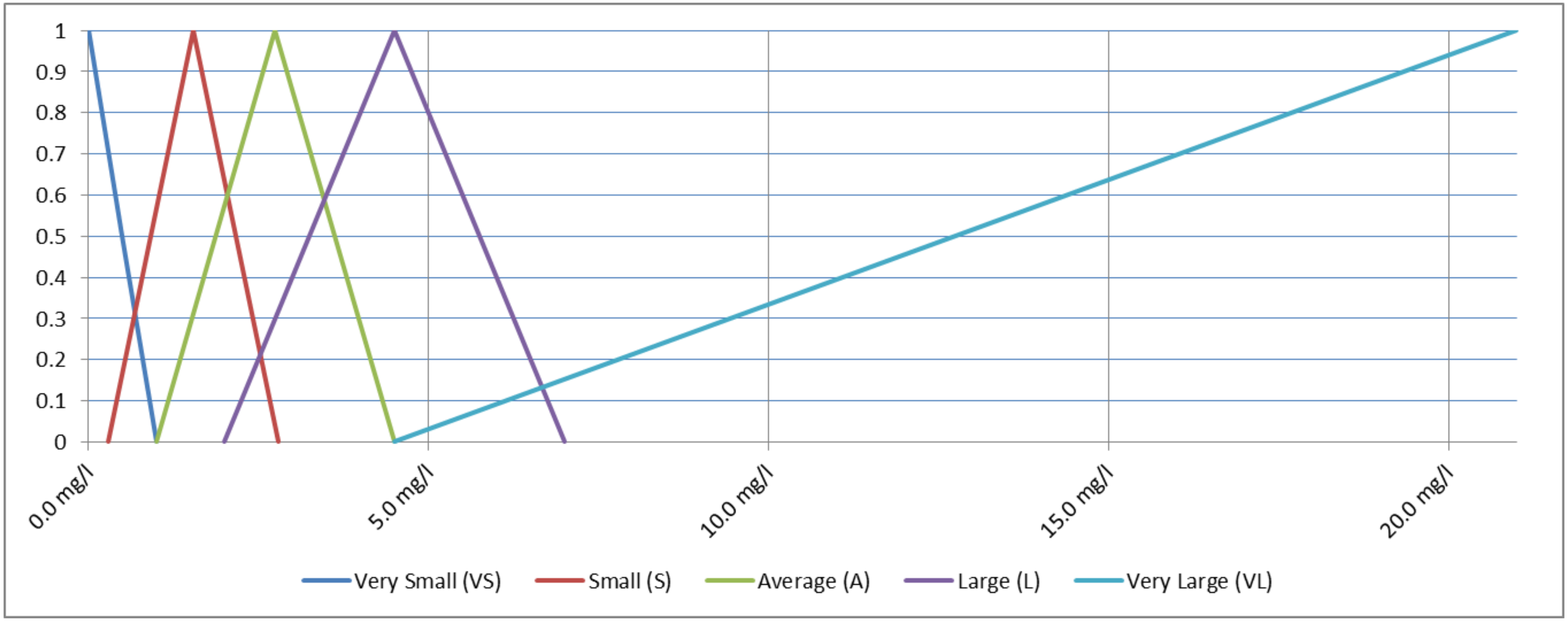
	Type	Name	Stage	Determinand	Minimum	Maximum	VS	S1	S2	A1	A2	L1	L2	VL
1	Stream	aeration effluent	1	Ammonia (mg/l)	0.00	21.00	1.00	0.30	2.80	1.00	4.50	2.00	7.00	4.50
2	Stream	aeration effluent	1	Nitrate (mg/l)	0.00	10.00	5.00	3.00	7.00	5.00	8.50	7.00	10.00	8.50
3														

Symbol	Meaning
VS	Very Small
S1 … S2	Small
A1 … A2	Average
L1 … L2	Large
VL	Very Large

The effect of the selected limits on the input values can best be understood through the so-called **membership function**.

