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# Development of a Plant-Wide Steady-State Wastewater Treatment Plant Design and Analysis Program

Dissertation for partial fulfilment of the requirement for the degree of

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This dissertation involved the development of design and analysis program for municipal wastewater treatment plants. In this program, steady-state models for various wastewater treatment unit processes are linked together to form a holistic plant-wide design, system sizing and performance analysis program. Additional functionalities developed for this program include a wastewater characterisation component and capacity estimation tool.

# Declaration

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# List of Acronyms and Symbols

| | |
|---|---|
| ˚C | Degrees Celsius |
| $\mu_{Am20}$ | Maximum specific growth rate of nitrifiers at 20°C |
| $\mu_{AmT}$ | Maximum specific growth rate of nitrifiers at design temperature (/d) |
| 1DFT | Idealised 1-Dimensional Flux Theory |
| 4BPHO | 4-Stage Bardpenpho |
| 5BPHO | 5-Stage Bardenpho |
| | |
| AD | Anaerobic digestion (or digester) |
| ADWF | Average dry weather flow |
| AE | Aerobic reactor |
| AeroD | Aerobic digestion (or digester) |
| AGS | Activated Granular Sludge |
| Alk | Alkalinity (as mg$CaCO_3$/L) |
| AN | Anaerobic reactor |
| ANn | Number of anaerobic reactors in series |
| aRec (or a) | a-Recycle, aerobic reactor to anoxic reactor |
| AS | Activated sludge |
| ASM1 | Activated Sludge Model Number 1 |
| ASM2 | Activated Sludge Model Number 2 |
| ASM2d | Activated Sludge Model Number 2d |
| ASM3 | Activated Sludge Model Number 3 |
| AX1 | Primary anoxic reactor |
| AX2 | Secondary mainstream anoxic reactor |
| AX3 | Secondary underflow anoxic Reactor |
| AxAeD | Anoxic-aerobic digestion (or digester) |
| | |
| BEPR | Biologically enhanced phosphorus removal |
| $BOD_5$ | 5 day Biochemical Oxygen Demand |

| | |
|---|---|
| BNR | Biological nutrient removal |
| BPO | Biodegradable particulate organics (mgCOD/L or mgVSS/L) |
| BSO | Biodegradable soluble organics (mgCOD/L) |
| C | Carbon |
| Ca | Calcium |
| $CaCO_3$ | Calcium carbonate |
| CapEst | Capacity Estimation |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| COD | Chemical oxygen demand |
| $C_XH_YO_ZN_AP_B$ | Biomass empirical composition |
| d | Day |
| DAF | Dissolved air flotation |
| DFData | Diurnal Flow Data Wastewater Characterisation Method |
| DFP | Diurnal flow pattern |
| DO | Dissolved oxygen concentration (mgO/L) |
| $DO_a$ | Dissolved oxygen concentration (mgO/L) in the a-recycle |
| $DO_r$ | Dissolved oxygen concentration (mgO/L) in the r-recycle |
| $DO_s$ | Dissolved oxygen concentration (mgO/L) in the s-recycle |
| $D_{p1}$ | Denitrification potential in primary anoxic reactor |
| $D_{p3}$ | Denitrification potential in secondary underflow anoxic reactor |
| DSVI | Diluted Sludge Volume Index (ml/gTSS) |
| E | Fraction of the biodegradable COD converted to biomass |
| $EqN_{n1}$ | Equivalent nitrate load on primary anoxic reactor (mgN/L) |
| $EqN_{n3}$ | Equivalent nitrate load on secondary underflow anoxic reactor (mgN/L) |
| F/M | Food to Microorganism ratio |

