Guidelines for the Dimensioning of Activated Sludge Plants Outside Germany Based on Standard DWA-A 131

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Summary

In the context of the project "Transfer-orientated research and development in the wastewater sector, validation of dimensioning and operating guidelines for activated sludge plants – EXPOVAL", sponsored by the German Federal Ministry of Education and Research (BMBF), complementary guidelines for the dimensioning of activated sludge plants in other climatic zones have been developed in accordance with the internationally well-known DWA Standard DWA-A 131 (2016). Relevant data was used from large scale wastewater treatment plants, laboratory tests and mathematical simulations. Excerpts thereof are presented here with special emphasis on the dimensioning of the aerobic sludge age and the required process factor value. Recommendations are given on how to proceed in when the design is not based on qualified random sampling but average values. References are also given on the dimensioning of simultaneous aerobic sludge stabilization, the expected surplus sludge production and on denitrification. The results of the joint EXPOVAL project, which has focused on activated sludge plants as well as on many other methods of wastewater and sludge treatment, have been published in DWA Topic T4/2016 [2], which is released as English version in 2018.

Key words: wastewater treatment, municipal, activated sludge plant, design, DWA-A 131, international, climatic zone, hot, cold, sludge treatment, excess sludge, biological nitrogen removal

1 Introduction

Municipal activated sludge plants in Germany are usually designed in accordance with DWA Standard DWA-A 131 [1]. This worksheet also receives high acceptance abroad. This steady state dimensioning approach for activated sludge plants also facilitates dimensioning of the aeration tank volume and of the secondary clarifier. In addition, many detailed operation-relevant values can be calculated, including the surplus sludge production and oxygen demand. It is recommended that the dimensioning approach is applied at temperatures found in moderate climatic zones (8–20 °C). With the following recommendations, an expanded temperature range of 5–30 °C is covered [2].

The underlying safety concept of DWA-A 131 [1] is based on monitoring the discharge concentrations using qualified random samples, this being typical for Germany. Outside Germany however the requirement is often only to meet average values (dayly, monthly) respectively an annual maximum load or an annual elimination value is defined. If DWA-A 131 [1] is used for the dimensioning of activated sludge plants outside Germany, its application involves the question of how to deal with other process requirements abroad, or to what extent, for example, design volumes can be reduced if dimension is based on daily average values.

Fig. 1: Secondary Clarifier of the wastewater treatment plant of Fujairah, United Arab Emirates (UAE) (Photo: EW)

2 Dimensioning guidelines

To make it easier to apply the following design references to high and low temperatures, all recommendations are based on the newly published DWA-A 131 [1]. The underlying calculation process (Figure 2) has not changed from DWA-A 131. The following dimensioning recommendations refer primarily to the modification of individual parameters or equations.

2.1 Input data

As per the new DWA-A 131, the chemical oxygen demand replaces the biochemical oxygen demand. When planning for other climatic zones, particular attention must be paid to the inflow characteristic and input data of the plant. These can vary both in terms of dynamics and with respect to the prevailing substances (concentrations, ratios, etc.) from catchment area to catchment area and thus from plant to plant. As countries in other climatic zones often have very different dietary habits