STOAT simulation of WWTP Stahnsdorf

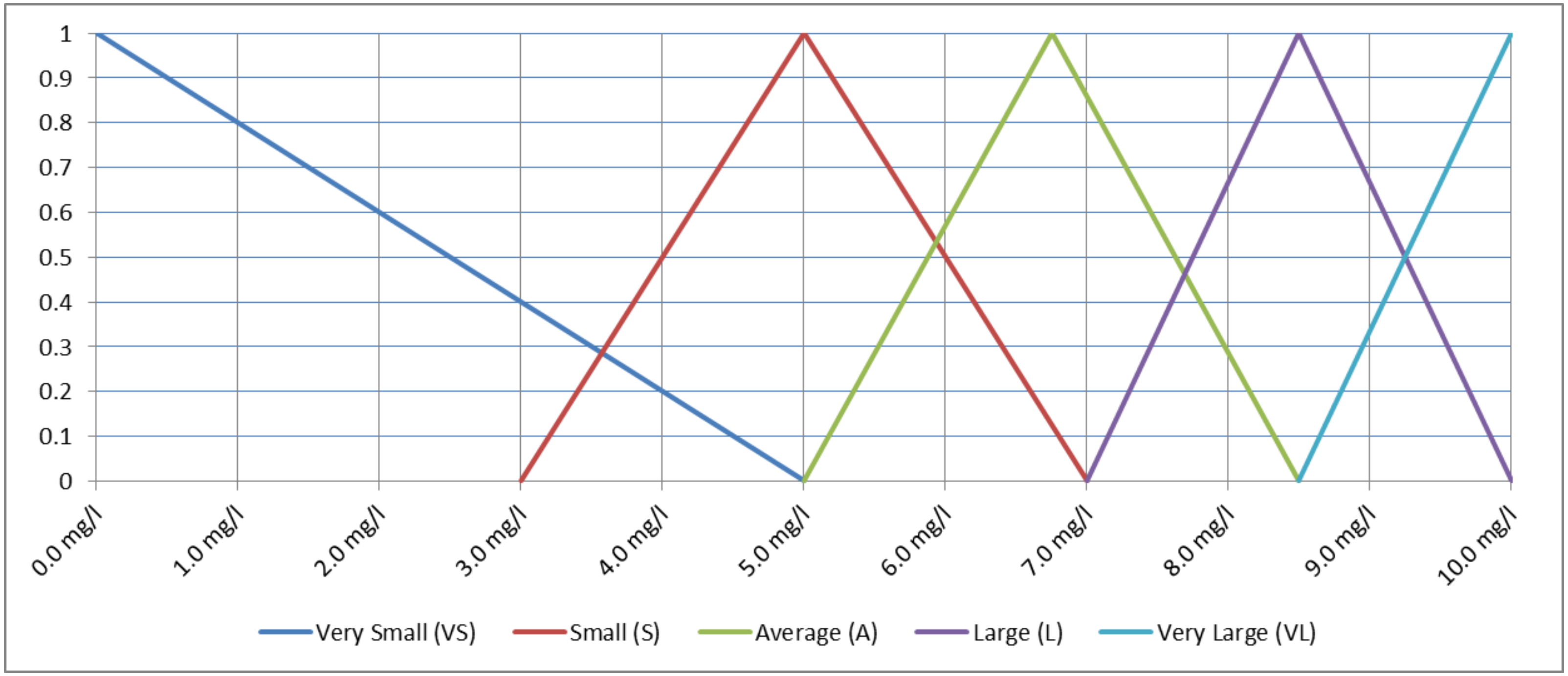
Membership function of Ammonia:



See Excel file „WWTP Stahnsdorf STOAT background calculations.xlsx“, Register „Fuzzy Logic aeration“

STOAT simulation of WWTP Stahnsdorf

Membership function of Nitrate:

