11 Wastewater Treatment

11.1 Boundary conditions

Wastewater treatment in Germany

In 2000 more than 10‘000 communal WWTPs

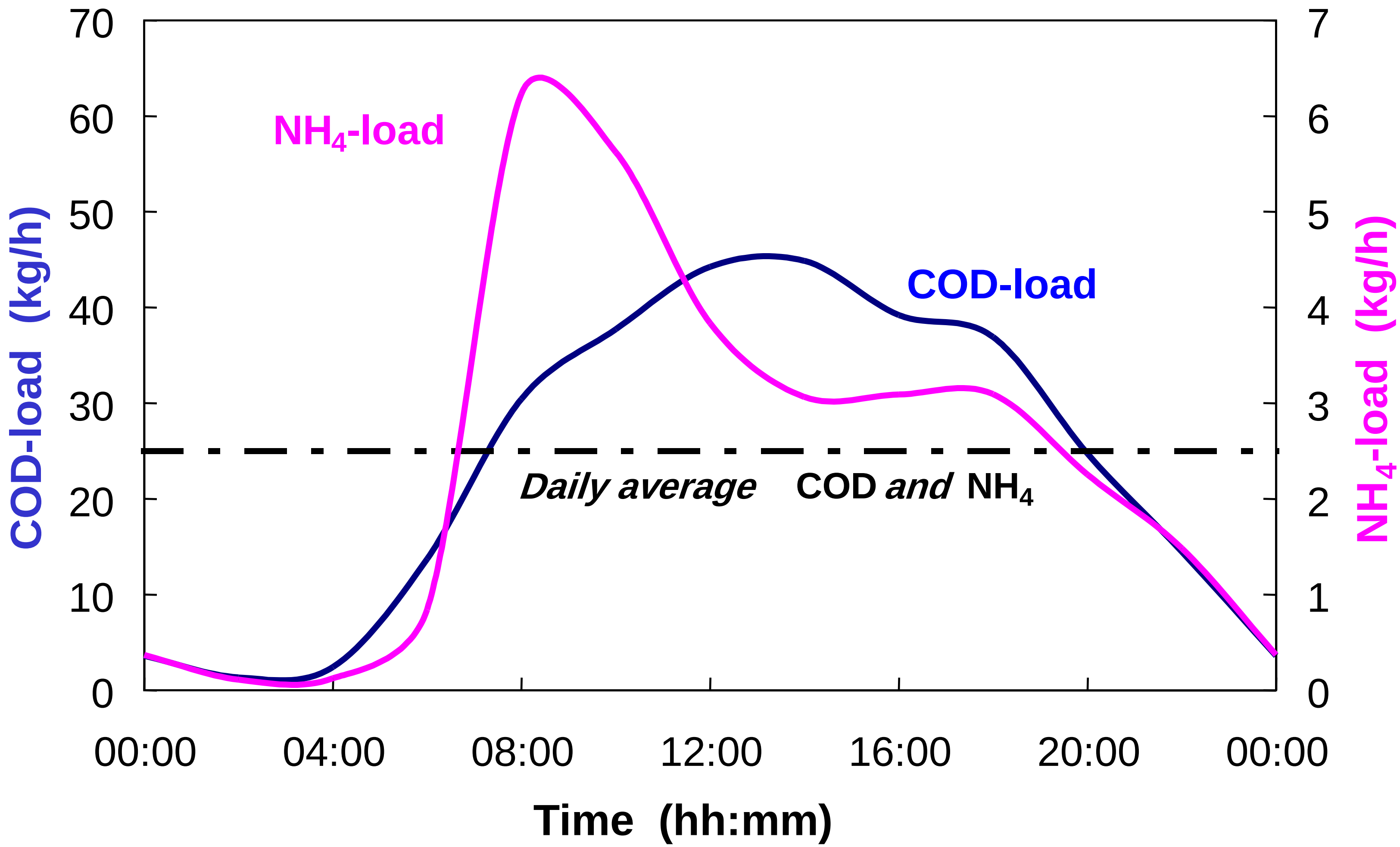
Class	Number	Total capacity in mio PE
> 100’000	272	83.1
10’000 – 100’000	1’817	56.1
2’000 – 10’000	2’617	12.3
50 – 2’000	5’677	3.2

Effluent standards

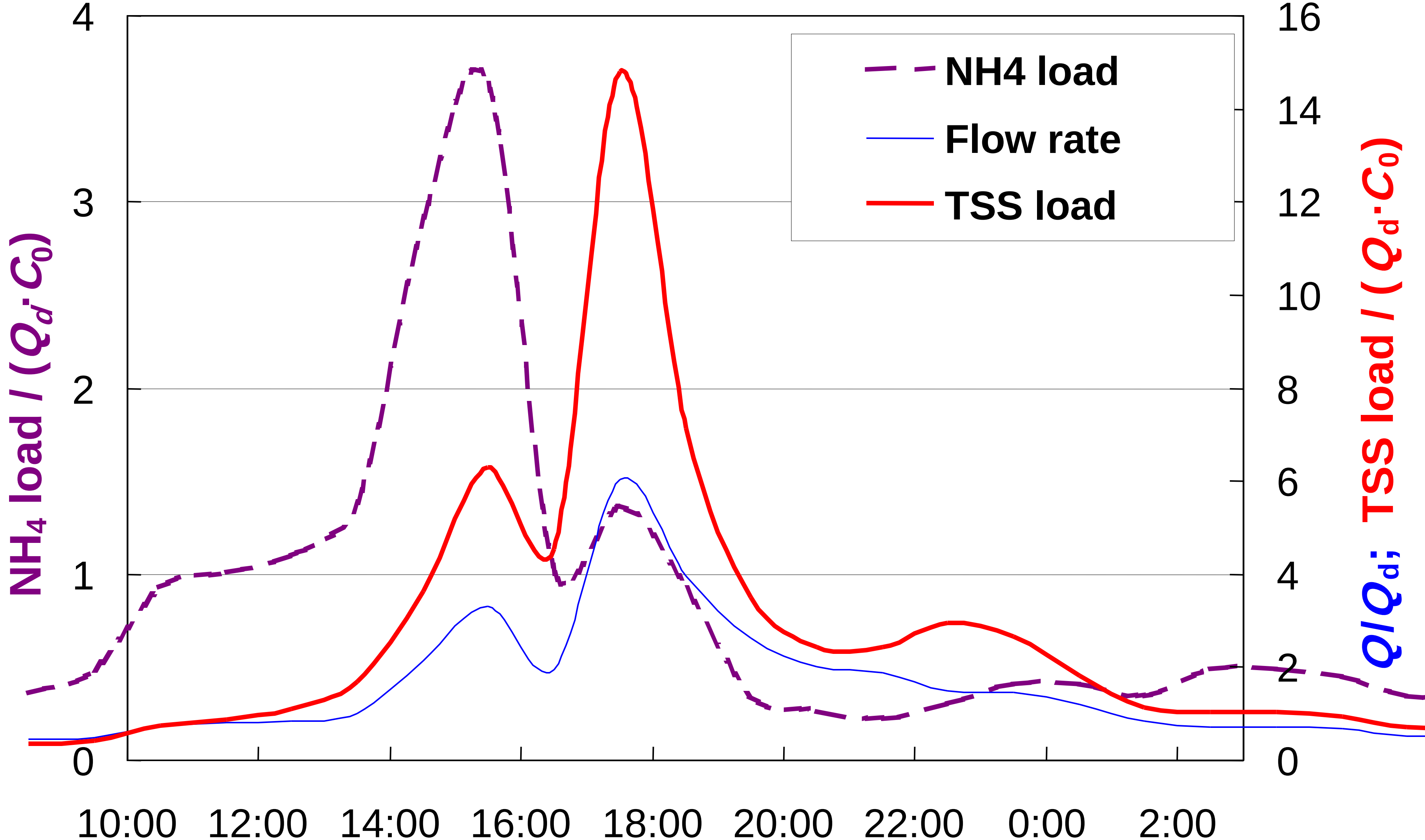
Class		COD (mg/l)	BOD_5 (mg/l)	NH_4-N (mg/l)	N* (mg/l)	P_{tot} (mg/l)
1	< 1000 PE 60 kg BOD_5 / d	150	40	-	-	-
2	< 5000 PE 300 kg BOD_5 / d	110	25	-	-	-
3	< 10000 PE 600 kg BOD_5 / d	90	20	10	-	-
4	< 100000 PE 6000 kg BOD_5 / d	90	20	10	18	2
5	> 100000 PE 6000 kg BOD_5 / d	75	15	10	13	1

