# Adaptation of WWTP design parameters to warm climates using mass balancing of a full scale plant

C. Walder[1,2], S. Lindtner[3], A. Proesl[1], F. Klegraf[1], T. Vasanthakumar[4] and N. Weissenbacher[2]*

[1]VA TECH WABAG GmbH, Dresdner Str. 87-91, 1200 Vienna, Austria
[2]University of Natural Resources and Life Sciences, Muthgasse 18, 1190 Vienna, Austria
[3]eDAB GmbH, Obere Augartenstr. 18A/5/1, 1020 Vienna, Austria
[4]VA TECH WABAG Ltd. No.11 Murray's Gate Road, Alwarpet, Chennai-600018, India.

*Corresponding author: norbert.weissenbacher@boku.ac.at

**Abstract**

The ATV-DVWK-A-131 guideline and the METCALF & EDDY approach are widely used for the design of wastewater treatment plants. They are both based on simplified steady-state assumptions tailored to the boundary conditions of temperate climates. Using design guidelines beyond the designated temperature range may lead to inappropriate results. To be able to apply these well-proven guidelines under warm climate condition appropriately, adaptation is needed. Hence, the objectives are (1) to summarize their temperature relevant differences, (2) to show the related design components and to (3) to demonstrate the adaptation to warm climate conditions. Full scale plant data from warm climate conditions was acquired for a period of one year as basis for analyses and adaptation. Mass balances were carried out for analyzing excess sludge production. The two approaches showed relevant temperature related differences. METCALF & EDDY default application resulted in lower deviation to the mass balance results for excess sludge production. However, with the adaptation of the heterotrophic decay rates for both approaches and the inert organic and mineral solids fraction additionally for ATV-A-131, a good fit to the observed excess sludge production could be achieved.

**Keywords**
ATV-A-131, Metcalf & Eddy, WWTP design, warm climates, adaptation, mass balancing

## NOMENCLATURE

| | |
|---|---|
| a | coefficient for the inert particulate solids |
| b | coefficient for the cell debris |
| BOD | biochemical oxygen demand |
| bCOD | biodegradable chemical oxygen demand |
| $C_{BOD}$ | BOD concentration in the influent to the aeration tank |
| $C_{bCOD}$ | bCOD concentration in the influent to the aeration tank |
| DO | dissolved oxygen concentration in the aeration tank |
| $f_T$ | temperature correction factor |
| $k_{dH}$ | endogenous decay coefficient for heterotrophic organisms |
| $k_{dN}$ | endogenous decay coefficient for nitrifying organisms |
| $K_N$ | half-velocity constant for ammonium |
| $K_O$ | half-saturation coefficient for DO |
| MLSS | mixed liquor suspended solids concentration in the aeration tank |
| $\mu_N$ | net growth rate of nitrifying organisms |
| $\mu_{N,max}$ | maximum growth rate of nitrifying organisms |
| $N_{EFF}$ | ammonium concentration in the effluent |
| p.e. | population equivalents |
| $Q_d$ | daily influent flow rate into the aeration tank |
| S | effluent substrate concentration |
| $S_0$ | influent substrate concentration |
| SF | safety factor |
| $SP_{d,X,TSS}$ | daily sludge production in terms of total suspended solids |
| SRT | solids retention time |

| | |
|---|---|
| $SRT_{N,AER}$ | aerobic solids retention time required for nitrification |
| T | temperature |
| $X_{iTSS}$ | inert mineral suspended solids in the influent to the aeration tank |
| $X_{nbVSS}$ | inert organic suspended solids in the influent to the aeration tank |
| $X_{TSS}$ | total suspended solids in the influent to the aeration tank |
| $X_{VSS}$ | volatile suspended solids in the influent to the aeration tank |
| $Y_H$ | coefficient for the heterotrophic yield |