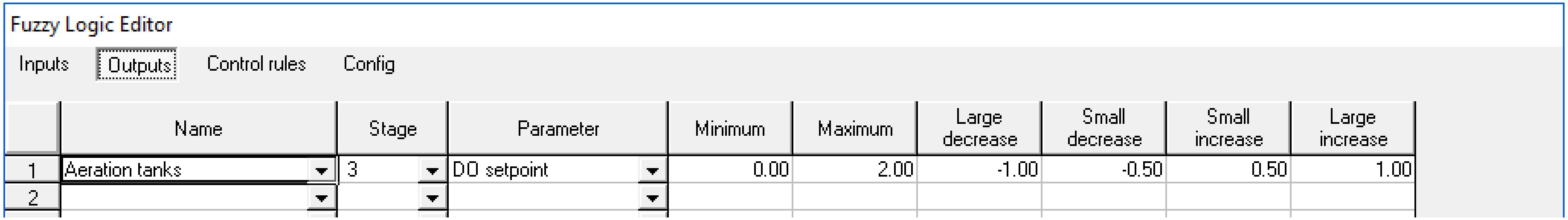


See Excel file „WWTP Stahnsdorf STOAT background calculations.xlsx“, Register „Fuzzy Logic aeration“

STOAT simulation of WWTP Stahnsdorf

Have a look inside the <u>outputs </u>of Fuzzy Logic Controller:

Fuzzy Logic aeration → Input data → Operation → reg. Outputs



	Name	Stage	Parameter	Minimum	Maximum	Large decrease	Small decrease	Small increase	Large increase
1	Aeration tanks	3	DO setpoint	0.00	2.00	-1.00	-0.50	0.50	1.00
2									

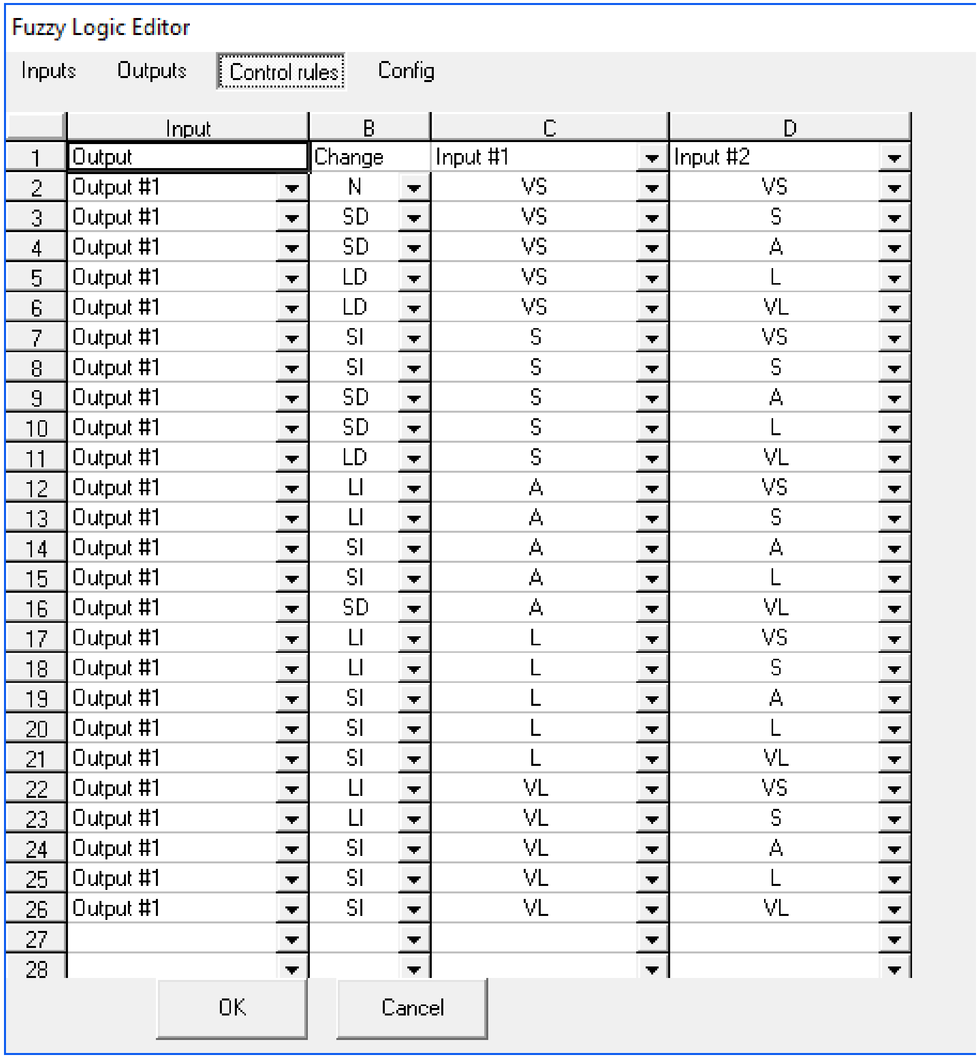
The fuzzy logic controller influences only the DO set point of the aeration tanks, stage 3. This stage can be operated anoxic (for denitrification) as well as aerobic (for nitrification) according the stage data of the aeration tanks (see slide 10). Because of the interaction between fuzzy logic controller and aeration tank stage 3 this stage will be operated anoxic if ammonia is low and nitrate is high and aerobic if nitrate is low and ammonia is high.