* N = Sum of NH_4^+, NO_3^-, und NO_2^-

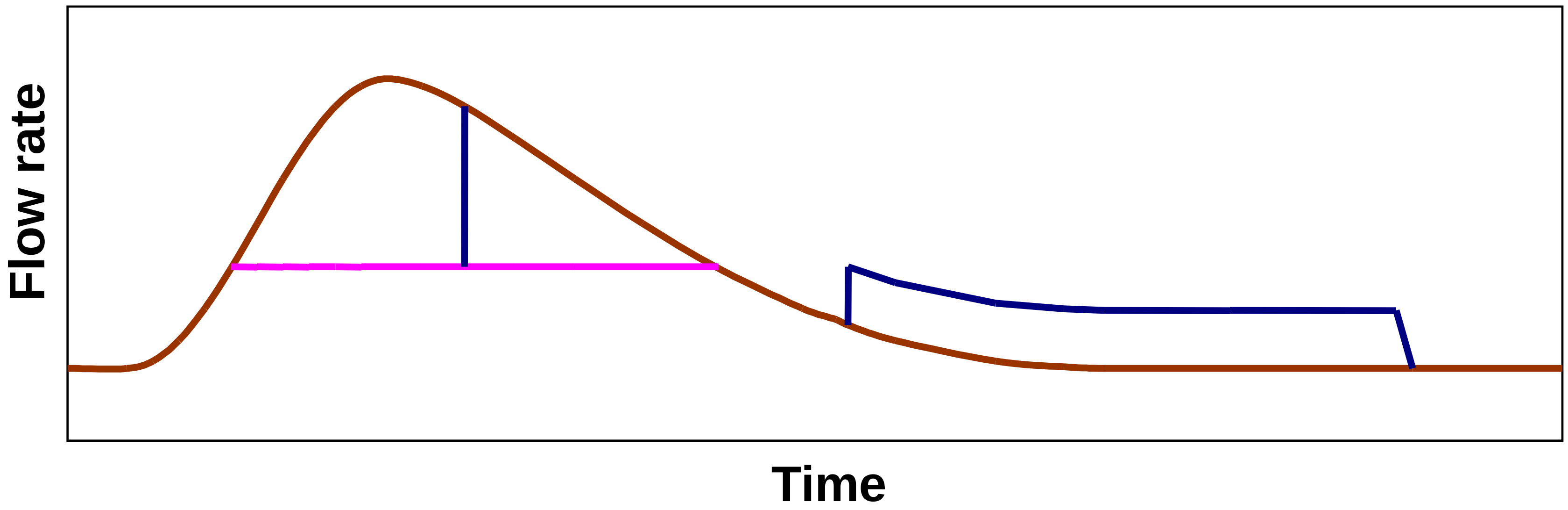
Load variation in WWTP inlet

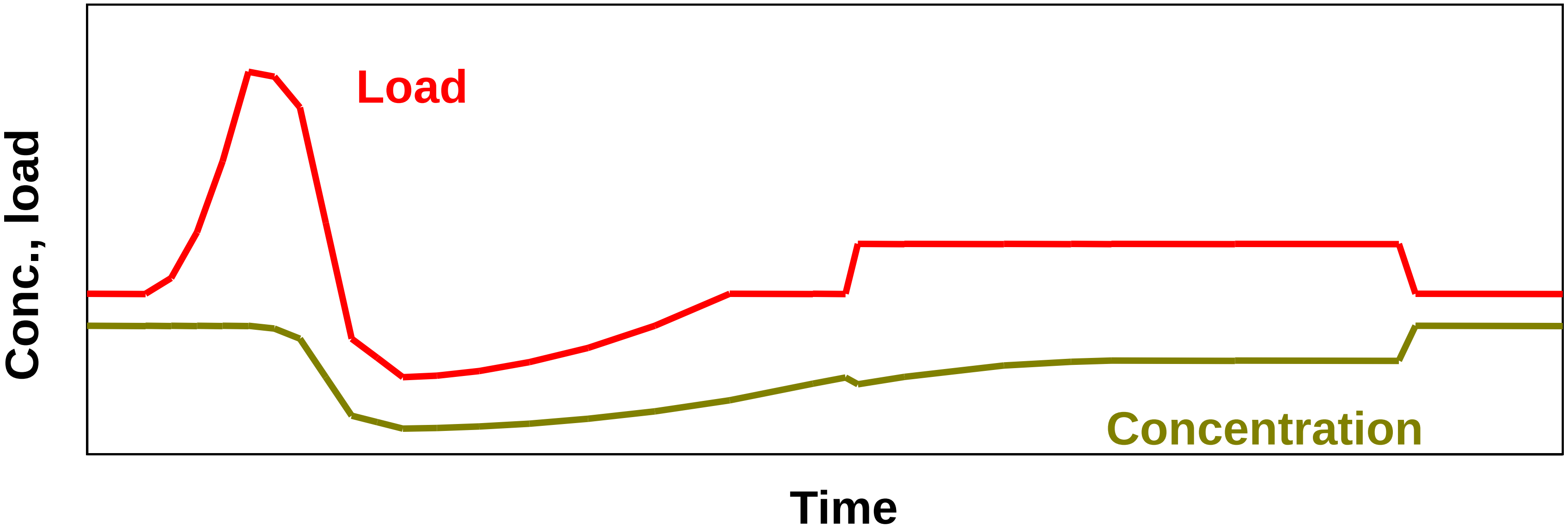


Wet-weather load of NH_4 and TSS from sewer



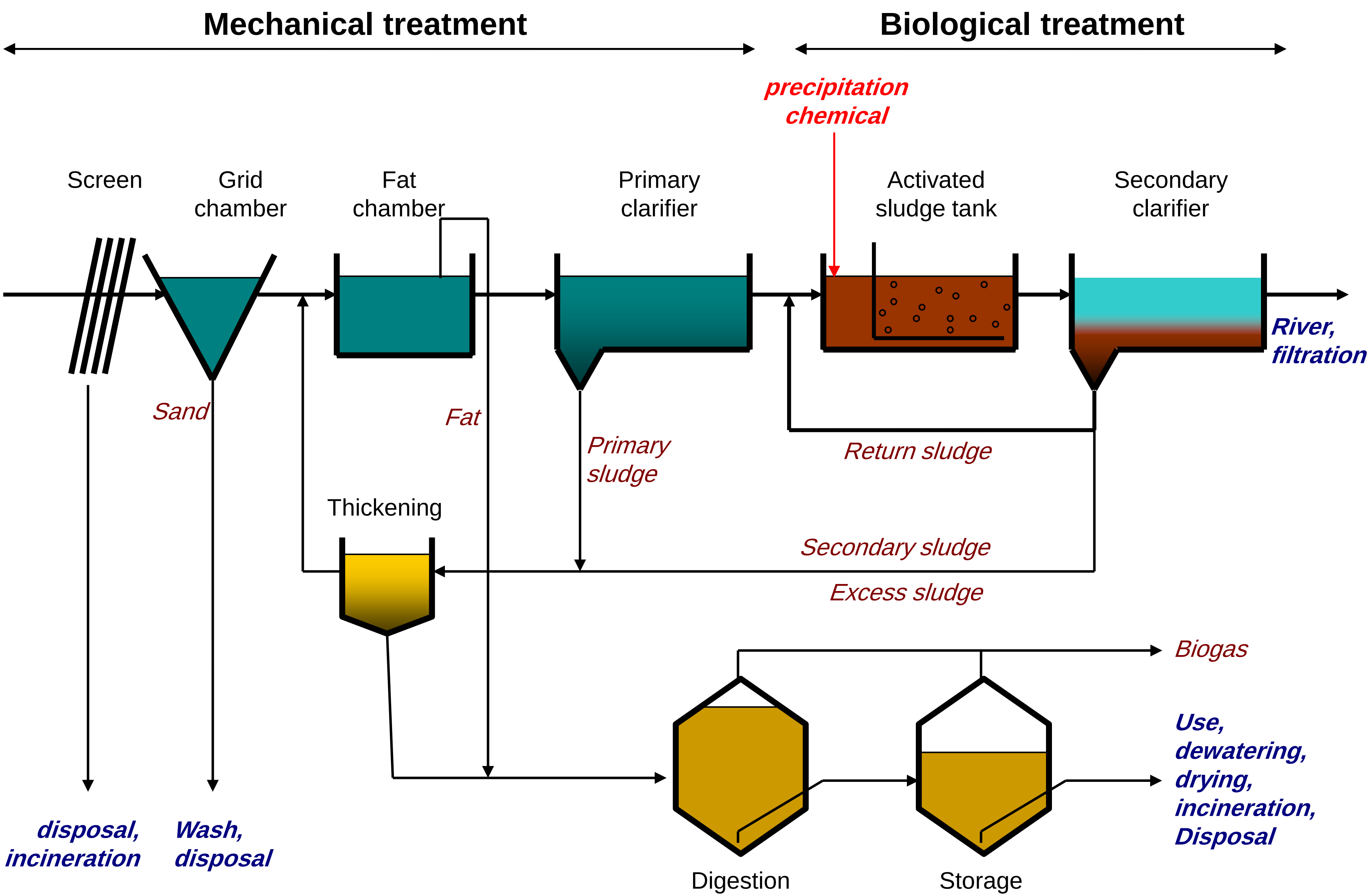
WWTP load with NH_4^+ at storm event



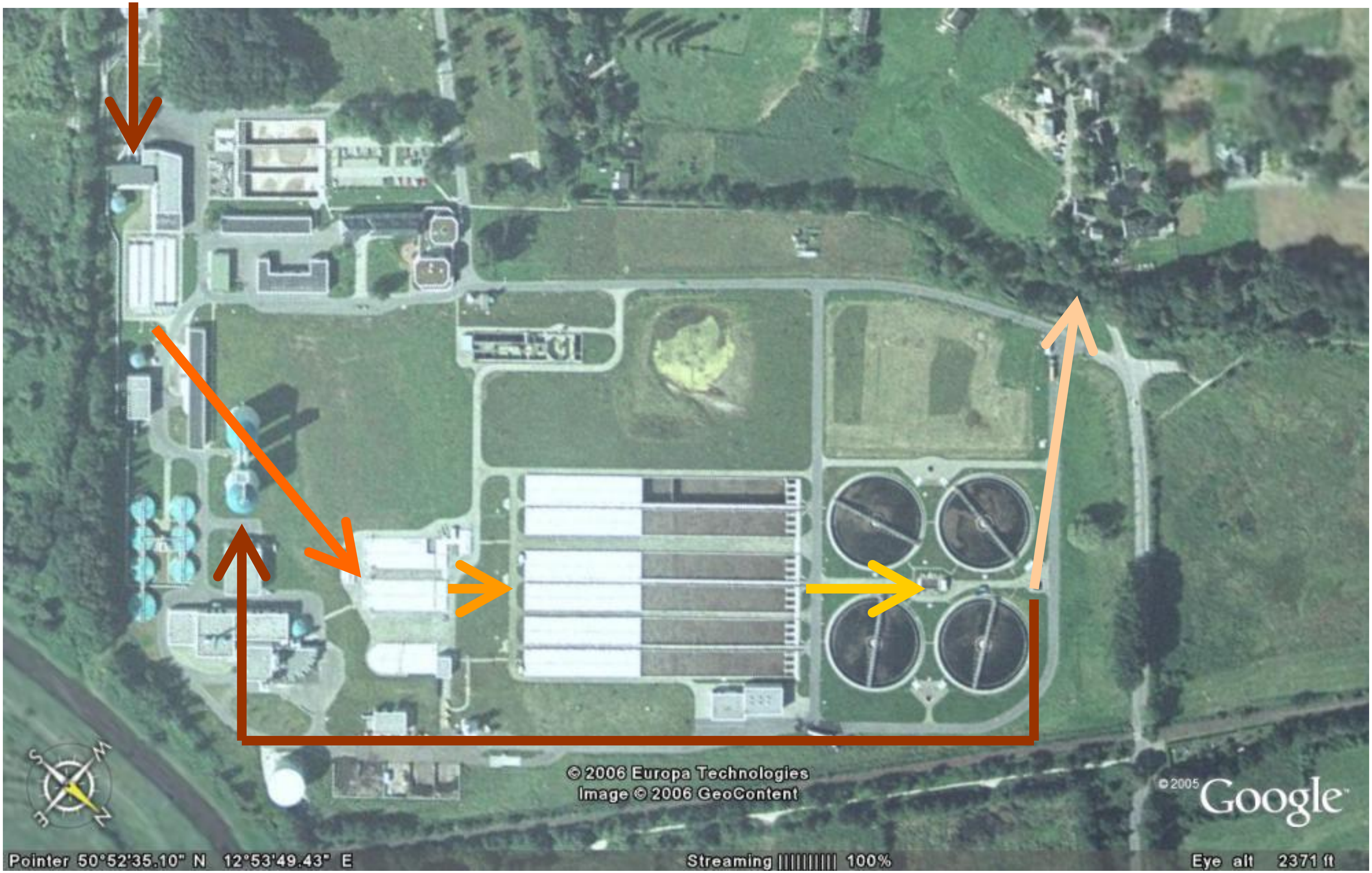


11.2 Layout of a wastewater treatment plant (WWTP)

Layout of a WWTP



Example: WWTP Chemnitz-Heinersdorf

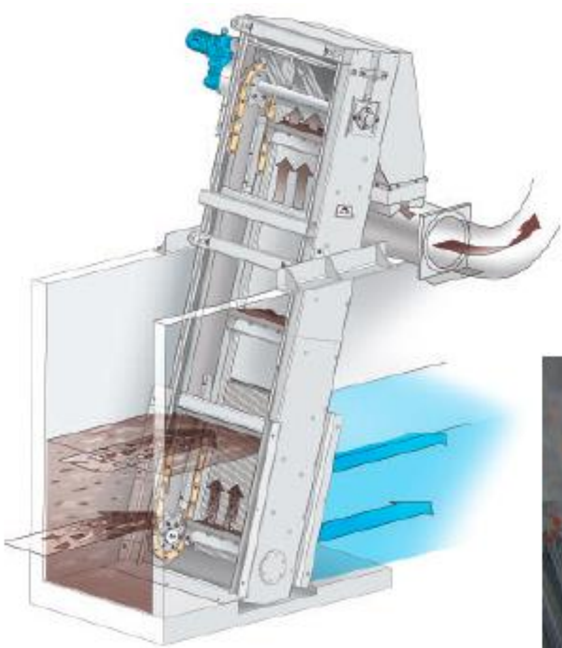


Typical residence time in reactors

	Wastewater HRT (h)	Sludge SRT (d)
Mechanical pre-treatment	0.2	0.01
Primary clarifier	1.5	1
Activated sludge tank	10	10
Secondary clarifier	5	2
Sludge thickener		2
Digester		20
Storage		100
	< 1 d	**> 100 d**

11.3 Mechanical treatment

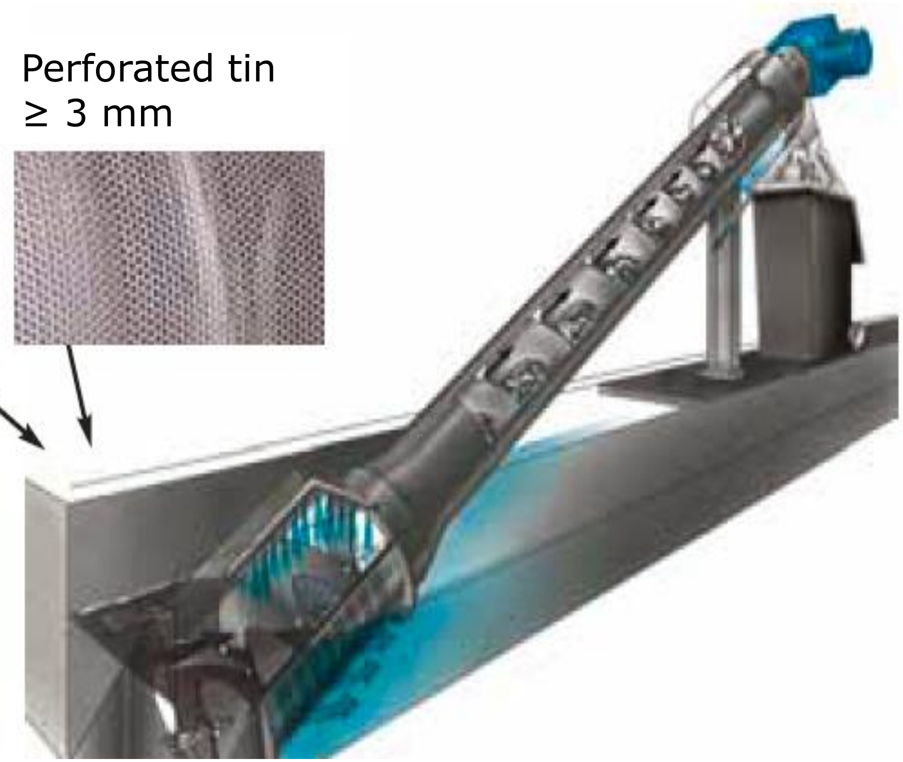
Automatically cleaned trash rack



Sieve

Slotted sieve
≥ 0.5 mm

Perforated tin
≥ 3 mm



Hans Huber AG, Typ Ro9

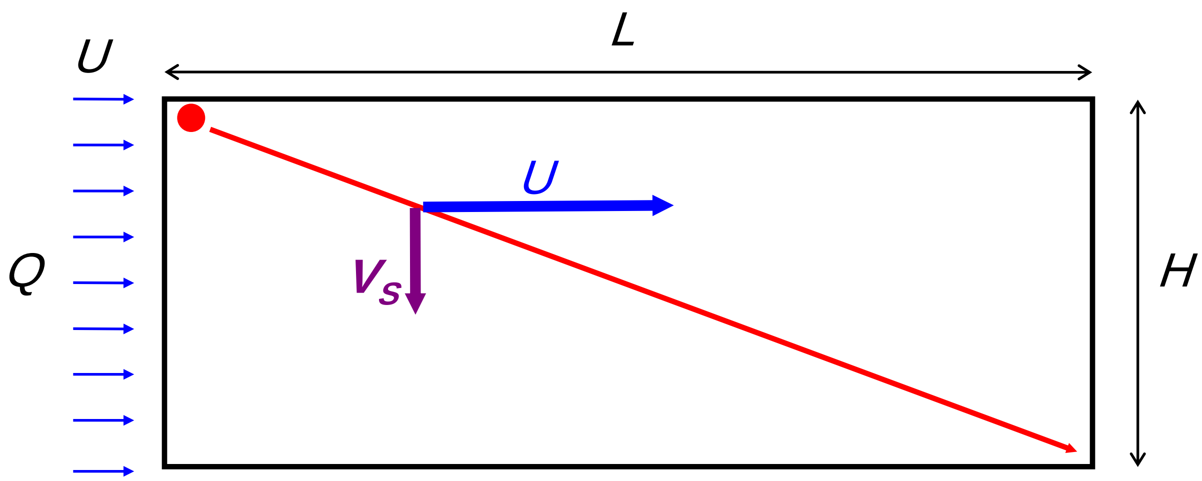
Basics for rack design

- Flow velocity: $0{,}6 \le v \le 2{,}5$ m/s
- Widen flume to compensate for racks cross section
- Consider backwater effect
  - Hydraulics: $$\Delta h = \beta \cdot \left(\frac{d}{e}\right)^{4/3} \cdot \frac{v^2}{2g} \cdot \sin\alpha$$
  - + due to clogging

  ➔ lower bottom to compensate for backwater effect

- Safety for maintenance (redundant)
- Building around racks (Frost, smell)

Surface load: $q_A = Q / A$ (Hazen, 1904)



Critical case $$U = \frac{L}{HRT} \qquad V_S = \frac{H}{HRT}$$

Settling condition $$\frac{L}{U} \geq \frac{H}{V_S}$$

$$V_S \geq \frac{UBH}{LB} = \frac{Q}{A_{SC}} \qquad \rightarrow \; V_S \geq q_A$$

→ Independent of H !