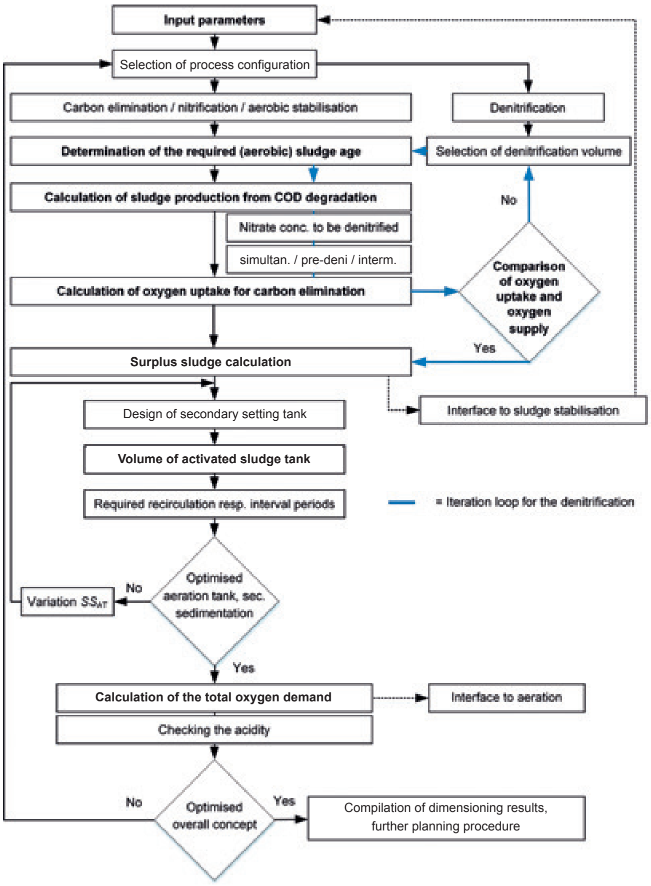

Fig. 2: Design process for an activated sludge plant (according to DWA-A 131 [1])

compared to Central Europe or North America, it is extremely important to conduct investigations of local wastewater composition.

2.2 Dimensioning criterion – aerobic minimum sludge age

Scientific investigations have shown that apart from *Nitrosomonas* and *Nitrobacter,* nitrification also involves other groups of organisms such as *Nitrospira*. DWA-A 131 applies typical nitrification kinetics which identify *Nitrosomonas* as a key nitrification organism in the temperature range between 8 and 20 °C. We recommend applying the same specification for the temperature ranges of 5–8 °C and 20–30 °C.

Wastewater temperature T_W [°C]	Recommended sludge age $t_{SS,design}$ [d]
< 10	4
10 to 20	3
$> 20^{*)}$	(2) 3 including anoxic volumes or phases

*) At temperatures above 20 °C, plant design including nitrification and at least partial denitrification is recommended.

Table 1: Design sludge age for plants with carbon elimination (without nitrification)

$S_{NH4, EST, dM}$	f_N					
	1.4	**1.6**	**1.8**	**2.0**	**2.2**	**2.4**
1.0 mg/l	1.5	1.6	1.8	2.0	2.2	2.4
2.0 mg/l	1.2	1.2	1.2	1.3	1.4	1.6
2.5 mg/l	1.2	1.2	1.2	1.2	1.3	1.5

Table 2: Process factor PF depending on the KN inflow fluctuations f_N and the secondary clarifier effluent concentration $S_{NH4, EST, dM}$ (5–30 °C)

$S_{NH4,EST,dM}$	**Design temperature T [°C]**					
	5	**10**	**15**	**20**	**25**	**30**
1.0 mg/l	21.8	13.3	8.2	5.0	3.1	2.0
2.0 mg/l	14.5	8.9	5.4	3.1	2.0	2.0
2.5 mg/l	13.6	8.3	5.1	3.1	2.0	2.0

Table 3: Aerobic sludge age [d] for plant sizes of up to 20,000 I depending on the temperature and the ammonium nitrogen concentrations in the secondary clarifier effluent

$S_{NH4,EST,dM}$	**Design temperature T [°C]**					
	5	**10**	**15**	**20**	**25**	**30**
1.0 mg/l	13.6	8.3	5.1	3.1	2.0	2.0
2.0 mg/l	10.9	6.7	4.1	2.5	2.0	2.0
2.5 mg/l	10.9	6.7	4.1	2.5	2.0	2.0

Table 4: Aerobic sludge age [d] for plant sizes of up to 100,000 I depending on the temperature and the ammonium nitrogen concentrations in the secondary clarifier effluent

$$t_{SS,aerob,design} = PF \cdot 1{,}6 \cdot \frac{1}{\mu_{A,max}} \cdot 1.103^{(15-T)} =$$

$$PF \cdot 1.6 \cdot \frac{1}{0.47} \cdot 1.103^{(15-T)} \qquad [d]\ (1)$$

Although nitrite oxidizing bacteria can limit nitrification performance at higher temperatures, the effect of correspondingly altered kinetics on the aerobic sludge age in the 27–30 °C range is minimal. For the sake of a simplified, practical design no explicit equation is introduced for the nitrite-oxidizing bacterial group.