STOAT simulation of WWTP Stahnsdorf

The operating principles of the fuzzy logic controller have to be set in detail in its so-called **Control rules**.

Symbol	Meaning
N	Not firing
SD	Small Decrease
LD	Large Decrease
LI	Large Increase
SI	Small Increase

See Excel file „WWTP Stahnsdorf STOAT background calculations.xlsx“, Register „Fuzzy Logic aeration“



	Input	B	C	D
1	Output	Change	Input #1	Input #2
2	Output #1	N	VS	VS
3	Output #1	SD	VS	S
4	Output #1	SD	VS	A
5	Output #1	LD	VS	L
6	Output #1	LD	VS	VL
7	Output #1	SI	S	VS
8	Output #1	SI	S	S
9	Output #1	SD	S	A
10	Output #1	SD	S	L
11	Output #1	LD	S	VL
12	Output #1	LI	A	VS
13	Output #1	LI	A	S
14	Output #1	SI	A	A
15	Output #1	SI	A	L
16	Output #1	SD	A	VL
17	Output #1	LI	L	VS
18	Output #1	LI	L	S
19	Output #1	SI	L	A
20	Output #1	SI	L	L
21	Output #1	SI	L	VL
22	Output #1	LI	VL	VS
23	Output #1	LI	VL	S
24	Output #1	SI	VL	A
25	Output #1	SI	VL	L
26	Output #1	SI	VL	VL
27				
28				

10th Lecture

Exercises in preparation of final exams

Examples of questions to answer as text

Explain what happens with the different fractions of COD in the biological treatment step of a WWTP!

Why can both COD and BOD be balanced with the oxygen content in the planning and design of activated sludge plants? Explain the difference between COD and BOD in terms of biodegradability!

For the microorganisms in the activated sludge of a sewage treatment plant, a ratio of C:N:P of about 100 : 5 : 1 is optimal. To what extent does the nutrient composition of normally polluted domestic sewage deviate from this and what are the consequences for wastewater treatment?

What effects can be expected on the operation of an activated sludge plant if the excess sludge sampling is set incorrectly, that means, if either too much or too little excess sludge is removed?

Wastewater treatment is very expensive. Nevertheless, all progressive countries invest in sewage networks and sewage treatment plants - why?

Examples of questions to answer as text

The most important design parameter of activated sludge process is the sludge retention time (SRT). What does it mean? How to calculate it?

$$SRT = \frac{Mass\ of\ solids\ within\ the\ tanks\ for\ biological\ treatment\ [in\ kg]}{Mass\ of\ solids\ which\ is\ removed\ by\ wastage\ of\ activated\ sludge\ [in\ \frac{kg}{d}]}$$

When SRT is too short or too long, how does the sewage treatment process deteriorates?