Grid chamber

- In connection with combined systems
- Effects of non-organic particles:
  - Abrasion of steel (e.g. pumps)
  - Clogging (Sludge hopper, pipes, Pumps)
  - Sedimentation (activated sludge tank, digester)
    - → High maintenance requirements

Sludge in sand is hindering

Sand in sludge is detrimental for operation !

Empirical sedimentation velocities

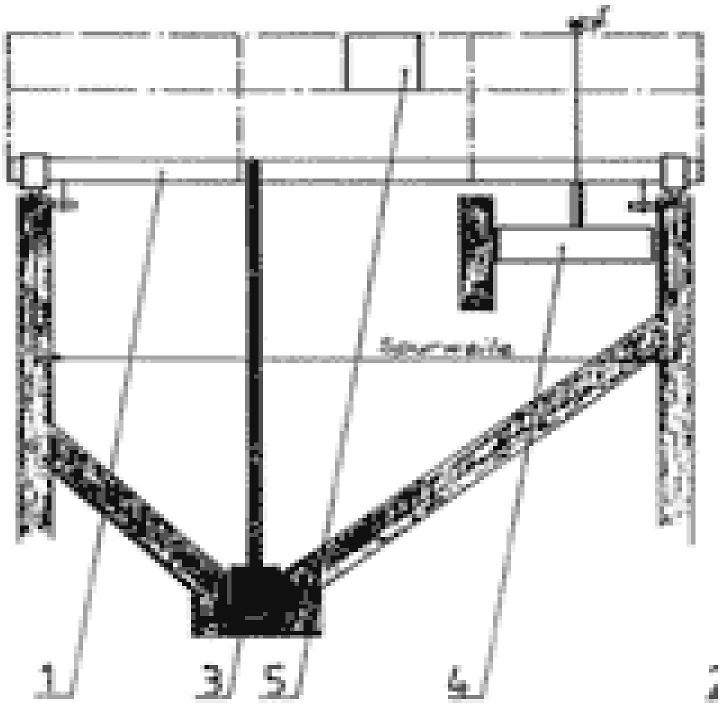
Kalbskopf, 1966

Particle diameter	Sedimentation velocity		
[mm]	η= 100% [cm/s]	η= 90% [cm/s]	η= 85% [cm/s]
0,125	0,17	0,26	0,31
0,160	0,29	0,44	0,56
0,200	0,46	0,78	0,99
0,250	0,74	1,25	1,60
0,315	1,23	2,00	2,35

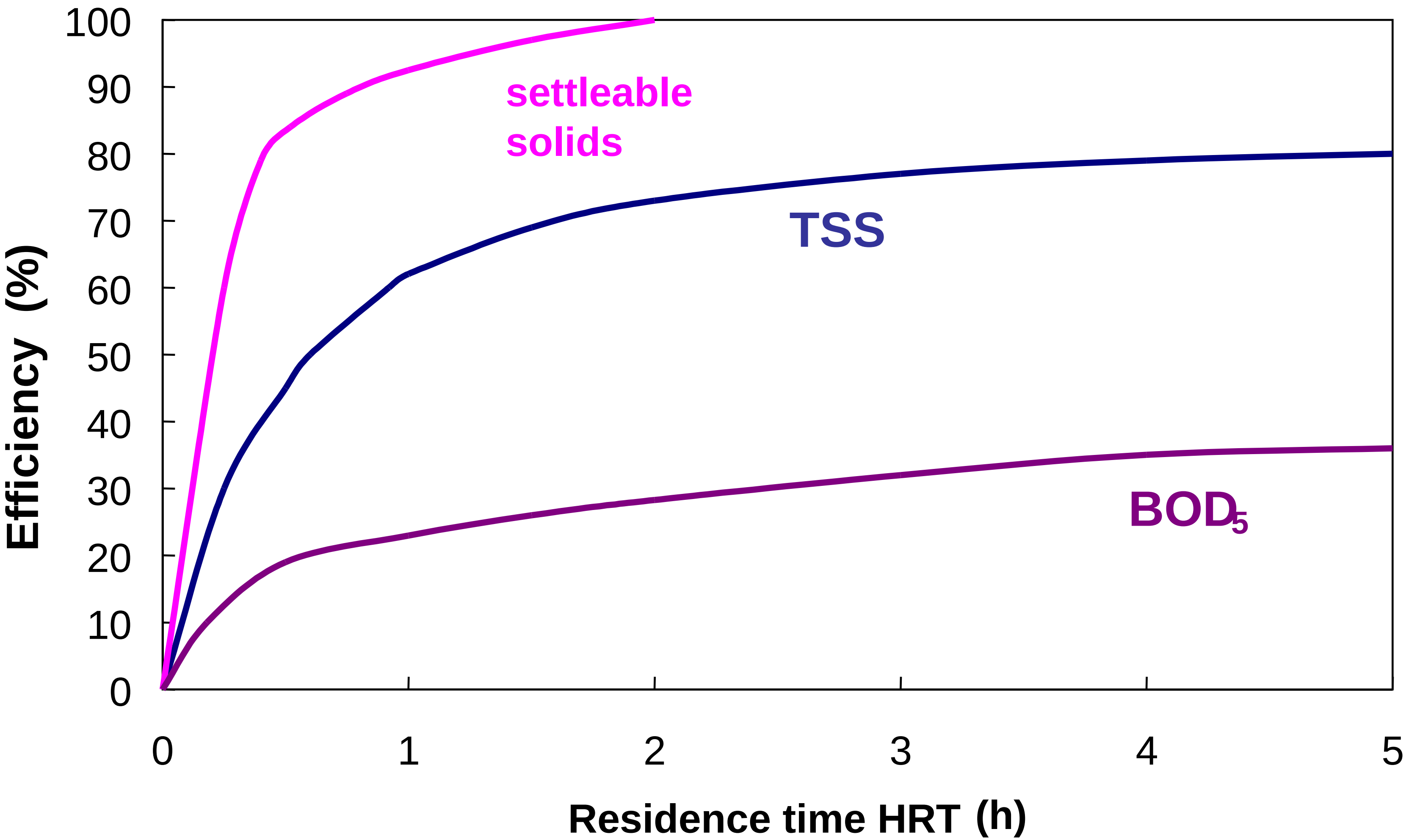
Design rules

- Flow velocity: ≈ 0,3 m/s
- Width extending with height $b \approx \frac{5 \cdot Q}{h}$
- Length: $l = h \cdot \frac{u}{v_s}$
- Sand collector: appr. 0,2 x 0,3 m (not too large!)
- Venturi flow measurement after grid chamber

Aerated grid chamber



Efficiency of primary clarifier

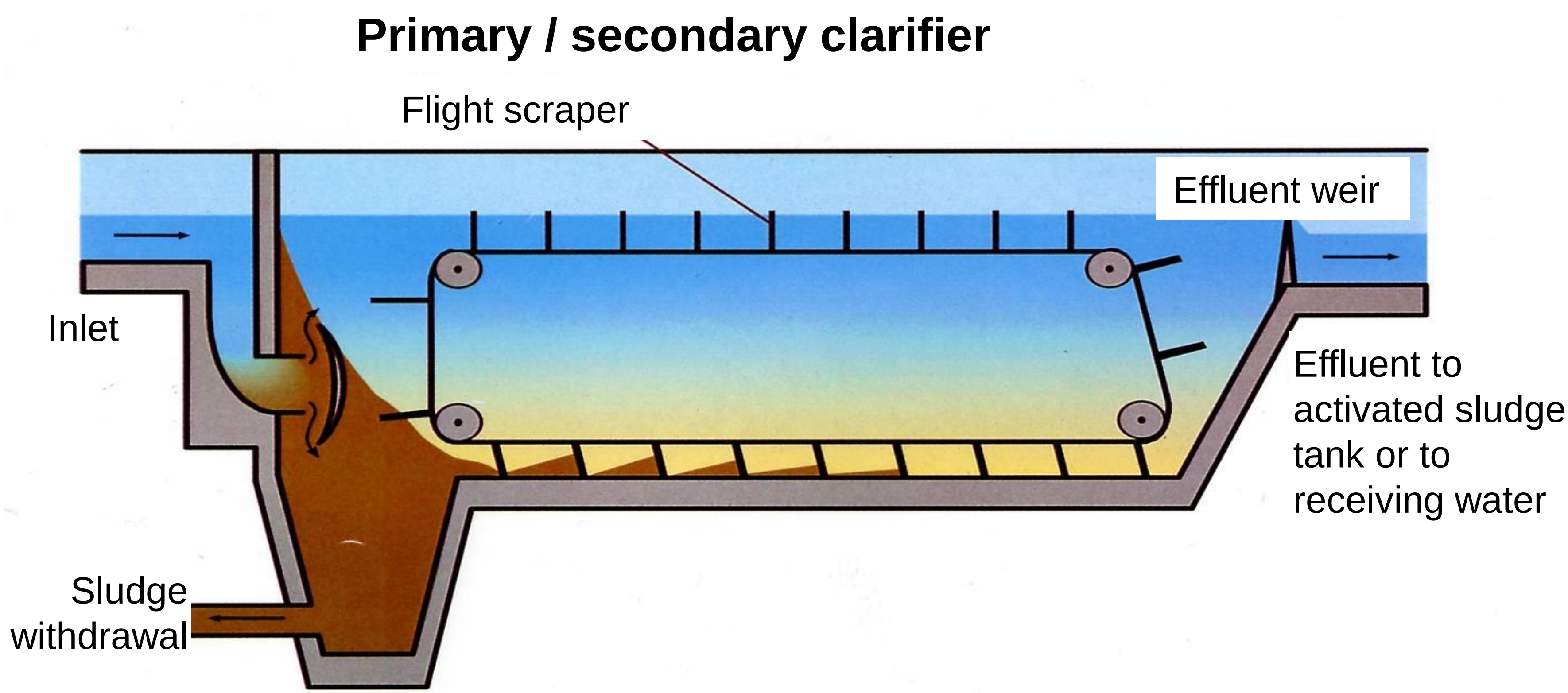


Effects of primary clarifier on wastewater

Compound	Unit	Inlet	Outlet*	$\eta = \frac{C_{in} - C_{out}}{C_{in}}$
TSS	g TSS / m^3	360	180	0.5
BOD_5	g O_2 / m^3	300	230	0.23
COD	g O_2 / m^3	600	450	0.25
TKN	g N / m^3	60	56	0.067
NH_4-N	g N / m^3	40	40	0
NO_2-N	g N / m^3	0	0	0
NO_3-N	g N / m^3	1	1	0
P_{tot}	g P / m^3	10	9	0.1
Alkalinity	mol HCO_3^- / m^3	= f(Drinking water) + NH_4-N		

* Short residence time

Rectangular sedimentation tank



Surface:

Primary clarifier	q_A = 2 to 6 m/h
Secondary clarifier	q_A = 0.5 to 1.5 m/h

11.4 Biological treatment

Biological treatment

Suspended biomass → **Activated sludge system**

- suspended through turbulence
- sludge flocs with 0.1 – 1 mm diameter
- degradation related to biomass

→ Increase suspended biomass concentration

Sessile biomass → **Biofilm system**

- biofilm on carrier
- little erosion
- degradation related to biofilm surface area

→ Increase of specific surface area

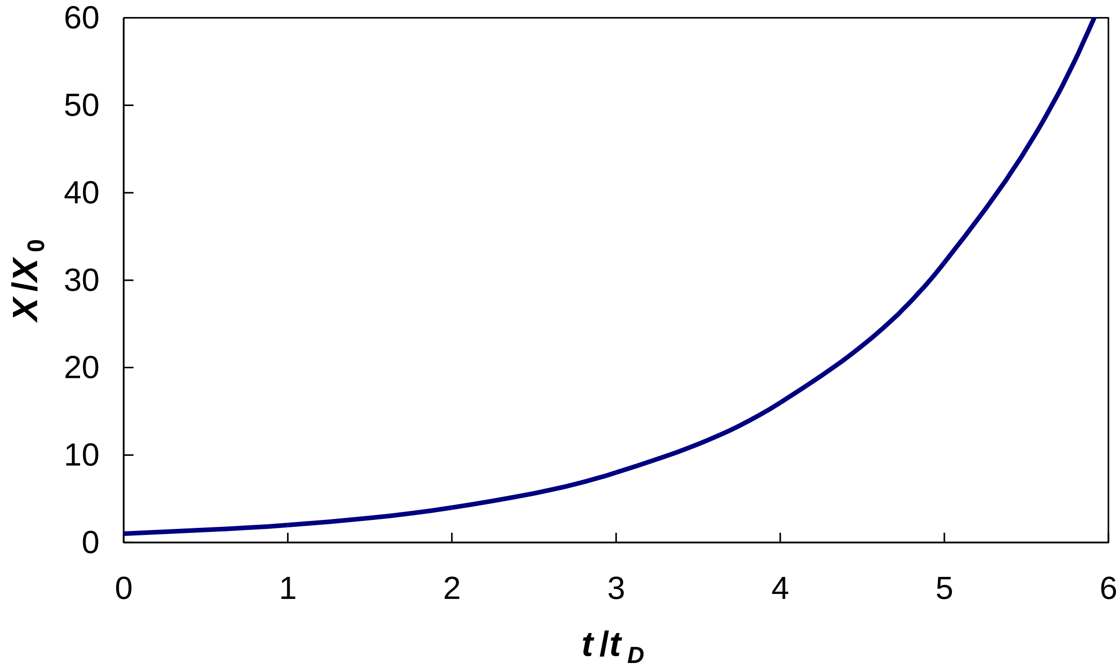
Important micro-biological processes

Growth	Implementation of C, N, P in biomass
Decay	If external nutrients are rare
Hydrolysis	Heavily → easily degradable substances, through encymes
Aerobic degradation	organic compounds $CH_2O + O_2 \rightarrow CO_2 + H_2O$
Nitrification	$NH_4^+ + 2\ O_2 \rightarrow NO_3^- + H_2O + 2\ H^+$
Denitrification	$5\ CH_2O + 4\ NO_3^- + 4\ H^+ \rightarrow 2\ N_2 + 5\ CO_2 + 7\ H_2O$