| | |
|---|---|
| $f_{ae}$ | Aerobic mass fraction |
| $f_{AN}$ | Anaerobic mass fraction |
| $f_{at}$ | Active fraction of active biomass with respect to total suspended solids concentration |
| $f_{av}$ | Active fraction of active biomass with respect to volatile suspended solids concentration |
| $f_c$ | Carbon (C) to mass (VSS or molar mass) ratio |
| $f_{cv}$ | COD to mass (VSS or molar mass) ratio |
| $f_{EG}$ | Endogenous residue fraction of PAOs |
| $f_{EH}$ | Endogenous residue fraction of OHOs |
| $f_H$ | Hydrogen (H) to mass (VSS or molar mass) ratio |
| $f_{ii}$ | VSS to TSS ratio of the influent wastewater (mgVSS/mgTSS) |
| $f_n$ | Nitrogen (N) to mass (VSS or molar mass) ratio |
| $f_o$ | Oxygen (O) to mass (VSS or molar mass) ratio |
| $FO_c$ | Flux of daily carbonaceous oxygen demand (kgO/d) |
| $FO_d$ | Flux of daily oxygen demand reduced by denitrification (kgO/d) |
| $FO_n$ | Flux of daily oxygen demand for nitrification (kgO/d) |
| $FO_{td}$ | Flux of daily oxygen demand adjusted for denitrification (kgO/d) |
| $f_p$ | Phosphorous (P) to mass (VSS or molar mass) ratio |
| $f_{PS'up}$ | Fraction of unbiodegradable particulate COD with respect to the total COD of primary sludge |
| F-RBCOD | Fermentable readily biodegradable COD (mgCOD/L) |
| $f_{S'up}$ | Fraction of unbiodegradable particulate COD with respect to the total influent COD of raw or settled wastewater |
| $f_{S'us}$ | Fraction of unbiodegradable soluble COD with respect to the total influent COD of raw or settled wastewater |
| FSA | Free and saline ammonia (mgN/L) |
| $f_{Sb's}$ | Fraction of biodegradable organics with respect to the total influent COD of raw or settled wastewater |
| FWA | Flow-weighted average |
| $f_{x1}$ | Primary anoxic mass fraction |

| | |
|---|---|
| $f_{x1m}$ | Maximum primary anoxic mass fraction allowed |
| $f_{x2}$ | Secondary anoxic mass fraction (mainstream anoxic reactor) |
| $f_{x3}$ | Secondary anoxic mass fraction (underflow anoxic reactor) |
| $f_{xbgp}$ | Total phosphorous content of PAOs |
| $f_{xbgpp}$ | Total polyphosphate content of PAOs |
| $f_{xm}$ | Maximum unaerated mass fraction |
| $f_{xt}$ | Total unaerated mass fraction |
| $f_{xt,min}$ | Minimum total unaerated mass fraction |
| | |
| g | Gram |
| GravThk | Gravity thickener |
| | |
| H | Elemental hydrogen |
| h | Hour |
| $HCO_3^-$ | Bi-carbonate |
| HRT (or $R_h$) | Hydraulic retention time (days) |
| | |
| InOrg | Inorganic |
| ISetS | Inorganic settleable solids (mgISetS/L) |
| ISS | Inorganic suspended solids (mgISS/L) |
| ISuspS | Inorganic suspended solids (mgISS/L) |
| IWA | International Water Association |
| | |
| JHB | Johannesburg |
| | |
| $J_L$ | Liming flux (kgTSS/$m^2$/h) |
| | |
| L | Litre |
| | |
| MaxT | Maximum temperature (˚C) |