## INTRODUCTION

Among others, the German ATV-DVWK-A-131 (ATV-DVWK, 2000) guidelines and the design approach of METCALF & EDDY (Metcalf & Eddy, 2003) are widely used for the design of wastewater treatment plants (Ekama *et al.,* 1984; Metcalf & Eddy, 2003; EPA, 1993). These approaches are both based on more or less simplified steady-state assumptions and have been proven in practice since decades. ATV-A-131 is tailored to the boundary conditions of temperate climates in Europe, whereas the METCALF & EDDY approach is widely used especially in Anglo-American and Asian regions. The main design parameters of these guidelines are the solids retention time (SRT), the mixed liquor suspended solids (MLSS) concentration and the related excess sludge production of the activated sludge system. All three parameters are connected to each other, basically as a result of the incoming load (characteristics) and the growth rate of the heterotrophic and autotrophic microorganisms under the present operational conditions. One of the most important operational conditions is the wastewater temperature. It affects biomass activity on the one hand and many physico-chemical parameters on the other hand (e.g. dissolution of oxygen; Sedory & Stenstrom, 1995). Using design guidelines beyond the designated temperature range, e.g. in climates with significantly higher wastewater temperatures, may lead to inappropriate results. Oversized aerobic volumes cause unnecessary costs and operational problems (Parker, 1999; Parker & Goehring, 2002). To be able to apply the well-proven guidelines under warm climate condition appropriately, adaptation is needed. Hence, the objectives of this paper are (1) to summarize the relevant differences between ATV-A-131 and METCALF & EDDY and (2) to show the main temperature influenced design components. Finally, the authors intend (3) to demonstrate a procedure for the adaptation of these design parameters to warm climate conditions that is based on the operation of a full scale activated sludge plant located in India.

## MATERIALS AND METHODS

With the help of mass balances of a full-scale activated sludge plant located in warm respectively tropical climate, the two design standards of ATV-A-131 and METCALF & EDDY have been analysed. The daily excess sludge production has been chosen are target parameter for investigation and adaptation (Nowak *et al.,* 1999; Petersen *et al.,* 2002). Measured excess sludge production has been compared to the results of design guideline calculations.

### Basic analyses of guidelines

The calculation procedures of the required SRT for nitrification and denitrification of the ATV-A-131 and METCALF & EDDY design guidelines were compared focusing on the temperature influences on the daily excess sludge production.

### Mass balancing

*Data acquisition.* Data from a full scale activated sludge plant were used as basis for the identification of relevant temperature influences of the design approaches under practice conditions. The treatment plant located in south-western India has been designed as a typical single-stage activated sludge process for carbon removal only with anaerobic sludge digestions and has a total treatment capacity of 110,000 m³/d (730,000 p.e.). With a SRT of 7.5 days the plant performs partly nitrification-denitrification. An intensive monitoring programme has been carried out at the sewage treatment plant between 01.08.2008 and 31.07.2009. The influent wastewater showed typical temperatures between 27 and 33°C. 24-h composite samples were taken at the inlet, after the grit chamber, after the primary clarifier and at the plant outlet after the secondary clarifier. Daily grab samples from the primary sludge, excess- and return sludge were also analysed in order to reflect plant performance and operation conditions. Additionally, daily grab samples were taken and analysed from the thickener, the digester, the balancing tank and the dewatering unit. The volatile suspended solids fraction ($X_{VSS}$) in the influent was measured through the ignition of the total suspended solids ($X_{TSS}$) at 500±50°C. By subtracting the $X_{VSS}$ fraction from the $X_{TSS}$ fraction, the $X_{iTSS}$ concentration was determined. For the inert organic solids concentration ($X_{nbVSS}$) after the primary clarifier, a typical value of 30 mg/l was assumed (Metcalf & Eddy, 2003).

*Mass balances.* Based on the data gained from the sewage treatment plant, mass balances were conducted to derive the main process parameters (e.g. solids retention time, daily excess sludge production) for the period of one year (2008/2009). The mass balances have been conducted for COD, TN and TP using the eDAB© software tool (eDAB GmbH, Austria). They have been also used to analyse the general validity of the data base (Nowak *et al.*, 1999). Also Puig *et al.* (2008) showed that mass balance calculations of a full-scale WWTP are a useful tool to receive reliable data for process evaluation, WWTP design and benchmarking.

### Parameter adaptation

The results of mass balances have been used as basis for the adaptation of the identified main parameters for the ATV-A-131 and METCALF &EDDY design procedures.