Growth of bacteria

Doubling time t_D

$0 \cdot t_D$	$1 \cdot t_D$	$2 \cdot t_D$	$3 \cdot t_D$	$i \cdot t_D$	...	$n \cdot t_D$
2^0	2^1	2^2	2^3	2^i	...	2^n



Activated sludge:

$t_D = 6$ h

Sludge age = 10 d

Growth of bacteria

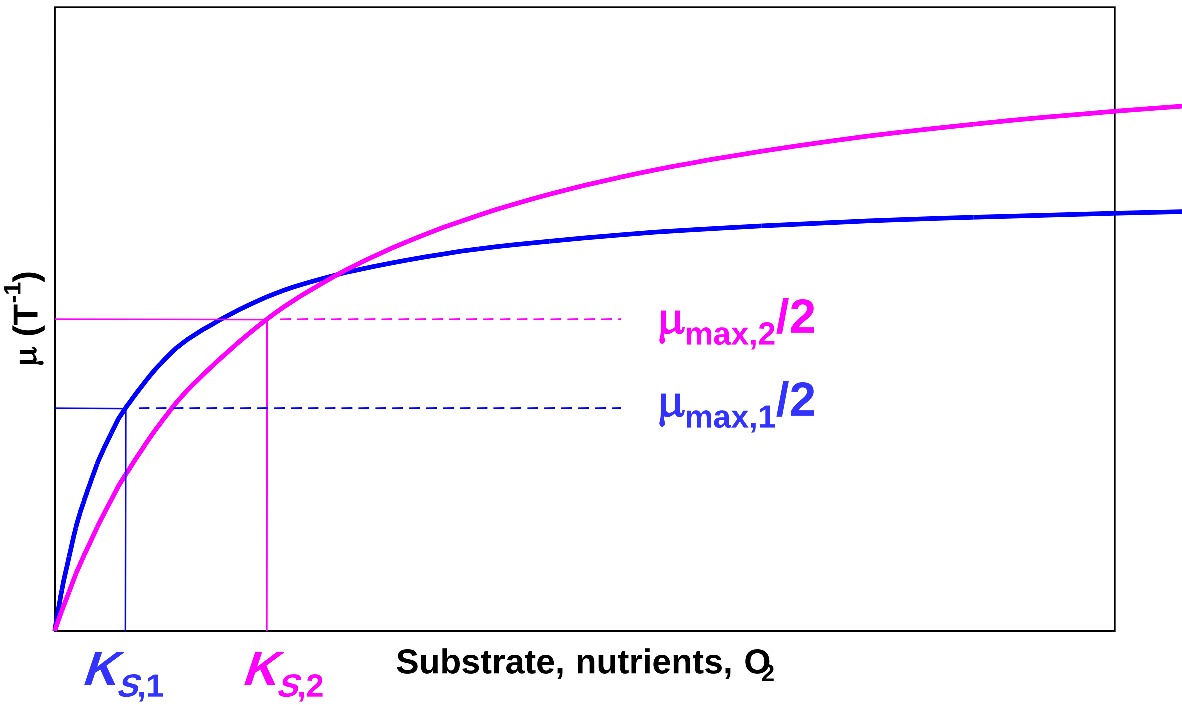
→ Growth is limited through nutrients and oxygen

Growth

$$r = \frac{d\,X_B}{d\,t} = \mu \cdot X_B$$

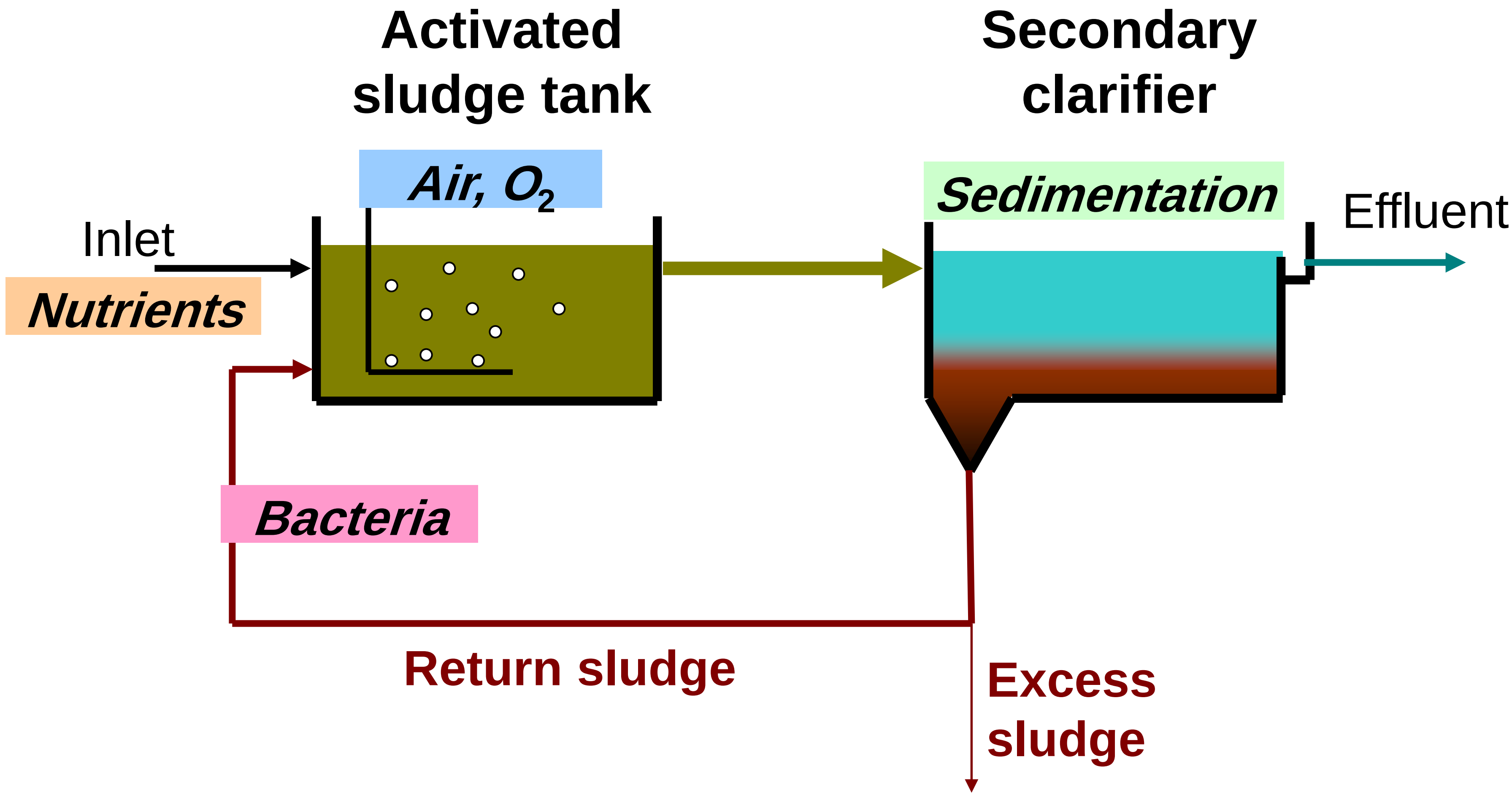
Specific growth rate

$$\mu = \mu_{\mathbf{max}} \cdot \frac{S}{S + K_S}$$

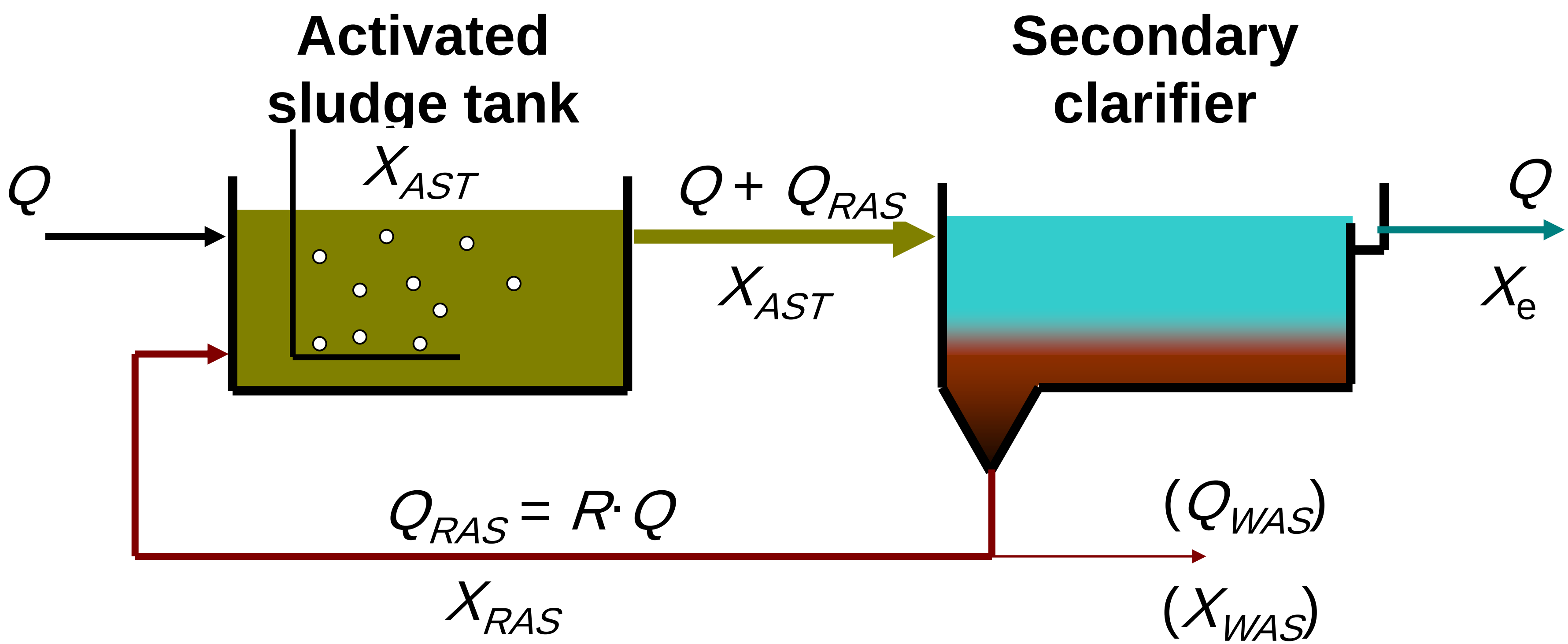


X_B = Biomass concentration
μ_{max} = Maximum specific growth rate
S = Substrate concentration
K_S = Half saturation constant

Activated sludge system



Sludge inventory in activated sludge system



Sludge balance in equilibrium

$$X_{RAS} = X_{AST} \frac{1+R}{R} \qquad \text{mit} \qquad R = \frac{Q_{RAS}}{Q}$$

Flow scheme of activated sludge system

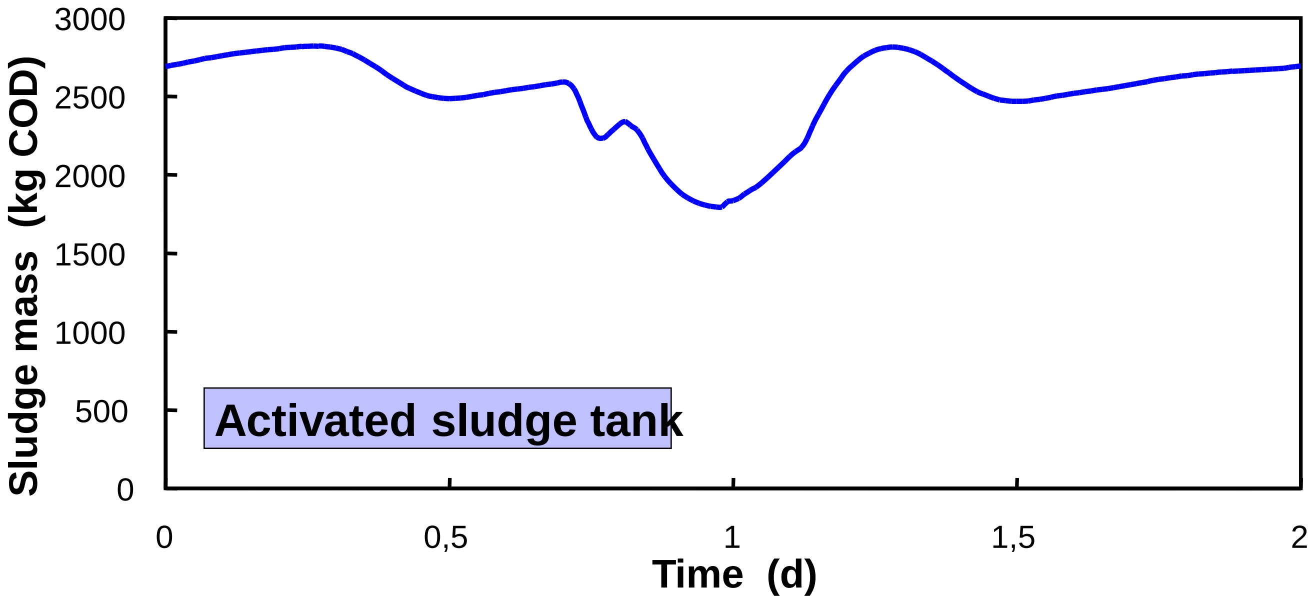
Hydraulic wash-out of sludge to secondary clarifier
→ sludge must be returned to activated sludge tank