| | |
|---|---|
| MBR | Membrane biological reactor |
| $MePO_3$ | Polyphosphate |
| Mg | Magnesium |
| mg | Milligram |
| $MgNH_4PO_4.6H_2O$ | Struvite |
| MinT | Minimum temperature (˚C) |
| ML | Mega Litre ($10^6$ L or $10^3$ $m^3$) |
| MLE | Modified Ludzack–Ettinger activated sludge system configuration |
| MLSS | Mixed liquor suspended solids (mgSuspS/L) |
| $MX_{BG}$ | Mass of active PAO in the AS system (kgVSS) |
| $MX_{BH}$ | Mass of active OHO in the AS system (kgVSS) |
| $MX_{EH}$ | Mass of endogenous OHO in the AS system (kgVSS) |
| $MX_{EG}$ | Mass of endogenous PAO in the AS system (kgVSS) |
| $MX_U$ | Mass of unbiodegradable particulate organics in the AS system (kgVSS) |
| $MX_v$ | Mass of volatile suspended solids in the AS system (kgVSS) |
| $MX_{Io}$ | Mass of inorganic suspended solids in the AS system (kgISS) |
| $MX_t$ | Mass of total suspended solids in the AS system (kgTSS) |
| | |
| n | Hindered settling parameter ($m^3$/kg) |
| N | Elemental nitrogen |
| $N_2$ | Nitrogen gas |
| $N_{ae}$ | Effluent ammonia concentration (mgN/L) |
| $N_c$ | Nitrification capacity of the aerobic reactor (mgN/L) |
| ND | Nitrification-denitrification |
| NDBEPR | Nitrification-denitrification biologically enhanced phosphorus removal |
| $NH_4^+$ | Ammonium (mgN/L) |
| $N_{ne}$ | Effluent nitrate concentration (mgN/L) |
| $NO_3^-$ | Nitrate (mgN/L) |
| $N_{ouse}$ | Organic unbiodegradable soluble effluent nitrogen (mgN/L) |

| | |
|---|---|
| $N_{ousi}$ | Organic unbiodegradable soluble influent nitrogen (mgN/L) |
| $N_{ti}$ | Total Kjeldahl Nitrogen in the influent wastewater(mgN/L) |
| $N_{te}$ | Total Kjeldahl Nitrogen nitrogen in the effluent wastewater(mgN/L) |
| | |
| O | Elemental oxygen |
| OHO | Ordinary heterotrophic organism |
| OP | Ortho-phosphates (mgP/L) |
| OrgN | Organic nitrogen (mgN/L) |
| OrgP | Organic phosphorous (mgP/L) |
| Ortho-P | Ortho-phosphates (mgP/L) |
| OUR | Oxygen Utilization Rate (mgO/L/h) |
| $OUR_c$ | Carbonaceous oxygen utilization rate (mgO/L/h) |
| $OUR_n$ | Nitrification oxygen utilization rate (mgO/L/h) |
| $OUR_{td}$ | Total oxygen utilization rate (mgO/L/h) adjusted for denitrification |
| | |
| P | Elemental phosphorus |
| $P_{ae}$ | Effluent ortho-phosphates (mgP/L) |
| PAO | Phosphorus accumulating organism |
| $p_{CO2}$ | Partial pressure of carbon dioxide ($CO_2$) |
| PDWF | Peak dry weather flow |
| pH | Activity of hydrogen ions |
| PP | Polyphosphate |
| PS | Primary sludge |
| PST | Primary settling tank |
| $P_{te}$ | Total effluent phosphorous (mgP/L) |
| PWSSD | Plant-Wide Steady-State Design |
| PWWF | Peak Wet Weather Flow |
| | |
| Q | Flow rate (L/d) |
| $Q_e$ | Effluent flow rate (L/d) |