## RESULTS AND DISCUSSION

### Analyses of fundamental design parameters

*Solids retention time (SRT).* The SRT is the basis for the required reactor volumes in connection to the excess sludge production and the reactor biomass concentration (MLSS) that has to be chosen in adjustment to the subsequent settling stage. The design accounts for the weakest link in the biological treatment chain, setting the required SRT according to the expected growth rate of nitrifiers. Both ATV-A-131 and METCALF & EDDY include safety factors (SF) in the procedure for the calculation of the required SRT for nitrification (Equ. 1 and 2). The safety factor used in the ATV-A-131 standard accounts for the variability of ammonium and dissolved oxygen, the alkalinity and the peak loading rates and varies depending on the plant size between 1.80 (for plants < 20,000 p.e.) and 1.45 (for plants > 100,000 p.e.) (Equ.1). The safety factor used by METCALF & EDDY accounts for peak loading rates only while the required nitrogen concentration in the effluent ($N_{EFF}$), the dissolved oxygen concentration in the aeration tank (DO) and endogenous decay coefficients for nitrifying organisms ($k_{dN}$) are separately incorporated (Equ. 2).

$$SRT_{N,AER} = SF \cdot \frac{1}{\mu_N} = SF \cdot 1.6 \cdot \frac{1}{0.47} \cdot 1.103^{(T-15)} \qquad \text{Equ. (1)}$$

$$SRT_{N,AER} = SF \cdot \frac{1}{\mu_{N,\max} \cdot 1.07^{(T-20)} \cdot \left( \frac{N_{EFF}}{K_N \cdot 1.053^{(T-20)} + N_{EFF}} \right) \cdot \left( \frac{DO}{K_O + DO} \right) - k_{dN} \cdot 1.04^{(T-20)}} \qquad \text{Equ. (2)}$$

ATV-A-131 combines the default nitrifier growth rate with a further safety factor of 1.6 for oxygen transfer limitations and wash-out prevention. The temperature influence on nitrification rate is given in relation to a reference temperature of 15°C (Equ. 1). METCALF & EDDY account for the temperature dependence of nitrification by adjusting the terms for the maximal growth rate of nitrifying organisms ($\mu_{N,max}$), the half velocity constant for ammonium ($K_N$) and the endogenous decay coefficient for nitrifying organisms $k_{dN}$ in reference to a temperature of 20°C (Equ. 2).

For both design approaches, temperature correction is only valid in a small range out of reference. The use of temperature correction factors at deviations >10°C from the reference temperature may lead to invalid SRTs (Metcalf & Eddy, 2003). Especially in warm climate regions, the information on nitrifier growth for design is still afflicted with uncertainty because most available information originates from temperate and cold climatic conditions (EPA, 1993). Due to this uncertainties and the enormous impact on activated sludge design Melcer *et al.* (2003) and Metcalf & Eddy (2003) recommend in-plant testing for the correct determination of the maximum specific growth rate of nitrifying bacteria.

*Excess sludge production.* As central design parameter and as important operational factor, the estimation of excess sludge production is of major importance. The excess sludge production of the ATV-A-131 (Equ. 3) and the METCALF & EDDY (Equ. 4) guidelines show many similarities. Both approaches include terms for the heterotrophic yield, the heterotrophic decay, the cell debris and the inert organic and inert mineral solid fraction. For nitrifying activated sludge plants, METCALF & EDDY include an additional term for the sludge production from nitrifier biomass (not shown due to limited impact on sludge production).

$$SP_{d,X,TSS} = \underbrace{Q_d \cdot C_{BOD} \cdot \left( Y_H \right.}_{\text{heterotrophic yield}} \underbrace{\left. - \frac{(1-b) \cdot k_{dH} \cdot f_T \cdot Y_H \cdot SRT}{1 + k_{dH} \cdot f_T \cdot SRT} \right)}_{\text{heterotrophic decay, cell debris}} + \underbrace{Q_d \cdot a \cdot X_{TSS}}_{\text{inert organic and mineral solids}} \qquad \text{Equ. (3)}$$

$$SP_{d,X,TSS} = \underbrace{Q_d \cdot (S_0 - S) \cdot \left[ Y_H \right.}_{\text{heterotrophic yield}} \underbrace{\left. - \frac{(1-b) \cdot k_{dH} \cdot f_T \cdot Y_H \cdot SRT}{1 + k_{dH} \cdot f_T \cdot SRT} \right]}_{\text{heterotrophic decay, cell debris}} + \underbrace{Q_d \cdot X_{nbVSS} + Q_d \cdot X_{iTSS}}_{\text{inert organic and mineral solids}} \qquad \text{Equ. (4)}$$