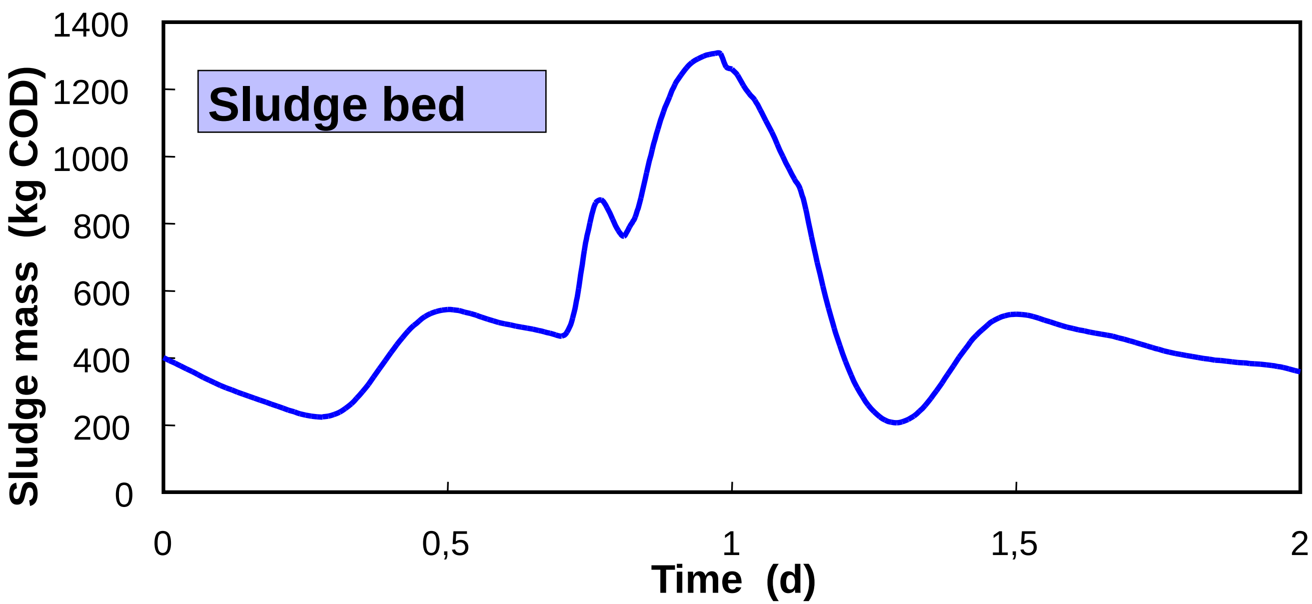
Activated sludge is circled 20 to 50 times
→ sludge concentration in activated sludge tank is maintained

Excess sludge is withdrawn from system
→ equivalent to sludge production

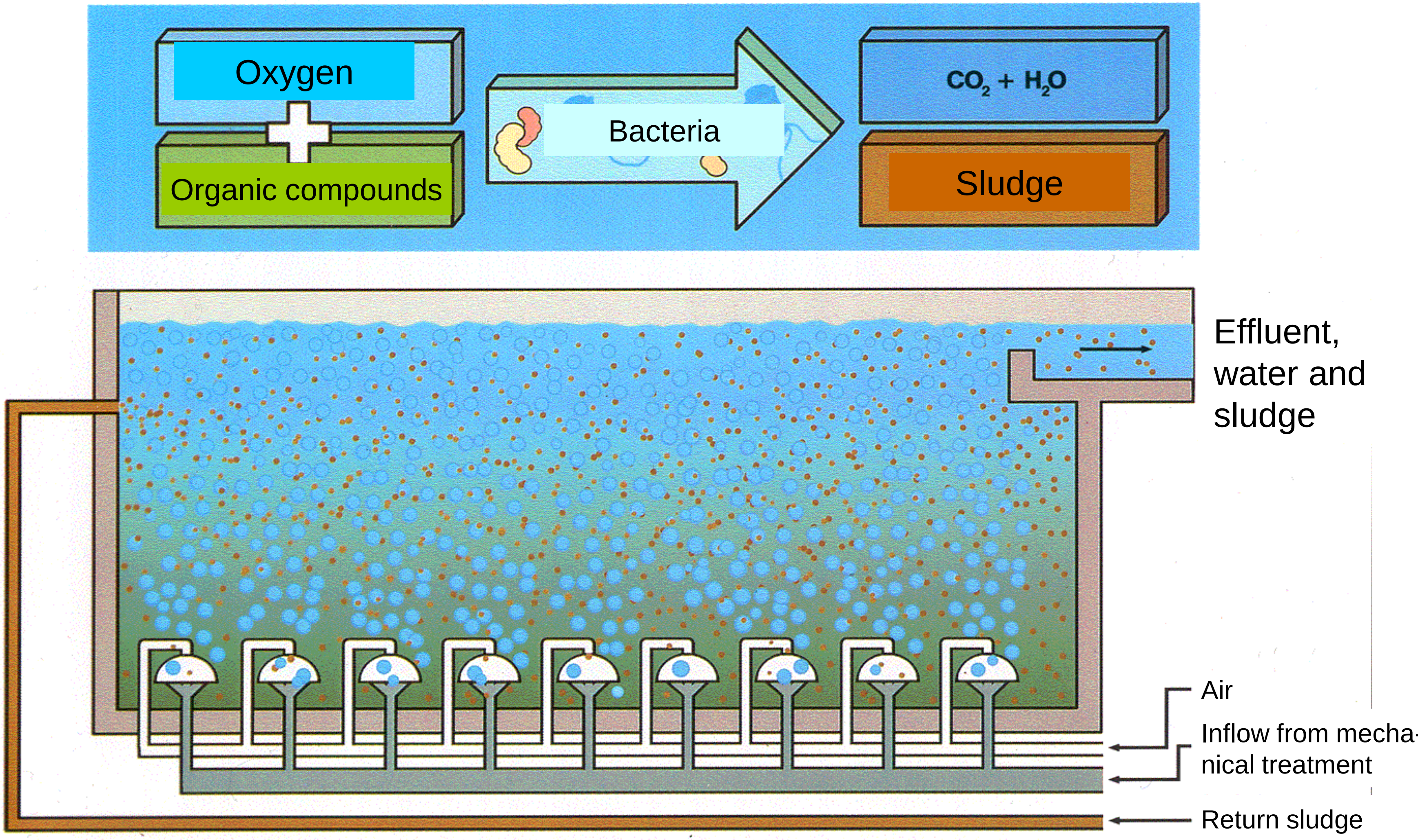
Through increased hydraulic loading (wet-weather condition) sludge is shifted to secondary clarifier

Dynamic sludge shift





Aeration in an actvated sludge tank



Dimension:

communal wastewater treatment 2 m^3 wastewater per m^3 reactor volume and day

Dimensioning on sludge loading

Sludge loading

$$F/M = \frac{Q \cdot BOD_{5,in}}{V_{AST} \cdot X_{AST}} \quad \text{in} \left(\frac{\text{kg BOD}_5}{\text{kg TSS} \cdot \text{d}} \right)$$

→ ***BOD_5 inlet load is related to sludge mass in activated sludge tank (AST)***

F/M	BOD_5 loading related to dry sludge mass (Food/Microorganisms)
Q	Inflow to WWTP (m^3/d)
$BOD_{5,in}$	BOD_5 concentration in inlet (kg BOD_5 / m^3)
V_{AST}	Volume of activated sludge tank (m^3)
X_{AST}	Sludge concentration in activated sludge tank (kg TSS / m^3)

Dimensioning on sludge age

Sludge age

$$SRT = \frac{V_{AST} \cdot X_{AST}}{SP} = \frac{V_{AST} \cdot X_{AST}}{ESP_{BOD} \cdot Q \cdot BOD_{5,in}} = \frac{1}{F/M \cdot ESP_{BOD}}$$

→ ***Sludge production is related to sludge mass in activated sludge tank***

SRT Sludge age in (d), 3 – 15 d

ESP_{BOD} Specific excess sludge production per BOD_5 converted (kg TSS / kg BOD_5)

SP Sludge production (kg TSS / d)

$$SP = ESP_{BOD} \cdot Q \cdot BOD_{5,in}$$

Nutrients demand of micro-organisms

Nitrogen i_N = 0.04 – 0.05 (g N / g BOD_5)

Phosphorous i_P = 0.01 – 0.02 (g P / g BOD_5)

→ Partial elimination of nutrients

Wastewater composition in the inlet

300 (g BOD_5/m^3)

60 (g TKN/m^3)

12 (g TP/m^3)

Effluent concentrations after 100% BOD_5 degradation

$$TKN_{eff} = TKN_{in} - i_N \cdot BOD_{5,in} = 60 - 0.045 \cdot 300 = 46.5 \ (g\ N / m^3)$$

$$TP_{eff} = TP_{in} - i_P \cdot BOD_{5,in} = 12 - 0.015 \cdot 300 = 7.5 \ (g\ P / m^3)$$

→ Enhanced nutrients removal is necessary!

Nitrification $NH_4^+ \rightarrow NO_3^-$

Nitrifying organisms („autotrophic biomass“ X_A) have a low growth rate μ_A

With production of autotrophic biomass

$$SP_A = r_A \cdot V_{AST} = \mu_A \cdot X_{A,AST} \cdot V_{AST}$$

and a safety factor SF the necessary sludge age yields

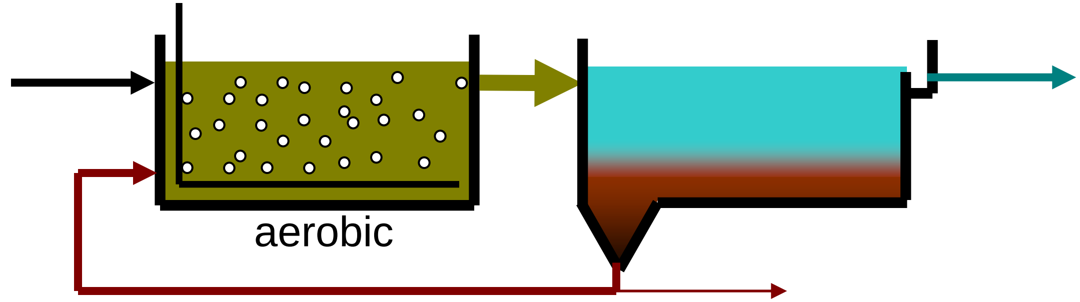
$$SRT = SF \frac{V_{AST} \cdot X_{A,AST}}{SP_A} = SF \frac{V_{AST} \cdot X_{A,AST}}{\mu_A \cdot X_{A,AST} \cdot V_{AST}} = SF \frac{1}{\mu_A}$$

→ **high sludge age necessary to omit nitrifiers from being washed out of the system**

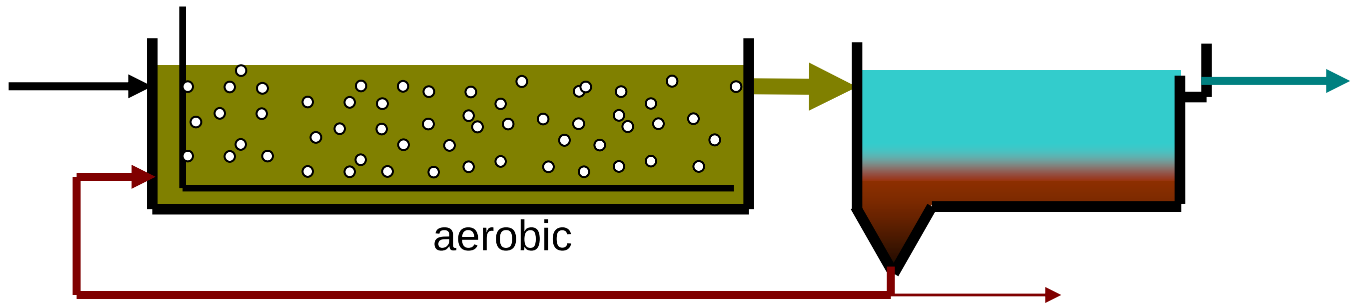
→ **Volume of activated sludge tank must be large**