| | |
|---|---|
| $Q_i$ | Influent flow rate (L/d) |
| $Q_P$ | Primary sludge flow rate (L/d) |
| $Q_w$ | Sludge waste flow rate (L/d) |
| | |
| $R_{act}$ | Actual, on-site, oxygen transfer rate of aerators (kgO/kWh) |
| RBCOD | Readily biodegradable COD (mgCOD/L) |
| $R_h$ (or HRT) | Hydraulic retention time (days) |
| rRec (or r) | r-Recycle, anoxic reactor to anaerobic reactor |
| $R_s$ (or SRT) | Solids retention time (days) |
| RSA | Republic of South Africa |
| $R_{std}$ | Standard oxygen transfer rate of aerators (kgO/kWh) |
| | |
| s | Second |
| $S_b$ | Biodegradable organics in reactor (mgCOD/L) |
| SBCOD | Slowly biodegradable COD (mgCOD/L) |
| $S_{bp}$ | Biodegradable particulate organics (mgCOD/L) |
| $S_{bs}$ | Biodegradable soluble COD (mgCOD/L) |
| $S_f$ | Nitrification safety factor |
| SHC1 | Solids handling criterion 1 |
| SHC2 | Solids handling criterion 2 |
| $SOUR_e$ | Specific oxygen utilisation rate (mgO/gVSS/h) |
| sRec (or s) | s-Recycle (SST underflow recycle) |
| SRT (or $R_h$) | Sludge age or sludge retention time (measured in days) |
| SST | Secondary settling tank |
| SSVI | Stirred Sludge Volume Index (gTSS/L) |
| $S_{ti}$ | Total influent COD concentration (mgCOD/L) |
| $S_{upi}$ | Influent unbiodegradable particulate organics as COD (mgCOD/L) |
| $S_{usi}$ | Influent unbiodegradable soluble COD (mgCOD/L) |
| SVI | Sludge Volume Index (mL/gTSS) |

| | |
|---|---|
| T | Temperature (˚C) |
| TKN | Total Kjeldahl Nitrogen (mgN/L) |
| TOC | Total organic carbon (mgC/L) |
| TOD | Total oxygen demand (kgO/d) |
| $TOD_{Amp}$ | Amplitude of TOD wave |
| TP | Total phosphorus (mgP/L) |
| TSetS | Total suspended solids (mgTSS/L) |
| TSS | Total suspended solids (mgTSS/L) |
| TSuspS | Total suspended solids (mgTSS/L) |
| | |
| UCT | University of Cape Town |
| UPO | Unbiodegradable particulate organics (mgCOD/L or mgVSS/L) |
| USO | Unbiodegradable soluble organics (mgCOD/L) |
| | |
| V | Volume |
| $V_0$ | Initial settling velocity (m/h) |
| VB | Visual Basic |
| VBA | Visual Basic for Applications |
| VFA | Volatile fatty acid (mgCOD/L) |
| VSetS | Volatile settleable solids (mgVSS/L) |
| VSS | Volatile suspended solid (mgVSS/L) |
| VSuspS | Volatile suspended solid (mgVSS/L) |
| WAS | Waste activated sludge |
| WRG | Water Research Group |
| WW | Wastewater |
| WWChar | Wastewater characterisation |
| WWTP | Wastewater treatment plant |
| | |
| $X_{BG}$ | Active biomass of the PAOs (mgVSS/L) |
| $X_{BH}$ | Active biomass of the OHOs (mgVSS/L) |

| | |
|---|---|
| $X_{EG}$ | Endogenous residue of the PAOs (mgVSS/L) |
| $X_{EH}$ | Endogenous residue of the OHOs (mgVSS/L) |
| $X_U$ | Unbiodegradable organics concentration in the AS system (mgVSS/L), settleable and non-settleable |
| $X_{U,Inf,NSet}$ | Non-settleable unbiodegradable particulate organics concentration in the AS system (mgVSS/L) |
| $X_{U,Inf,Set}$ | Settleable unbiodegradable particulate organics concentrationin the AS system (mgVSS/L) |
| $X_{Io}$ | Inorganic suspended solids concentration in the AS system (mgISS/L) |
| $X_{Ioi}$ | Influent inorganic suspended solids concentration (mgISS/L) |
| $X_s$ | Total suspended solids concentration underflow, s-recycle (mgVSS/L) |
| $X_t$ | Total suspended solids concentration (mgVSS/L) |
| $X_v$ | Volatile suspended solids concentration (mgVSS/L) |
| $Y_H$ | Ordinary heterotrophic cellyield coefficient (gAVSS/gCOD) |
| $Z_{AD}$ | Acidogens biomass concentration (gCOD/L) |
| $Z_{ED}$ | Acidogens endogenous biomass concentration (gCOD/L) |

# Abstract

Models are used as prognostic and diagnostic tools in order to design, analyse and optimise the biological and physical processes in a wastewater treatment plant (WWTP). This is done in order to save time and money and to improve the understanding of the behaviour of the treatment system.