Plants targeting carbon elimination (without targeted nitrification)

According to DWA-A 131 (2016), activated sludge plants targeting exclusively carbon elimination should be dimensioned for a sludge age of 4 d ($B_{d,COD,InAT} > 12{,}000$ kg/d) to 5 d ($B_{d,COD,InAT} < 2{,}400$ kg/d). In the case of permanently high wastewater temperatures, it is recommended to reduce the design sludge age for the sole purpose of carbon elimination according to Table 1. It is not necessary to differentiate for different plant sizes when monitoring daily average values of discharge concentrations.

It is to be expected that plants will also nitrify at temperatures above 20 °C and at an aerobic sludge age of 2 d. Therefore, it is necessary to take this un-targeted nitrification into consideration when dimensioning the aeration system and operating the clarifier. For this reason, an additional anoxic basin or non-aerated denitrification phases should be included in the design. Thus, the oxygen consumption can be reduced and acid capacity improved in case nitrification occurs. At temperatures above 20 °C therefore, a system design including nitrification and denitrification is recommended.

From around 27 °C, the actual growth rate (and hence the turnover rate) of the ammonium oxidizing bacteria may exceed that of the nitrite oxidizing bacteria. In municipal activated sludge plants with relatively low loads, fully mixed tanks and with a limited minimum aerobic sludge age, however, the effects are negligible up to 30 °C. However, it can have a significant effect in the design of Sequencing Batch Reactor (SBR) plants or high-load plants, especially at high wastewater temperatures (> 27 °C). If necessary, it should be taken into account and verified separately.

Plants targeting nitrification

The prevailing monitoring practice in Germany is based on a qualified random sample (2 h composite sample). This strict practice is special by international standards, as in other countries mainly 24-hour composite samples or annual loads are used. One of the consequences of this is that safety factors included in the dimensioning with A131 may be reduced.

DWA-A 131 (2016) includes a “Process Factor” (PF) which, amongst other things, takes into account the fluctuations of Kjeldahl nitrogen (KN) inflow load via the peak factor f_N. Normally f_N decreases as the size of the catchment area increases. For the 5-30 °C temperature range, the process factor was calculated by dynamic simulation. The values given in Table 2 can be used for calculation irrespective of temperature. Intermediate values may be interpolated.

If there is no information on fluctuations of the KN inflow load in case of new designs outside Germany, Tables 3 and 4 can be used for the sake of simplicity. The aerobic sludge age should not be less than two days or must be verified separately, for example, by experiment or dynamic simulation.

Plants with simultaneous aerobic sludge stabilization

Based on investigations in the research project it is suggested that the design sludge age for simultaneous aerobic sludge digestion with nitrification and denitrification should be determined as per DWA-A 131 (2016) for the extended temperature range:

$$t_{SS,\text{design}} \geq 25 \cdot 1.072^{(12-T)} \qquad [\text{d}]\ (2)$$

For simultaneous aerobic sludge digestion with nitrification applies analogical:

$$t_{SS,\text{design}} \geq 20 \cdot 1.072^{(12-T)} \qquad [\text{d}]\ (3)$$

In addition, a criterion is presented below defining when sludge is sufficiently stabilized. The degree of stabilization is determined based on how much of the heterotrophic gross biomass produced in the process being oxidized aerobically/anoxically in the same period of time. The following equation applies:

$$f_B \cdot Y \cdot C_{COD,degr} = Y \cdot C_{COD,degr} \cdot \left((1 - f_i) \cdot b_{H,T} \cdot \frac{t_{TS}}{(1 + b_{H,T} \cdot t_{TS})} \right) \qquad [\text{mg/l}]\ (4)$$