Development of activated sludge system

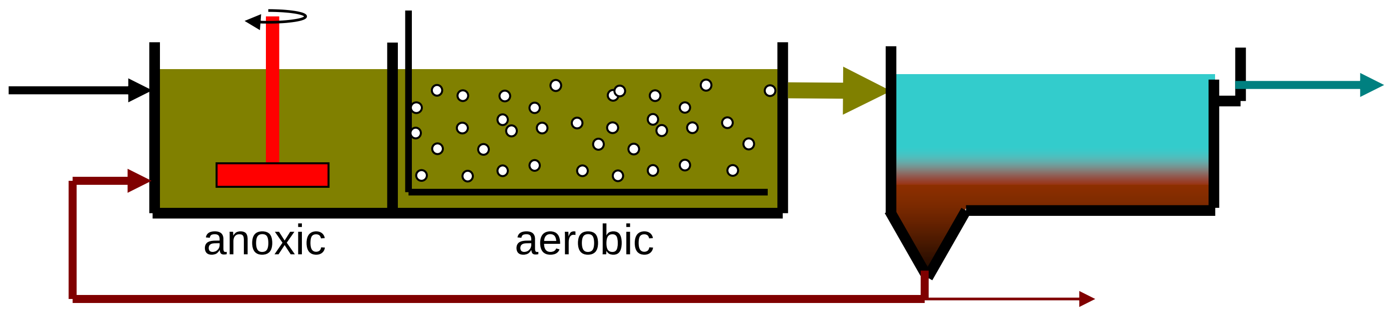
C-Elimination



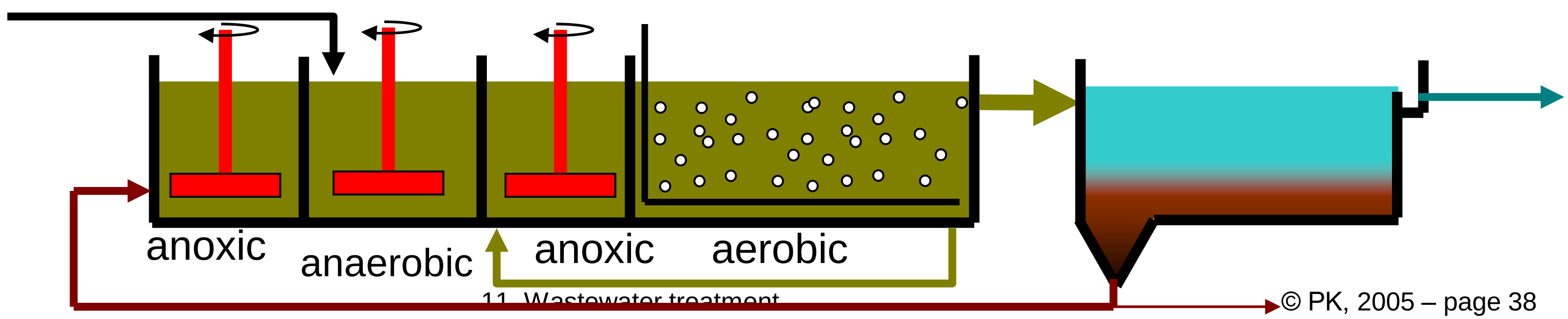
Nitrification



De-nitrification



„Bio-P“



Oxygen consumption

Oxygen introduction

$$\underbrace{\alpha \cdot SOI \cdot \frac{c_s - c}{c_s}}_{\text{Introduction}} = \underbrace{SOC \cdot f}_{\text{Consumption}}$$

SOC	Specific O_2-consumption	(kg O_2 / kg BOD_5)
c_s	O_2 saturation concentration	(g O_2 / m^3)
c	O_2 concentration	(g O_2 / m^3)
f	Peak factor for variations	(-)
SOI	Spec. O_2 introduction rate to clean water	(kg O_2 / ($m^3 \cdot h$))
α	Reduction factor for wastewater	(0.4) 0.6 – 0.8

→ **The smaller the actual oxygen concentration, the more efficient is the oxygen introduction**

Specific oxygen consumption *SOC* (kg O_2 / kg BOD_5)

T	**Sludge age in d**					
(°C)	4	8	10	15	20	25
10	0.85	0.99	1.04	1.13	1.18	1.22
12	0.87	1.02	1.07	1.15	1.21	1.24
15	0.92	1.07	1.12	1.19	1.24	1.27
18	0.96	1.11	1.16	1.23	1.27	1.30
20	0.99	1.14	1.18	1.25	1.29	1.32

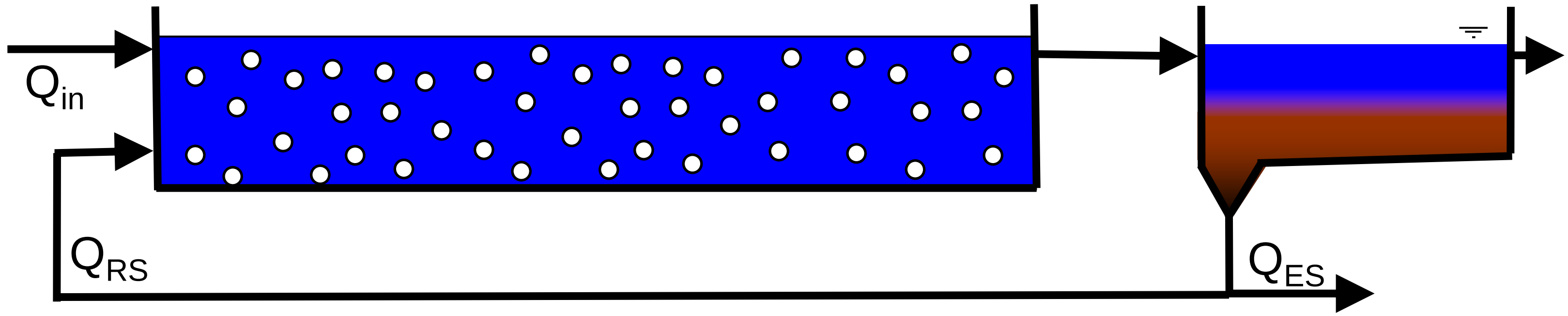
Peak factors for C und N degradation

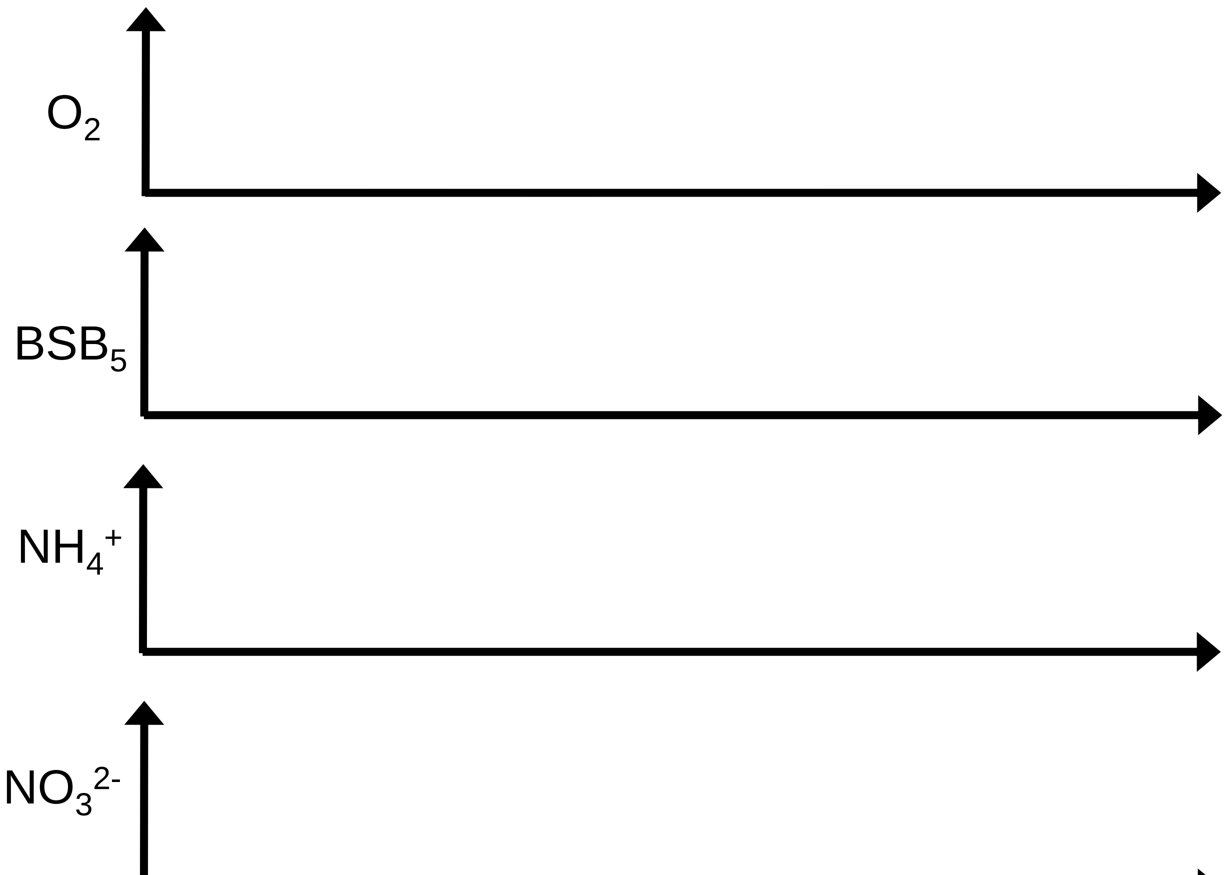
f_C	1.30	1.25	1.20	1.20	1.15	1.10
f_N < 20‘000 PE	-	-	-	2.50	2.00	1.50
> 100‘000 PE	-	-	2.00	1.80	1.50	-

Design rules

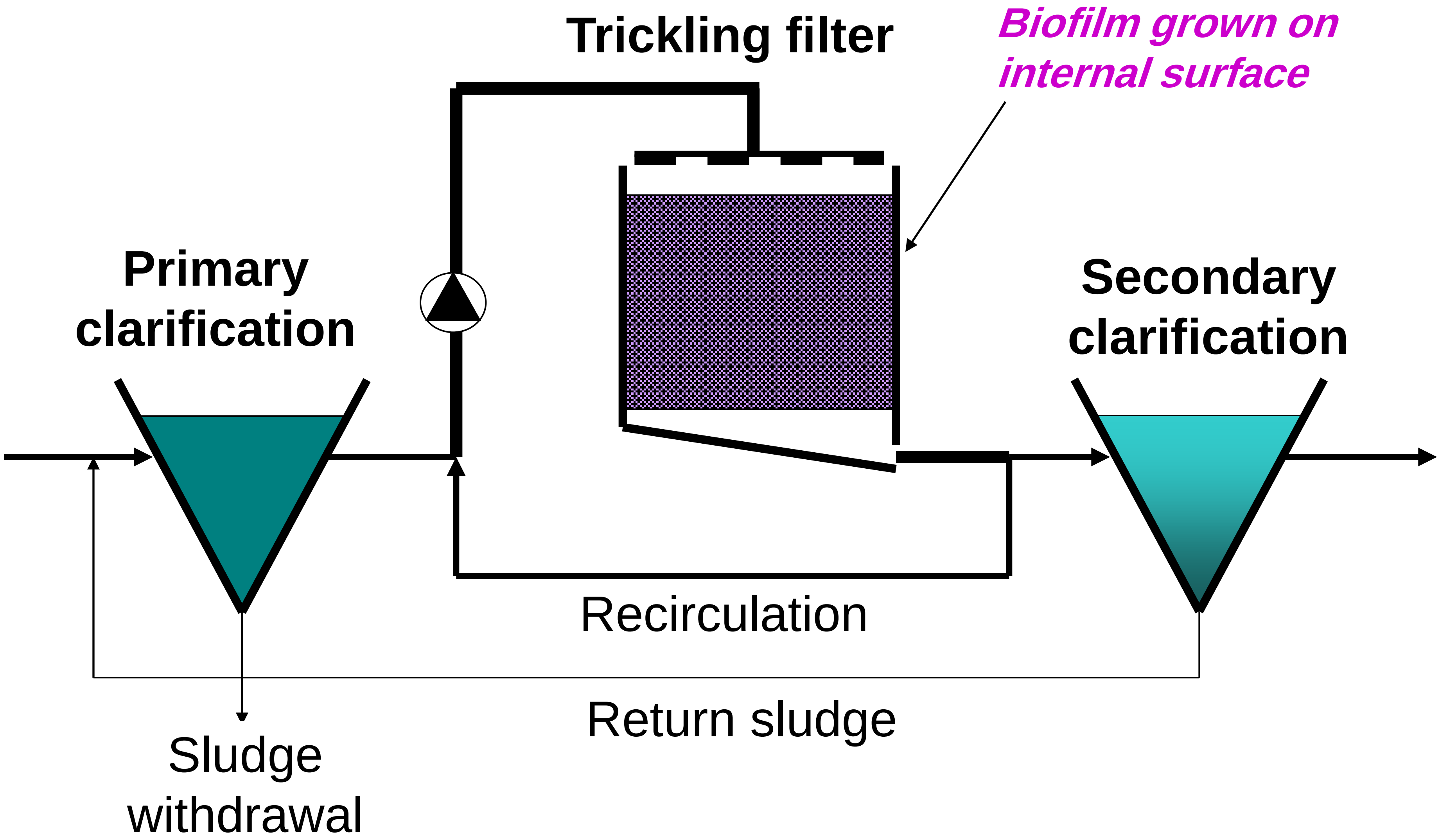
Type of biological reactor		Without nitrification	Nitrification >10°C	Denitrification	Simultaneous aerobic sludge stabilisation
SRT	< 20‘000 PE	5	10	12 – 18	25
	> 100‘000 PE	4	8	*10 – 16*	–
F/M	(kg BOD_5 / (kg TS · d))	*0.30*	*0.15*	*0.12*	*0.05*
ESP_{BOD}	(kg TS / kg BOD_5)	*0.9 – 1.2*	*0.8 – 1.1*	*0.7 – 1.0*	*1.0*

Concentrations in a plug flow areation tank





Trickling filter



Dimensioning of trickling filter

Surface loading

$$B_{Su} = \frac{Q \cdot BOD_{5,in}}{a \cdot V_{TF}}$$

B_{Su} Surface loading (g BOD_5 / ($m^2 \cdot d$))

without nitrification 4 (g BOD_5 / ($m^2 \cdot d$)), with nitrifi. 2 (g BOD_5 / ($m^2 \cdot d$))

Q Inflow to trickling filter (m^3/d)