There are two categories of models in wastewater (WW) treatments, steady-state and dynamic models. (i) Dynamic models consist of sophisticated mathematical solvers and are structured for the optimisation of WWTP's and not for system sizing. (ii) Steady-state models comprise simple and explicit algebraic equations. With these equations, high-level answers are found easily and quickly but with a much lower level of input information. Hence, steady-state models allow for system sizing and are powerful pre-processors for dynamic models. They can generate the overall WWTP scheme, main system defining parameters, and the initial conditions for starting the dynamic simulation. Currently, there is a lack of a plant-wide steady-state design (PWSSD) program. Numerous steady-state models for the different unit processes exist; however, they are yet to be integrated and presented in one holistic software package for the plant-wide design (and analysis) of WWTP. The availability of such program will be extremely beneficial to WWTP engineers as it can be used as a standalone tool for the steady-state design, system sizing and capacity estimation, or as a pre-processor to generate the plant-wide WWTP initial conditions for dynamic simulation.

To fill the above-mentioned software gap, a PWSSD program was developed within the Excel/VBA environment. The developed PWSSD program integrates various steady-state wastewater treatment models with an expert-guided user-interface, thereby creating a platform for step-by-step assisted interaction and exploration of the models. This program draws upon a large body of literature regarding the modelling of wastewater treatment processes. The current version of the program (1) caters for commonly used AS configurations (MLE, JHB and UCT) in South Africa. The steady-state AS models are holistically linked to important upstream and downstream biological and non-biological treatment processes. These unit processes include: flow balancing of raw wastewater (BalTank), primary settling (PST) and secondary settling (SST), mechanical surface aeration, anoxic-aerobic (AxAeD) digestion of waste activated sludge (WAS), and anaerobic digestion (AD) of primary sludge (PS) and WAS, either separately or blended.

Additional design, analysis, and optimisation tools have been developed and are available in the program. These include a wastewater characterisation (WWChar) component to characterise wastewater for different data level scenarios, a hypothetical cost and system modularisation tool, a capacity estimation (CapEst) tool to determine the maximum influent average dry weather flow (ADWF) capacity, and graphical summaries for the plant-wide design and COD, N, P, C and total oxygen demand (TOD=COD+4.57TKN) mass balances. The program is not limited to these items. It was developed with a flexible structure; addition of more steady-state models or tools is permissible. Future versions of the program will include

aspects such as membrane solid-liquid separation for the AS system, diffused bubble aeration for the aeration system, dissolved air flotation for WAS thickening, and the 4-stage and 5-stage Bardenpho AS configurations.

The holistic nature of this program allows a complete plant-wide WWTP design to be completed within a few minutes, for the generation of meaningful information that aids high-level decision making, such as system sludge age, reactor TSS concentration, inter-reactor and recycle flows, SST surface area, aeration power consumption, and AD biogas generation. It is envisioned that this program can be incorporated alongside dynamic simulation software as a pre-processor for the use of dynamic models. In future editions, with a simple click of a button, the outputs from the steady-state models can be transferred seamlessly to internal or external dynamic models where the systems' performance can be evaluated under dynamic loading.

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# 1. Introduction

## 1.1 The Importance of Wastewater Treatment and Development of Wastewater Treatment Models

Wastewater treatment is a vital chain in the urban water cycle. The purpose of a wastewater treatment plant (WWTP) is to treat municipal and industrial wastewater (WW) to an acceptable effluent quality, devoid of excess organics, ammonia, and nitrogen (N) and phosphorous (P) nutrients. Doing so will protect downstream water bodies from being harmfully contaminated. The consequences of polluting a water body is the loss of aquatic life, upsurge of eutrophication, and even loss of human life due to waterborne diseases. Therefore, WWTPs are crucial in protecting the urban water cycle and ensuring that water resources are maintained for future generations.