Differences can be found also with respect to the inflowing substrate. The ‘classic’ ATV-A-131 guideline, which forms the basis of the analysis in this work, is a BOD-based approach whereas METCALF & EDDY is a COD-based approach. The latest version of ATV-A-131 (ATV-DVWK, 2000) also provides a COD-based approach in Annex 2/3. COD based approaches require a more detailed wastewater characterisation because only a part of the total COD is biodegradable. Both approaches use total influent substrate concentrations but METCALF & EDDY subtract the soluble effluent substrate concentration (S) from the influent substrate concentration ($S_0$). S is calculated as a function of the SRT and kinetic coefficients of (heterotrophic) growth and decay. Generally it can be noted, that this fraction has only small influences on the total excess sludge production. With regard to the inert organic and mineral solids as shown in Equ. 3 and 4, the ATV-A-131 approach assumes that 60% (coefficient ‘a’) of the total suspended solids in the influent ($X_{TSS}$) are either inert organic ($X_{nbVSS}$) or inert mineral ($X_{iTSS}$) (Equ. 5; Hartwig, 1993; ATV-DVWK, 2000). In METCALF & EDDY both fractions are based on measurements. The $X_{nbVSS}$ fraction can be determined by measurements of the influent total and soluble BOD and COD and $X_{VSS}$ concentrations, respectively. The inert mineral fraction $X_{iTSS}$ is based on the measurement of the volatile and total suspended solids concentration of the influent. The relation between the inert organic and mineral solids of ATV-A-131 and METCALF & EDDY is given by:

$$0.60 \cdot X_{TSS} = X_{nbVSS} + X_{iTSS} \qquad \text{Equ. (5)}$$

Table 1 summarizes the default parameter values that are used by the two design approaches.

**Table 1.** Comparison of parameter values and temperature correction factors of ATV-A-131 and METCALF & EDDY for the calculation of excess sludge production (ATV-DVWK, 2000; Metcalf & Eddy, 2003; Hartwig, 1993).

| Term | Parameter | ATV-A-131 | METCALF & EDDY |
|---|---|---|---|
| $Y_H$ | heterotrophic yield coefficient | 0.75 kg $X_{TSS}$/kg $C_{BOD}$ | 0.40 kg $X_{VSS}$/kg $C_{bCOD}$ |
| b | cell debris coefficient | 0.20 | 0.15 |
| $k_{dH}$ | heterotrophic decay coefficient | 0.17 kg $X_{TSS}$/kg $X_{TSS}\cdot$d | 0.12 kg $X_{VSS}$/kg $X_{VSS}\cdot$d |
| $f_T$ | temperature correction factor for $k_{dH}$ | $1.072^{(T-15)}$ | $1.04^{(T-20)}$ |
| a | inert organic and mineral solids coefficient | 0.60 kg /kg $X_{TSS}$ | - |
| $X_{nbVSS}$ | inert organic suspended solids | - | measured |
| $X_{iTSS}$ | inert mineral suspended solids | - | measured |

## COD mass balance

Figure 1 shows the results of the COD mass balance of the investigated WWTP. 39% of the inflowing COD to the primary clarifier was removed via the primary sludge and 32% of the COD was removed by oxygen uptake and 15% by excess sludge removal. Another 8% of the inflowing COD left the system via the effluent. The overall balance of the whole plant was 6%.