Resolved according to the sludge age and taking into account the temperature-dependent decay coefficient for the heterotrophic biomass $b_{H,T} = b_{H,15°C} \cdot 1.072^{(T-15)}$:

$$t_{SS} = \frac{f_B}{b_{H,15°C} \cdot 1.072^{(T-15)} (1 - f_B - f_i)} \qquad [\text{d}]\ (5)$$

With a decay coefficient of $b_H = 0.17\ \text{d}^{-1}$ at 15 °C, an inert fraction of $f_i = 20\ \%$ and $f_B = 62\ \%$, a stabilization period of 25 d results for T = 12 °C, which corresponds to the value according to DWA-A 131 (2016) for simultaneous aerobic sludge stabilization with nitrification and denitrification. The percentage of 62 % for f_B means that 62 % of the active gross heterotrophic biomass produced is oxidized simultaneously during the same period.

The values of the design sludge age required for simultaneous aerobic stabilization are given depending on process (nitrification with/without denitrification) in Figure 3 and are in accordance with the recommendations of DWA-M 368 [3].

A long stabilization time is required at low temperatures. At a required design sludge age of more than 30 d plants with si-

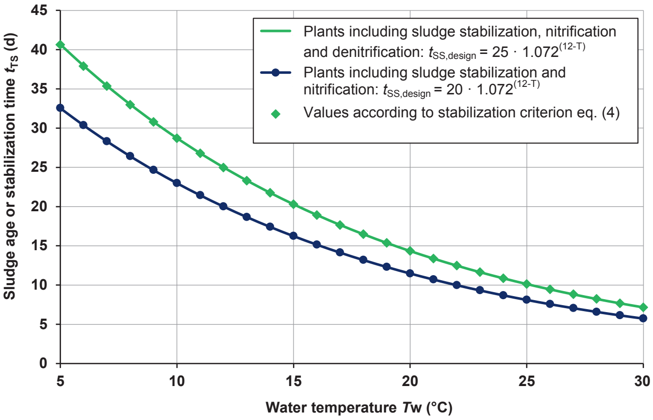

Fig. 3: Required design sludge age based on wastewater temperature for simultaneous aerobic sludge stabilization

multaneous aerobic sludge stabilization must be assessed for economic efficiency. Separate stabilization processes might be more economical: i.e. separate aerobic stabilization with thickening, composting after dewatering or the addition of lime. Separate anaerobic sludge stabilization is worthwhile in larger plants.

2.3 Denitrification

The non-aerated activated sludge tank volume required for denitrification is calculated with DWA-A 131 by comparing the oxygen equivalents from the nitrogen load to be denitrified versus the proportional chemical oxygen demand available in the denitrification tank. Accordingly, in the case of pre-denitrification, the COD in the plant inflow and the hydrolysis of the non readily biodegradable COD plays a decisive role for the question of how much nitrate can be eliminated.

In other climatic zones, a different composition of the wastewater as well as in many cases a greater degree of pre-degradation in the sewer system and different process rates can be found.

Different process rates due to temperature can be taken into consideration for pre-denitrification by adjusting the exponent α_{DB} (Equation 6).

$$OU_{C,D,pre} = 0.75 \cdot \Bigg(OU_{C,la,pre} + \left(OU_C - OU_{C,la,pre}\right) \cdot \left(\frac{V_{D,pre}}{V_{AT}}\right)^{\alpha DB}\Bigg) \quad [mg/l] \tag{6}$$

Table 5 displays the relationship between α_{DB} and the temperature in the activated sludge tank and allows equation 3 to be applied for temperature ranges outside DWA-A 131 (2016).

There are no changes for intermittent and simultaneous denitrification processes.