Wastewater entering a sewage treatment plant after a longer way in the sewer network normally does not contain oxidised nitrogen (NO_3-N resp. NO_2-N). Explain why!

The processes of artificial biological wastewater treatment in an activated sludge installation are copies of the self-cleaning in natural rivers, but under a polluting level, which is much higher than in nature. Therefore some additional conditions have to be met. When these conditions are not fulfilled, activated sludge plants cannot work. Which conditions are these? How the technical solution for this looks like?

Fractions of COD and solids

The following values are measured in a sanitary sewer before entering the WWTP:

Total COD (taken from homogenized sample)	600 mg/l
Total BOD (taken from homogenized sample)	300 mg/l
Soluble BOD (taken from filtrated sample)	200 mg/l
Total Suspended Solids	400 mg/l

How much are

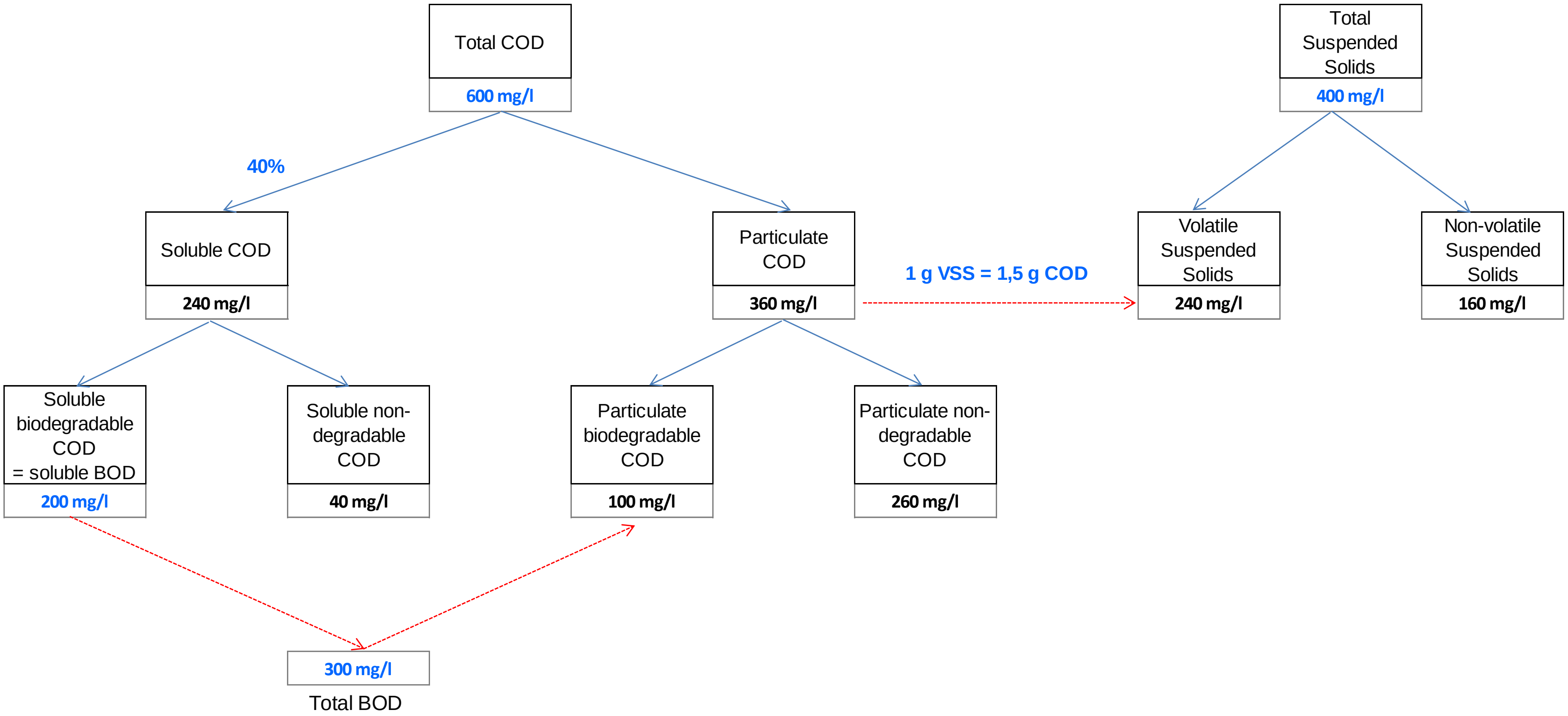
Soluble COD,
Particulate COD
Particulate non-degradable COD,
Particulate biodegradable COD,
Soluble non-degradable COD,
Non-volatile Suspended Solids