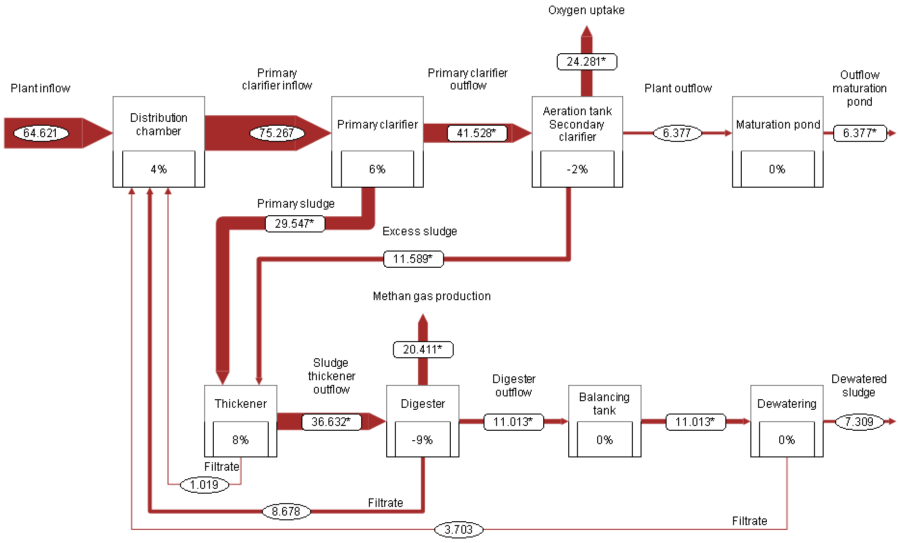


**Figure 1:** COD mass balance of the investigated sewage treatment plant. The listed flows are in kg COD/day. Values inside the boxes represent the balance results in % (eDAB® full plant view).

Compared to values from literature (ATV-DVWK, 2000; Cao *et al.*, 2003), the amount of COD removed via primary sludge was slightly higher at the observed treatment plant. The observed BOD/COD ratio at the plant inflow was at a lower range indicating higher rates of inorganic or slowly degradable organic matter (Henze *et al.*, 2002; Melcer *et al.*, 2003). This is assumed to result from biodegradation in the sewer system due to the high wastewater temperatures (Raunkjær *et al.* 1995; Cao *et al.*, 2008). The COD removed by excess sludge was significantly lower than values reported in the literature whereas the overall COD load was at a comparable level (Nowak, 1995; Cao *et al.*, 2008). Further, the COD-mass balance resulted in significant differences to the excess sludge production estimated by ATV (+20%) and METCALF & EDDY (+12%) using the default values as described in Table 1. Nowak *et al.* (1999) suggest varying the concentration of particulate inert organics in the influent ($X_{nbVSS}$) until the observed excess sludge production from the mass balance is in accordance with the calculated result. In activated sludge systems with high SRT's, the heterotrophic decay rate $k_{dH}$ is the second variable which was suggested to be varied until the calculated results are equal to the measured data (Nowak *et al.*, 1999). Also Petersen *et al*. (2002) confirm that a change of the influent $X_{nbVSS}$ fraction is one of the most appropriate tools to adapt the sludge production in the system during a steady state model calibration.

## Parameter adaptation

As describe above in Equ. 5, the inert solid fraction in ATV-A-131 is assumed to be 60% of the inflowing total suspended solids ($a \cdot X_{TSS}$) and no further distinction between inert organic as $X_{nbVSS}$ or inert mineral as $X_{iTSS}$ is foreseen. The investigated plant showed that the proportion of the inert solids (factor 'a') varied between 30 and 50% during steady state conditions. Hence, coefficient 'a' has been reduced. Further, to account for higher metabolic turnover under higher temperatures the heterotrophic decay rates have been increased for ATV-A-131 and for METCALF & EDDY, respectively. A $k_{dH}$ of 0.20 is given as the upper limit by Metcalf & Eddy (2003). Table 2 gives an overview on the parameter adaptation to achieve optimal data fit.

**Table 2.** Adaptation of particulate, nonbiodegradable fractions and the heterotrophic decay rates.

| **Design guidelines** | **Parameter** | | | |
|---|---|---|---|---|
| | a | | $k_{dH}$ | |
| | default | adapted | default | adapted |
| ATV-A-131 | 0.60 | 0.50 | 0.17 | 0.20 |
| METCALF & EDDY | | | 0.12 | 0.20 |

Figure 2 shows the results of the adapted ATV-A-131 excess sludge calculation in comparison to the results using default values and the measured excess sludge production. The adaptation resulted in a difference of approx. 13% to the default calculation which corresponds to 2,000 kg $X_{TSS}$/day.