WWTPs are complex systems that amalgamate numerous engineering fields and areas of knowledge. The field of wastewater treatment has grown tremendously from simple fill and draw aeration systems to modern activated sludge systems that comprise of intricate interrelated physical-chemical-biological processes (Makinia, 2010) which are mediated by sophisticated civil, electrical, and mechanical systems that treat wastewater to exceptionally high standards while consuming as little resources as possible. The modelling of the activated sludge system and the various unit processes linked to it has grown with the development of wastewater treatments systems. The traditional models (pre-1980s) had a black-box approach, where the actual biological and physical processes were not fully understood. These models were based on empirical relationships, experiences, and the rule-of-thumb which were established by recognising important parameters that seemed to describe behavioural patterns and observations on the system (van Loosdrecht *et al.*, 2008). These parameters such as the F/M ratio, $BOD_5$, Load Factor, can be used to design the wastewater treatment system and are not inherently incorrect, but are only appropriate depending on the purpose and requirements of the model (van Loosdrecht *et al.*, 2008). For current wastewater treatment systems, in order to meet the modern day environmental pressures, stringent effluent standards, and the economic costs of starting and running a WWTP, the traditional models do not provide the necessary depth and accuracy that are needed by WWTP modellers and designers.

The inaccuracies and inadequacies of the traditional models prompted improvements into the design procedures and a shift to models that are based on the behavioural patterns of the microorganism mediating the wastewater treatment processes (Ikumi *et al*., 2014a). The development of the activated sludge (AS) models (e.g. ASM1 by Henze *et al.* (1987); ASM2 by Henze *et al.* (1995); and ASM2D by Henze *et al.* (1999) etc.) was deemed as the most significant contribution for the modelling of biological wastewater processes (Makinia, 2010). These models unified wastewater treatment concepts and standardised the way the processes are modelled, thus allowing them to be coded into computer simulation programs where multiple, complex mathematical equations could be solved with a simple click of a button.

## 1.2 Current State of Wastewater Treatment Modelling

A model is defined as a representation of a real object, an environment, or a process. A numerical model is a specific type of model that uses mathematical equations to represent the reality. Numerical models, combined with computers, are powerful tools that have the ability to solve complicated mathematical equations, and to summarise and increase the understanding of complex interaction and systems (Vanhooren *et al.*, 2003). Hug *et al.*, (2009) identify three distinct usages of a model: prognostic, diagnostic and educational (Figure 1.1). Models are used to predict future results (prognostic), to understand the mechanisms or processes that are modelled (diagnostic), or to communicate knowledge between users (educational).