2.4 Surplus sludge production

The required volume of the activated sludge tank is determined from the calculated surplus sludge production together with

Type of process	T [°C]			
	5–8	8–20*)	20–25	25–30
Plants with primary settling tank	0.64	0.68	0.75	0.76

*) Temperature range 8–20 °C according to DWA-A 131 [1]

Table 5: α_{DB} depending on temperature in the activated sludge tank

Glossary of abbreviations

Abbreviation	Unit	Description
α_{DB}	–	Exponent considering the proportional oxygen consumption with pre-denitrification
$B_{d,COD,InAT}$	kg/d	Daily total COD load at the inflow of the aeration tank
$b_{H,T}$	d^{-1}	Temperature-dependent decay rate of the heterotrophic biomass
$C_{COD,deg}$	mg/l	Concentration of biodegradable COD in the homogenized sample
f_B	–	Proportion of biomass being oxidized aerobically/anoxically per gross active heterotrophic biomass produced
f_i	–	Inert proportion of the decayed biomass
f_N	–	Peak factor of the nitrogen load
I		Inhabitants
KN		Total Kjehldahl nitrogen (KN = org. N + NH_4-N)
OU_C	mg/l	Oxygen uptake for carbon elimination in relation to the wastewater inflow
$OU_{C,D,pre}$	mg/l	Oxygen uptake equivalent for carbon removal at the pre-denitrification
$OU_{C,ed,pre}$	mg/l	Oxygen uptake from easily degradable COD and externally added carbon with pre-denitrification
PF	–	Process factor for nitrification
$S_{NH4,EST,dM}$	mg/l	Concentration of ammonium nitrogen in the effluent of secondary sedimentation tank as daily mean
$t_{SS,aeob}$	d	Aerobic design sludge age
$t_{SS,design}$	d	Total sludge age upon which dimensioning is based
T_W	°C	Wastewater temperature
V_{AT}	m^3	Volume of the total activated sludge tank from nitrification and denitrification
V_D	m^3	Volume of the tank used for denitrification
$V_{D,pre}$	m^3	Volume used for pre-denitrification
V_N	m^3	Volume of tank used for nitrification
X_{BM}	mg/l	Concentration of biomass
$X_{inert,InAT}$	mg/l	Concentration of the inert particulate COD at the inflow of the activated sludge tank
$X_{P,BioP}$	mg/l	Concentration of phosphorus incorporated into the biomass
Y	g/g	Yield factor (gram of produced biomass (COD) per gram of biodegradable COD)
$\mu_{A,max}$	d^{-1}	Maximum gross growth rate of autotrophic organisms biomass at 15 °C

the total suspended solids resulting from secondary clarifier dimensioning. In addition, the amount and composition of the primary and secondary sludges determine the further design of the sludge treatment section.

The research project compared the surplus sludge production measured at large-scale plants abroad with calculated sludge production. The data from the large-scale plants showed that in reality the surplus sludge quantities at 30 °C are often greater than those resulting from steady-state plant design. Among others, this is due to the difference in wastewater composition compared to German wastewater. It is therefore strongly recommended to measure at least the mineral dry matter and the inert particulate COD in the inflow of the activated sludge tank or wastewater treatment plant. If measurements are not possible, it is to be expected that at temperatures above 25 °C, the proportion of mineral dry matter in the total dry matter of the inflow of the wastewater treatment plant is between 30 % (pre-treated wastewater) and 40 % (raw sewage). The proportion of inert particulate COD ($X_{\mathrm{COD,\,inert}}$) to the total particulate COD (X_{COD}) can be assumed to be between 30 and 40 % in the activated sludge tank inflow.

2.5 Composition of sludge masses – phosphorus balance

As design according to DWA-A 131 (2016) and the recommendations presented here cover a temperature range of 5–30 °C, it seems reasonable to link phosphor incorporation, similar to the nitrogen incorporation, to the sludge age. According to findings, which for example have been used in the EAWAG BioP module [4, 5], phosphorus incorporation can be assumed as follows:

$$X_{\mathrm{P,BioP}} = 0.014 \cdot X_{\mathrm{BM}} + 0.005 \cdot X_{\mathrm{inert,InAT+BM}} \quad [\mathrm{mg/l}] \qquad (7)$$

2.6 Oxygen demand

It is recommended to calculate the oxygen demand required for the microbial conversion of organic compounds according to DWA-A 131 [1]. Further information on dimensioning of aeration systems can be found in DWA Topic T4/2016 [2] in chapter 7 “Aeration systems”.