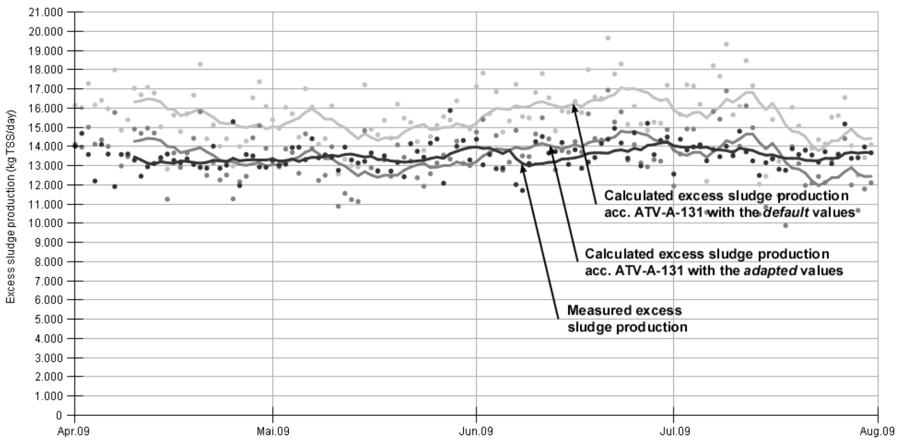


**Figure 2:** Observed and calculated sludge production at the investigated sewage treatment plant according to ATV-A-131. The calculations have been carried out with the default and the adapted values from Table 2.

Figure 3 shows the excess sludge production according to METCALF & EDDY in contrast to the measured production. The adaptation of the heterotrophic decay rate from 0.12 to 0.20 results in a lower calculated excess sludge production of about 1,200 kg $X_{TSS}$/d (9 %).

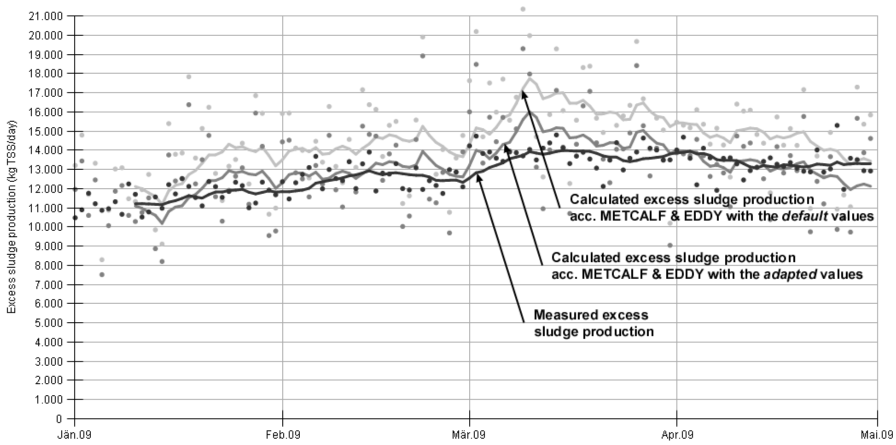


**Figure 3:** Observed and calculated sludge production at the investigated sewage treatment plant according to METCALF & EDDY. The calculations have been carried out with the default and the adapted values from Table 2.

## CONCLUSIONS

The ATV-A-131 and the METCALF & EDDY design approaches show relevant differences for practical application in warm climates. Whereas ATV-A-131 uses a default growth rate with temperature correction for SRT determination, more detailed parameter estimation is foreseen by METCALF & EDDY. Further, the influent characterisation assumed by ATV-A-131 has to be adapted for inert solids to account for extend biodegradation in the sewers of warm climates. In comparison, the inert fractions and the readily biodegradable fractions are to be measured for the METCALF & EDDY procedure. As result, the METCALF & EDDY default application resulted in lower deviation to the mass balance results in terms of excess sludge production. However, with the adaptation of the heterotrophic decay rate ($k_{dH}$) for both approaches and the inert organic and mineral solids fraction ($a \cdot X_{TSS}$) additionally for ATV-A-131, a good fit to the observed excess sludge production could be achieved for both design approaches. Using mass balancing based on full scale plant data under comparable conditions is a promising option for the application of the proven ATV-A-131 and METCALF & EDDY design guidelines in warm climates.

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