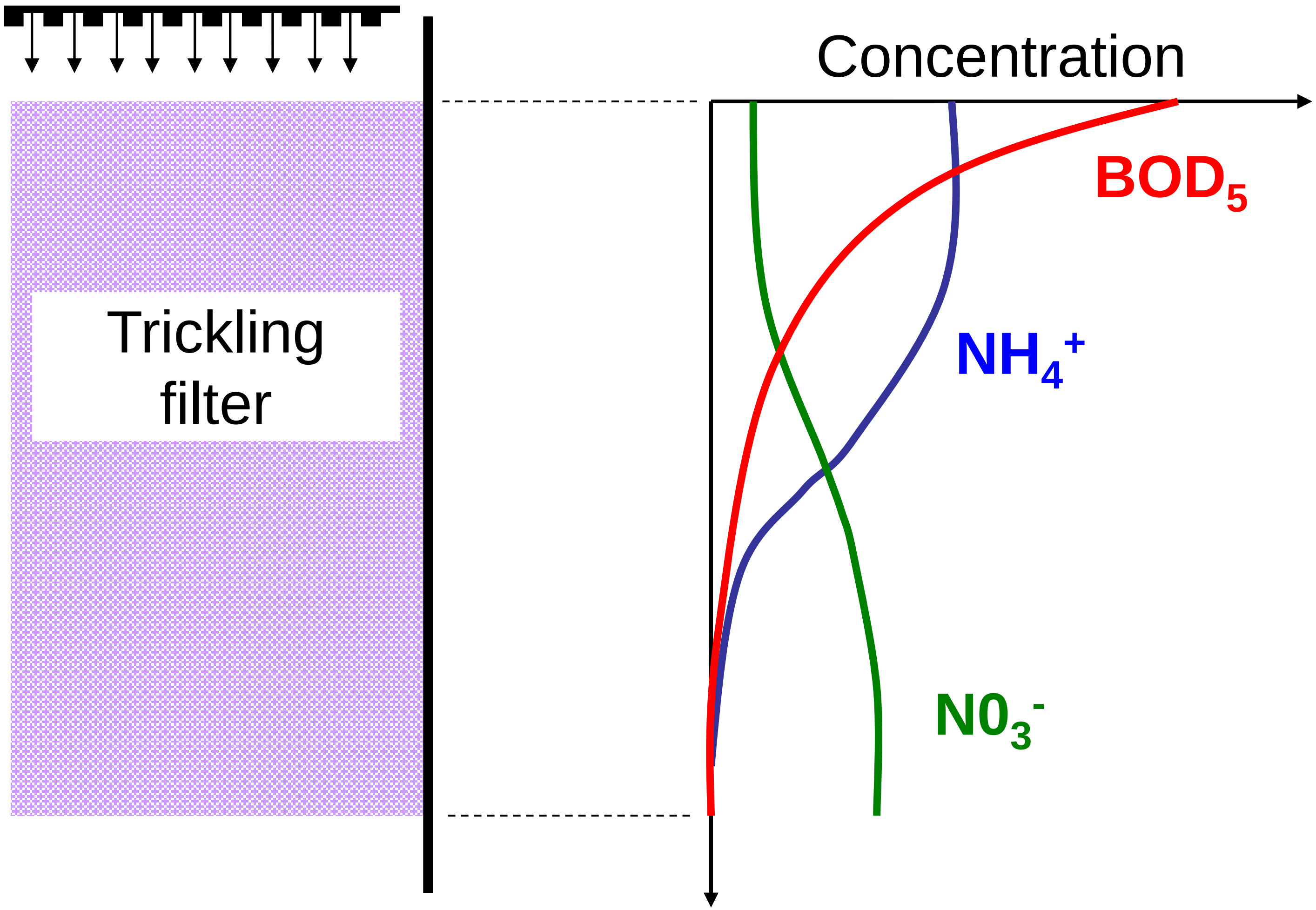
$BOD_{5,in}$ BOD_5 inlet concentration (kg BOD_5 / m^3)

V_{TF} Volume of trickling filter (m^3)

a Specific biofilm surface per volume of trickling filter (m^2 / m^3 TF)

100 – 140 – 180 (m^2 / m^3 TF)

Degradation in trickling filter



→ C-degradation and nitrification are separated in space

11.5 Final clarification

Functions of final clarifiers

Separation of sludge and cleaned wastewater through **Sedimentation**

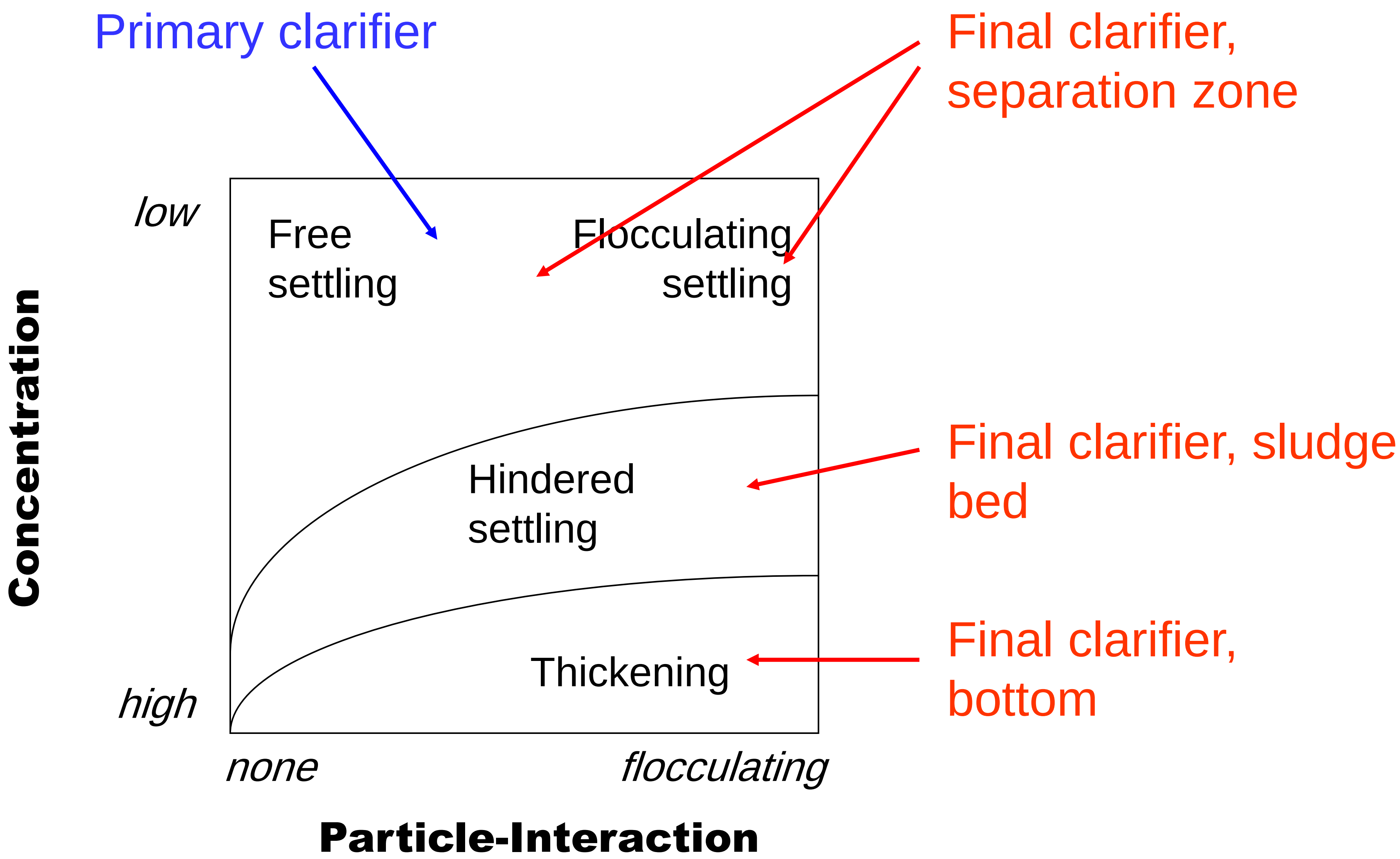
Clarification → Low effluent concentration

Storage of sludge shifted from actibated sludge tank, namely under wet-weather conditions

Thickening → High return sludge concentration

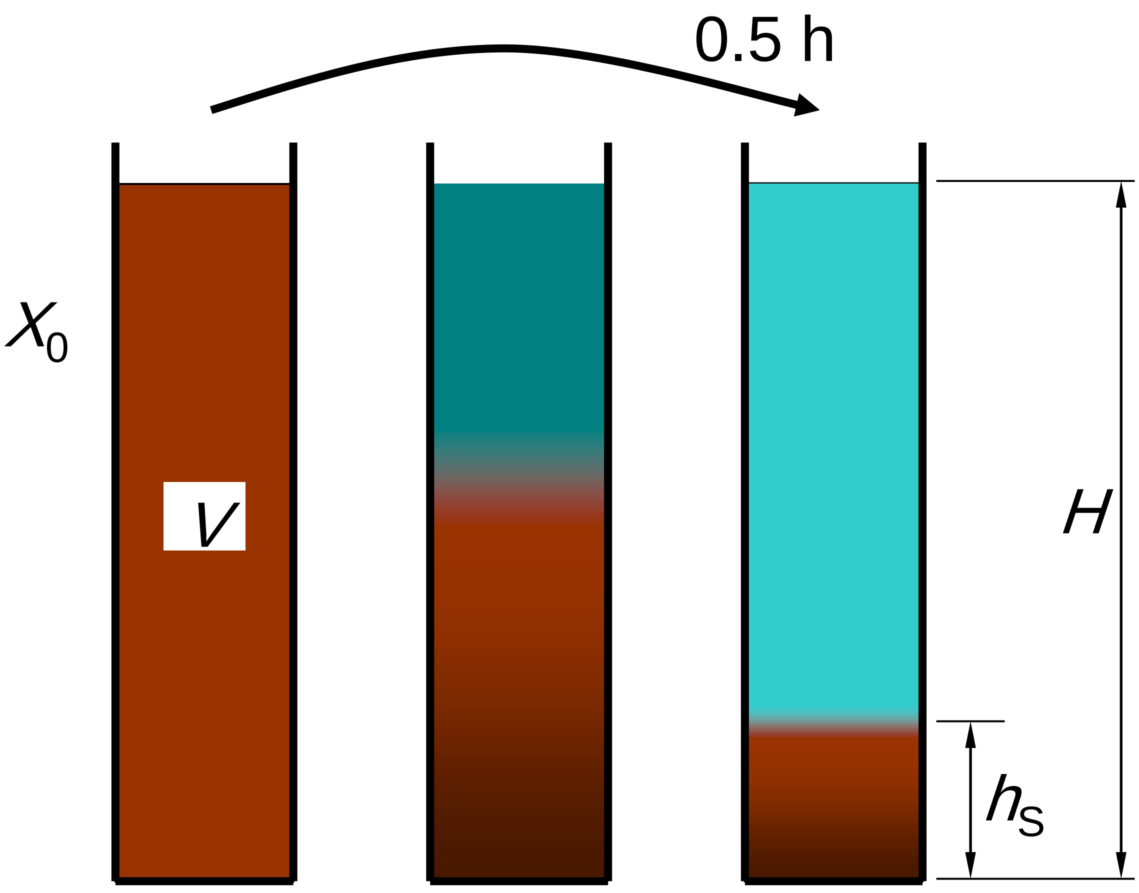
Geometry
- Circular, flow from centre to periphery
- Rectangular, longitudinal flow
- Rectangular, lateral flow
- Vertical, upward flow

Sedimentation



Sludge volume index *SVI*

SVI **is an indicator for volume of sludge flocs and their settling characteristics**

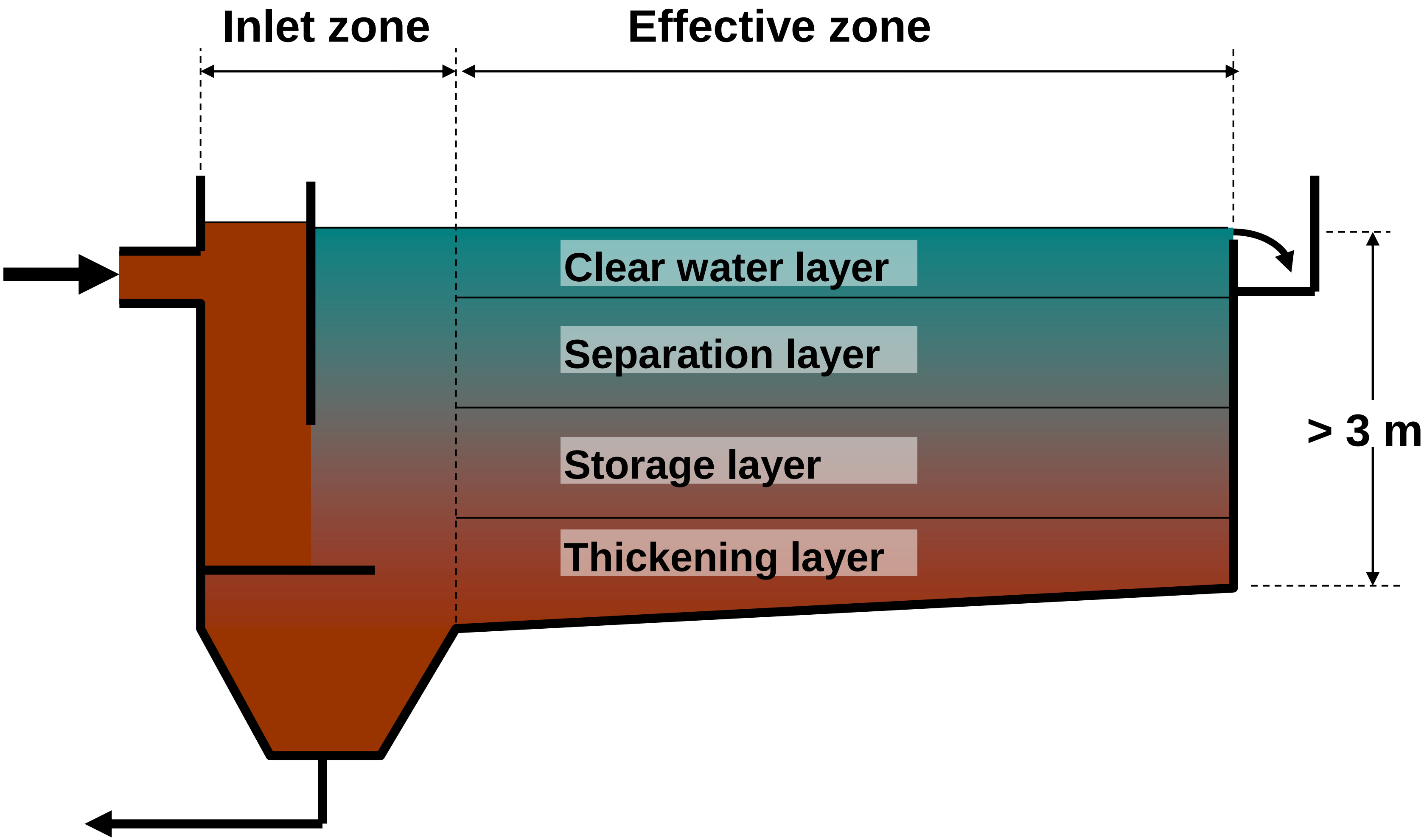


Sludge volume

$$SV = V\frac{h_S}{H} \quad \text{(ml/l)}$$

$$SVI = \frac{SV}{X_0} \quad \text{(ml / g TSS)}$$

Final clarifier, idealised functions



ATV A131 (2000)