and

Volatile Suspended Solids

when soluble COD is 40% of Total COD and 1 g volatile solids is about 1.5 g COD?

Fractions of COD and solids



Total COD

600 mg/l

40%

Soluble COD

240 mg/l

Particulate COD

360 mg/l

Soluble biodegradable COD = soluble BOD

200 mg/l

Soluble non-degradable COD

40 mg/l

Particulate biodegradable COD

100 mg/l

Particulate non-degradable COD

260 mg/l

300 mg/l

Total BOD

1 g VSS = 1,5 g COD

Total Suspended Solids

400 mg/l

Volatile Suspended Solids

240 mg/l

Non-volatile Suspended Solids

160 mg/l

Fractions of Nitrogen

The following values are known by measurement of a sanitary sewer:

Total Kjeldahl Nitrogen (taken from homogenized sample)	50 mg/l
Total Kjeldahl Nitrogen (taken from filtrated sample)	40 mg/l
Ammonia	30 mg/l
Nitrate	0 mg/l
Nitrite	0 mg/l

How much are
Total Nitrogen (TN),
Total Organic Nitrogen (TON),
Total Inorganic Nitrogen (TIN),
Dissolved Organic Nitrogen (DON),
Particulate Organic Nitrogen (PON),
Total Nitrogen bounded (TNb),
when gaseous nitrogen should be ignored?

Fractions of Nitrogen

<table>
<tr><td colspan="6">Total Nitrogen (TN)</td></tr>
<tr><td colspan="6">60,0 mg/l</td></tr>
<tr><td colspan="4">Total Inorganic Nitrogen (TIN)</td><td colspan="2">Total Organic Nitrogen (TON)</td></tr>
<tr><td colspan="4">30,0 mg/l</td><td colspan="2">30,0 mg/l</td></tr>
<tr><td>Gaseous nitrogen</td><td>Nitrite</td><td>Nitrate</td><td>Ammonium / Ammonia</td><td>Dissolved Organic Nitrogen (DON)</td><td>Particulate Organic Nitrogen (PON)</td></tr>
<tr><td>ignored</td><td>0,0 mg/l</td><td>0,0 mg/l</td><td>30,0 mg/l</td><td>20,0 mg/l</td><td>10,0 mg/l</td></tr>
<tr><td>TKN, homogenized sample</td><td colspan="2" rowspan="2"></td><td colspan="3">60,0 mg/l</td></tr>
<tr><td>TKN, filtrated sample</td><td colspan="2">50,0 mg/l</td><td></td></tr>
<tr><td>Total Nitrogen bounded (TNb)</td><td colspan="5">60,0 mg/l</td></tr>
</table>

Theoretical COD

Calculate the theoretical COD of the substance toluene ($C_6H_5CH_3$ bzw. C_7H_8) in $\frac{mg}{l}$!