2.7 Planning and operational guidelines

High wastewater temperatures result in lower required sludge ages and thus in reduced activated sludge tank volumes. As a result of shorter hydraulic retention times, peak loads in the inflow result more quickly to corresponding peak concentrations in the effluent. If peak concentrations are relevant for monitoring, this should be taken into account in the design process. Dynamic simulation [6, 7] can also be used for the design.

Furthermore, the solubility of oxygen decreases at high wastewater temperatures. A higher air supply is required due to the oxygen consumption for carbon degradation and nitrification. At the same time, high wastewater temperatures lead to lower sludge ages and thus to low activated sludge tank volumes. In the case of pressure aeration the base area of the aeration tank may not be large enough to allow the installation of the necessary number of aeration elements. Then a tank layout with a larger base area but a lower depth has to be taken into account. For international applications, especially in developing, emerging and transition countries, the use of surface ventilation systems should be considered as an alternative to pressure aeration, depending on local conditions. Advantages of the latter include operational safety and longer service life. The main disadvantage may be less efficiency, depending on the application.

High temperatures in wastewater systems can cause possible odors as a result of the decomposition processes. Pumping stations, mechanical treatment stages and sludge storage tanks should considered to be covered or include air collection and treatment.

In very hot climates, appropriate operating temperature ranges must be ensured by ventilation and air conditioning of the mechanical aggregates and electrics. In very cold temperatures, the design of the plant must guarantee adequate protection against frost (including enclosures, frost monitors in buildings and shafts with dry pumps, auxiliary heating of intermittently used pipes, heating of the scraper ways).

Aeration dimensioning for different temperature load cases is required if there is substantial fluctuation of the wastewater temperature throughout the year. This results in correspondingly different required biomass volumes. In the interests of energy efficiency and conservation of resources, with major fluctuations, it is not recommended to maintain the biomass volume for the worst-case low-temperature load all year round. Endogenous respiration and the energy required to mix the biomass would result in an inefficient system and increased energy consumption. In the case of substantial temperature fluctuations in larger plants it is recommended at the planning stage to consider a multi-line design or subdivision of the activated sludge tank volume with decommissioning of individual lines or partial volumes at high temperatures. In medium and large plants, two or more lines are generally recommended, not least from the perspective of operational reliability. Sufficient oxygen input must be ensured in all cases via the aeration installation of the operated tanks. As an alternative to take tank volumes out of order, the solids content can be reduced to adjust the required biomass.

3 Prospects

The design recommendations supplementary to DWA-A 131 given above and other calculation approaches of the EXPOVAL project are summarized in DWA Topic T4/2016 [2], which is available in English since 2018.

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References

[1] Arbeitsblatt DWA-A 131: *Bemessung von einstufigen Belebungsanlagen*, (Design of single-stage activated sludge plants) Hennef, 2016

[2] DWA Topic T4/2016: *Design of wastewater treatment plants in warm and cold climates*, Hennef, 2016, English version published in 2018

[3] Merkblatt DWA-M 368: *Biologische Stabilisierung von Klärschlamm*, Hennef, 2014

[4] Koch, G., Kühni, M., Gujer, W., Siegrist, H.: Calibration and validation of Activated Sludge Model No. 3 for Swiss municipal wastewater, *Water Res.* 2000, *34* (14), 3580–3590

[5] Rieger, L., Koch, G., Kühni, M., Gujer, W., Siegrist, H.: The EAWAG Bio-P Module for Activated Sludge Model No. 3, *Water Res.* 2001, *35* (16), 3887–3903

[6] Wichern, M., Gehring, T., Lübken, M.: Modeling of biological systems, in: IWA "Treatise on Water Science", IWA Publishing, London, 2011

[7] Alex, J., Wichern, M., Spering, V., Halft, N., Ahnert, M., Frehmann, T., Hobus, I., Langergraber, G., Plattes, M., Winkler, S., Wörner, D.: A method to use dynamic simulation in compliance to design rules to refine WWTP planning, 10th IWA Specialised Conference on Design, Operation and Economics of large Wastewater Treatment Plants, 9.–13. September 2007, Vienna/Austria

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