Dimensioning of surface

Surface overflow rate

$$q_A = \frac{Q}{A_{FC}} = \frac{q_{SV}}{SV} = \frac{q_{SV}}{X_{AST} \cdot SVI}$$

Sludge overflow rate

$$q_{SV} = q_A \cdot X_{AST} \cdot SVI$$

Limit values

	q_A (m/h)	q_{SV} (l/(m^2·h))
Horizontal flow tanks	1.6	500
Vertical flow tanks	2.0	650

ATV A131 (2000)

Dimensioning of water depth

Clear water layer $h_1 = 0.5\ \mathrm{m}$

Separation layer $$h_2 = \frac{0.5 \cdot q_A \cdot (1+R)}{1 - SV/1000}$$

Storage layer $$h_3 = \frac{1.5 \cdot 0.3 \cdot q_{SV} \cdot (1+R)}{500}$$

Thickening layer $$h_4 = \frac{X_{AST} \cdot q_A \cdot (1+R) \cdot t_{th}}{X_{BS}} \qquad X_{BS} = \frac{1000}{SVI} t_{th}^{1/3}$$

X_{BS}	Sludge concentration at bottom		
t_{th}	Thickening time	1.5 – 2.0 h	without nitrification
		1.0 – 1.5 h	with nitrification
		2.0 – (2.5) h	with denitrification

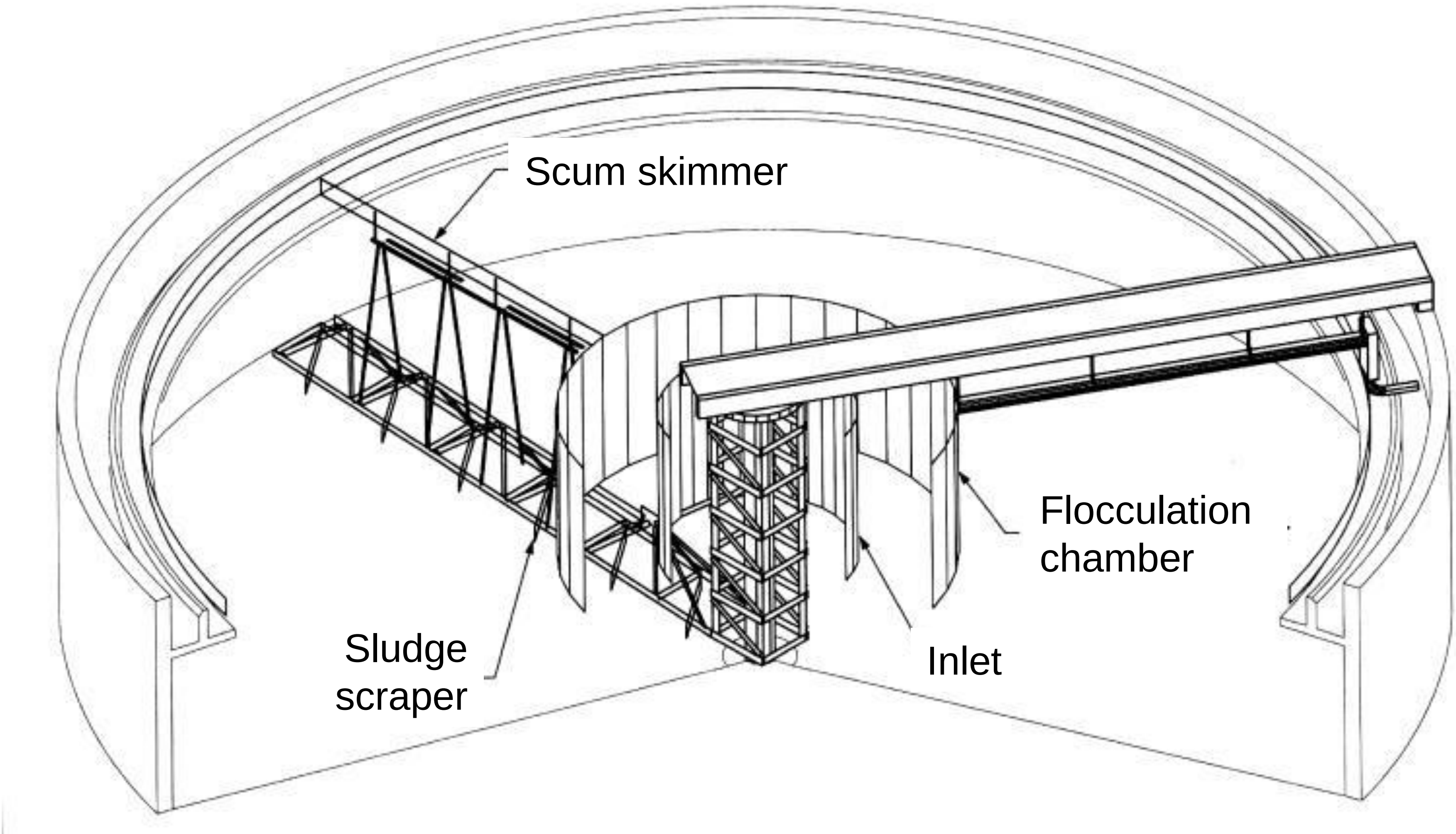
ATV A131 (2000)

Calculation procedure (plant without nitrogen elimination)

- estimate or measure inflow load
- choose system
- estimate sludge volume index
- choose thickening time
- calculate concentration of bottom sludge
- calculate return sludge concentration
- choose recycle ratio → estimate X_{AST}
- calculate surface of secondary clarifier
- calculate h_1, h_2, h_3, h_4 of secondary clarifier
- check thickening time
- calculate volume of activated sludge tank
- is balance between AST and SC optimised?

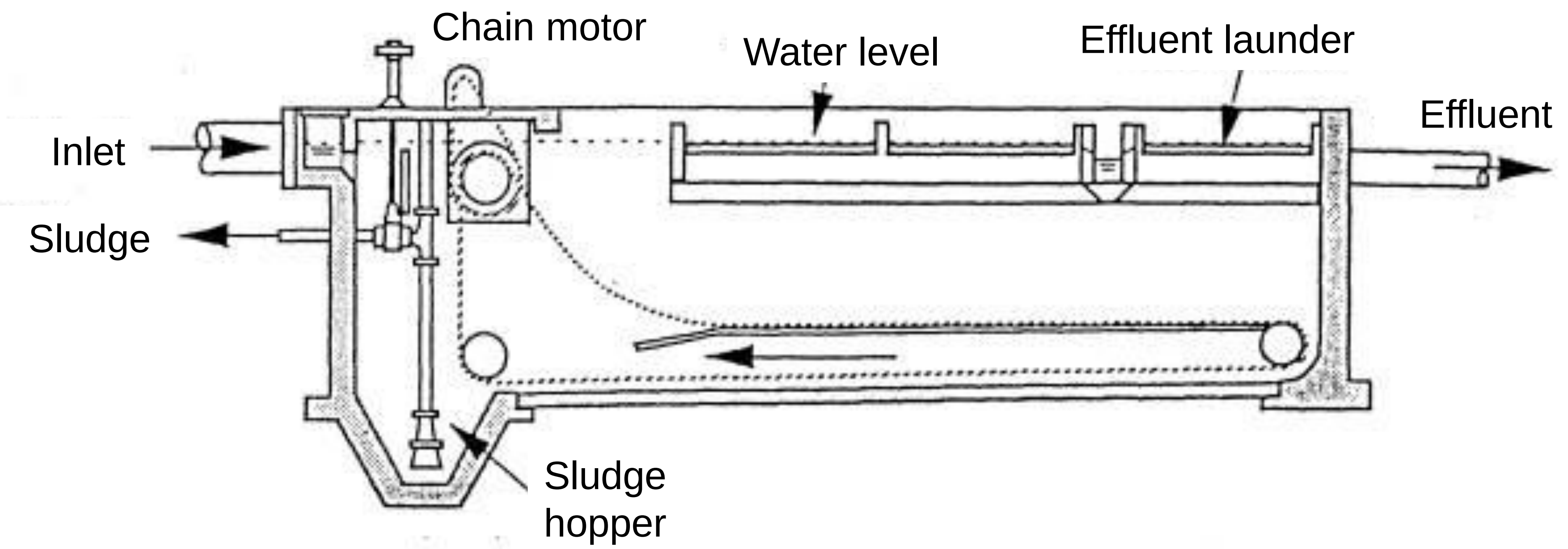
Variation X_{AST}

Circular tank

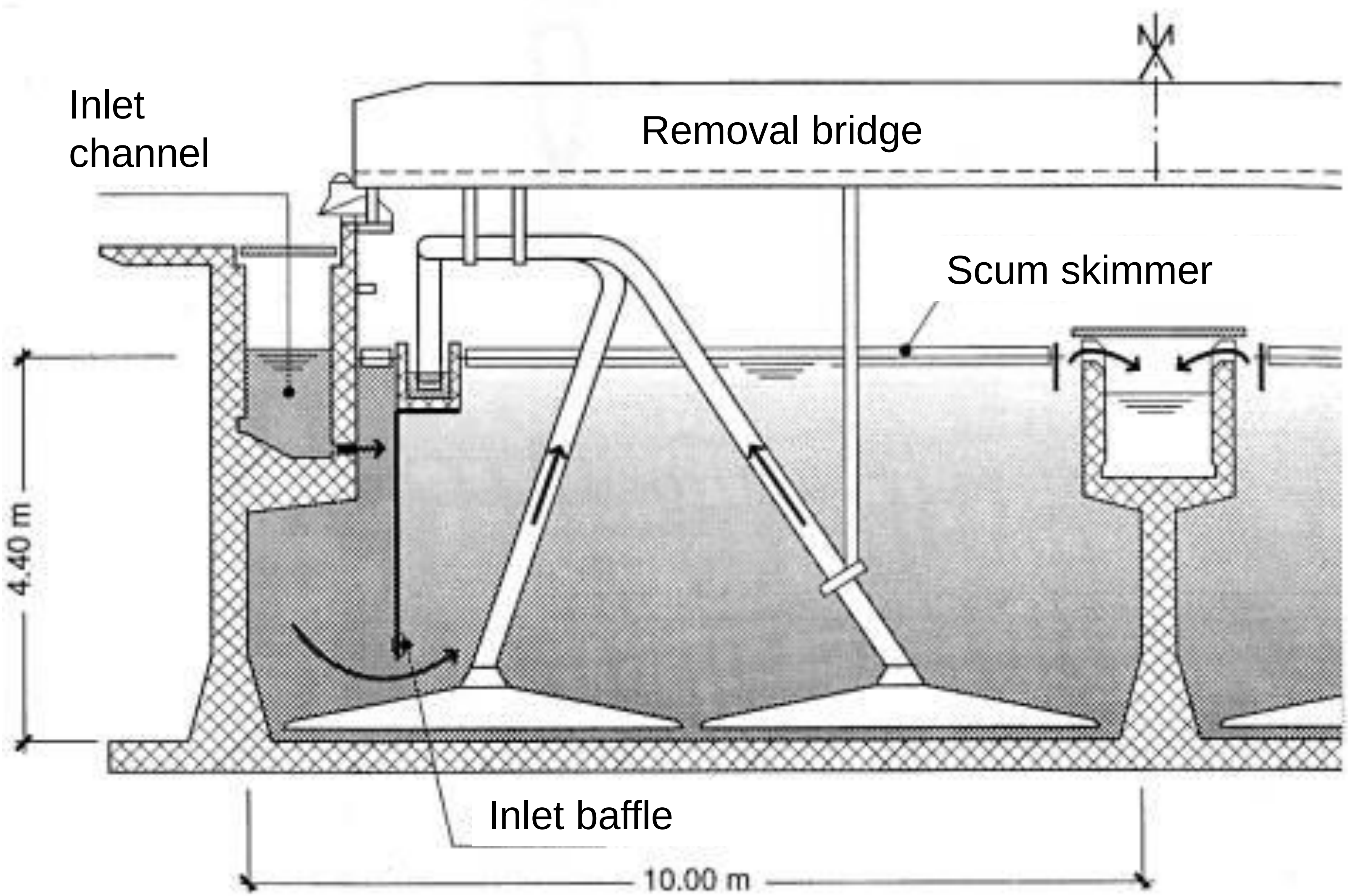


With scraper or suction removal device

Rectangular tank, longitudinal flow, flight scraper system



Rectangular tank, lateral flow, suction system



Vertical flow tank