Reaction: $C_7H_8 + 9\ O_2 \rightarrow 7\ CO_2 + 4\ H_2O$

Molecular weight of toluene (how much does 1 mole of toluene weigh?):

12*7 +1*8 = 92 g per mole of toluene

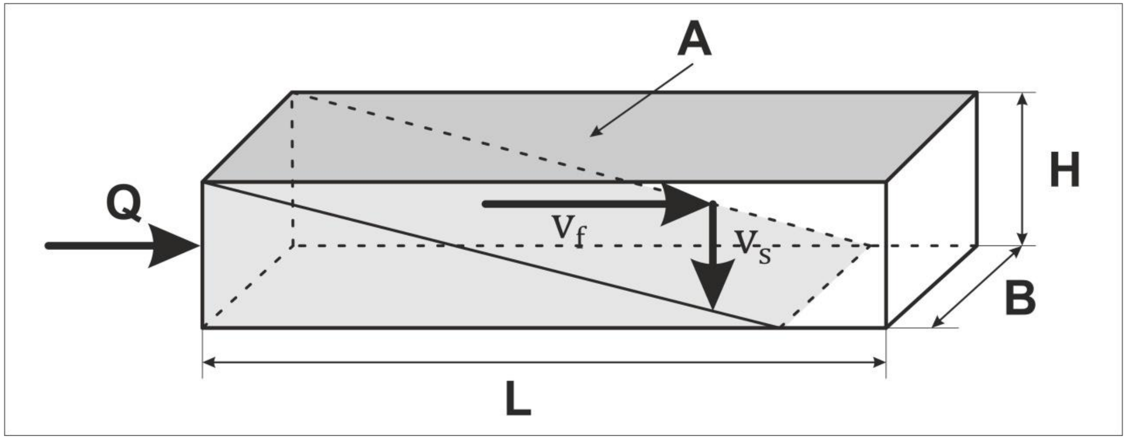
Oxygen demand for the oxidation of 1 mole of toluene = 9 moles of oxygen

= 9 * 16 * 2 = 288 g O_2

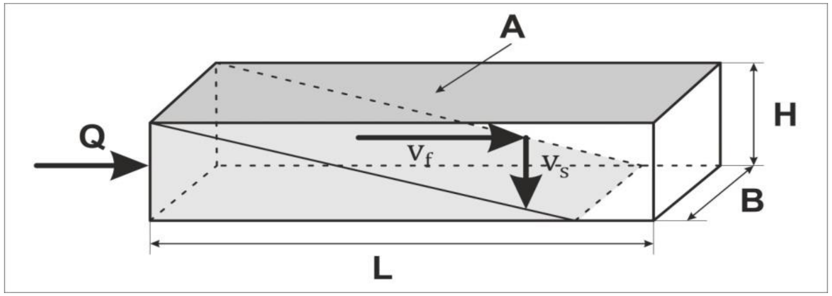
$$\frac{288\ g\ O_2}{92\ g\ toluene} = 3.1 \text{ g COD per g toluene}$$

Design of primary sedimentation tank

A primary sedimentation tank is planned as a rectangular one, a width B of 10.0 m, depth H of 5 m and a length L of 20.0 m. Maximum dry weather influent of the WWTP is 5000 m³/h. In case of stormy weather the combined sewer releases up to three times of the dry weather flow into the WWTP. Is the sedimentation tank big enough to properly treat these volumetric flow rates when the sedimentation velocity v_s is 1 cm/s?



Design of primary sedimentation tank



$$\frac{\boldsymbol{Q}}{\boldsymbol{L * B}} \leq \boldsymbol{v_s}$$

$$v_s = 1\,\frac{cm}{s} = \frac{1\ m}{100\ cm} * \frac{3600\ s}{1\ h} = 36\ m/h$$

Dry weather:

$$\frac{5000\ m^3/h}{20 * 10\ m^2} = 25\,\frac{m}{h} < v_s$$

Stormy weather:

$$\frac{15000\ m^3/h}{20 * 10\ m^2} = 75\,\frac{m}{h} > v_s$$

How long is the hydraulic residence time in the above example?

Design rate of elimination

For a new WWTP the water authority allowed discharge of 100 mg COD/l, 2 mg NH_4-N/l and 1 mg P/l. The average influent concentrations are expected to be 750 mg COD/l, 50 mg NH_4-N/l and 10 mg P/l. Buffers for security should be taken into account for properly operating the WWTP. These buffers are 30% for COD, 50% for NH_4-N and 25% for P. Which rates of elimination of COD, NH_4-N and P the design of the treatment steps should be based on?

$$\eta = \frac{C_{influent} - C_{effluent}}{C_{influent}} \qquad C_{design} = C_{effluent} * (1 - buffer\ for\ security)$$

$$\boldsymbol{\eta_{design}} = \frac{\boldsymbol{C_{influent} - C_{design}}}{\boldsymbol{C_{influent}}} = \frac{\boldsymbol{C_{influent} - C_{effluent} * (1 - buffer\ for\ security)}}{\boldsymbol{C_{influent}}}$$

$$\eta_{design,COD} = \frac{750 - 100 * (1 - 0.3)}{750} \approx 90.7\%$$

Flow balance of biological step of WWTP

The following is known of the biological treatment step of a WWTP:

Q_{In} (Influent flow) = 1000 m^3/h
Q_{WAS} (Waste activated sludge) = 480 m^3/d
RR (RAS Recycle ratio) = 1
DR (Internal recirculation ratio for denitrification) = 3

How much are

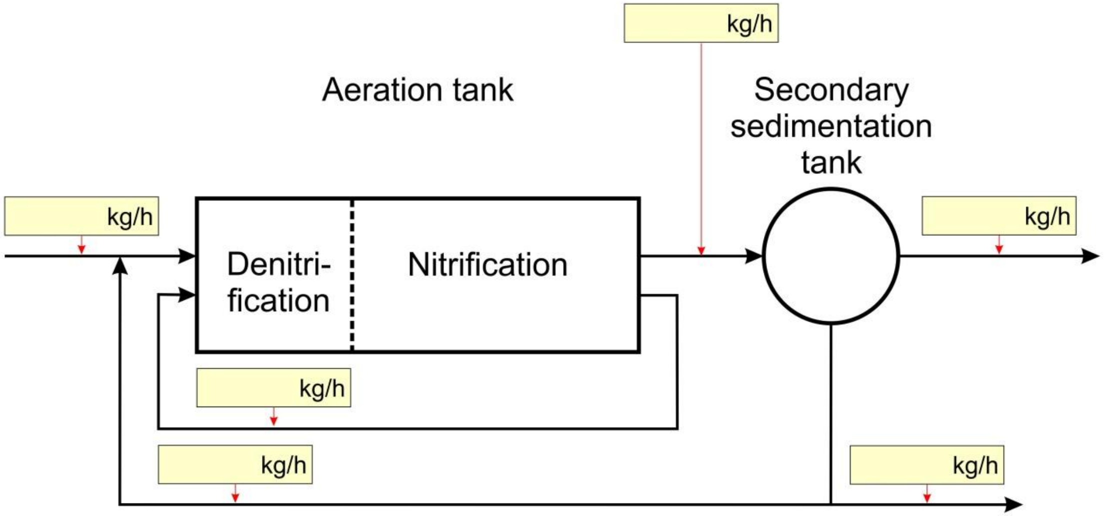
RAS (flow Recycle Activated Sludge),
Q_{IRD} (flow of recirculation for denitrification),
$Q_{Effl.aer.tank}$ (Effluent flow of aeration tank),
Q_{EOP} (Effluent flow End-of-the-pipe of WWTP)?

Solids balance of biological step of WWTP

In addition, there is known about the biological treatment of the sewage treatment plant from task before:

$MLSS$ (Mixed liquor suspended solids)	= 4000 mg/l
$\mathrm{TS}_{\mathrm{RAS}}$ (Total Solids of recycle activated sludge)	= 7000 mg/l
$X_{TS,In}$ (Influent suspended solids)	= 200 mg/l
$X_{TS,Out}$ (Effluent suspended solids)	= 10 mg/l

Complete the mass balance sheet of solids seen below!



Solids balance of biological step of WWTP