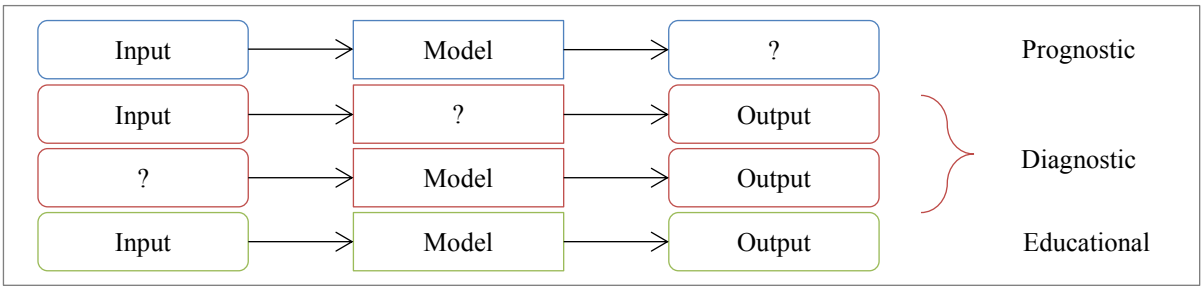



**Figure 1.1: Three distinct model uses** (adapted from Hug *et al.*, 2009)

In consulting engineering, WWTP models (e.g. activated sludge models) are used as prognostic and diagnostic tools in order to design and optimise the biological and physical processes in a WWTP. They are used to predict the behaviour of the treatment system so that the system can be designed accordingly, and to investigate problem areas and conduct sensitivity analyses. Van Loosdrecht *et al.* (2008) identify that WWTP models are tools to save time and money and possibly to decrease risk. However, to attain these benefits the user must use the models effectively by (i) entering the correct inputs and model parameters, and (ii) use the appropriate model for the required task. Once this is achieved, only then can the model provide meaningful and quantitative outputs to aid decision making (van Loosdrecht *et al.*, 2008). Therefore, these models are invaluable assets for operators, designers, and researchers.

Dynamic AS models are not always correctly applied. These models as explained by Makinia (2010: 57) comprise of "*numerous internal interactions between state variables and dynamic behaviour of input variables and local conditions*". Dynamic models require much exactly defined high-level of information such as reactor sizes, initial reactor concentrations, inter-connecting flow rates, influent wastewater (WW) characteristics, and kinetic and stoichiometric parameters (Ekama, 2009). This can make it difficult for prognostic or diagnostic tasks to be efficiently and correctly executed as this information is not always available – especially if only dynamic models are used.

Dynamic models are structured for the optimisation of WWTP's and if they are not used in this manner, but rather for system sizing and design, then the main problem loses focus and gaps in the knowledge and understanding of the dynamic models are covered by the simulation software (Ekama, 2009). These models, however useful they are, do not always provide the necessary information and at times can be too complicated for the design task. Thus, responsible modelling involves the familiarity of the purposes and structures of the models, which includes its limitations, calibration and validation procedures, and the uncertainties in its input parameters and model structure (Hug *et al.*, 2009). Responsible modelling does not involve only knowing "where the start simulation button is located". Responsible modelling cannot be achieved if there is a knowledge gap in the model user, and if the requirements for modelling are not met then there is an inefficient and incorrect application of the models (Takács *et al*., 2007). The issue is further exacerbated by the user-friendly nature of dynamic simulation software. The user-interface of modern day software and computer programs has a large impact on the success of the software; therefore, user-interfaces are made as user-friendly as possible so that navigation within the software is easy and enjoyable. This is problematic in that it masks the complexity of the models. For new model users or students, there is a likelihood of creating a mentality that real-world process and the functions of the models do not need to be understood because the modelling software seemingly understands it for them (Hug *et al.*, 2009).

Steady-state wastewater treatment models offer an alternative perspective for the modelling of wastewater treatment systems and can address the improper usage of the dynamic models. Steady-state models are powerful in the sense that they comprise of simple, explicit, algebraic equations that allow high-level answers to be found easily and quickly, but with much lesser input information (Ekama, 2009). In contrast, dynamic models require detailed input formation and sophisticated mathematical solvers. Steady-state models, however, are often overlooked due to their simplicity, even though they are extremely useful for the determining of WWTP size, capacity, and operating parameters. Steady-state models are therefore powerful pre-processors for dynamic models as they can generate the overall WWTP scheme, main system defining parameters, and major sources of plant data error, which should be known before dynamic models are used (Ekama, 2009).

Currently, there is a lack of a plant-wide steady-state design program. Numerous steady-state models for the different unit processes exist, however they are yet to be integrated and presented in one holistic design program. The availability of such program will be extremely beneficial to WWTP designers as a plant-wide steady-state design tool will be readily available to designers thus a custom design tool does not need to be created. In a broader perspective, the availability of such program can improve the reliability of the usage of dynamic models as the initial plant-wide conditions required for starting a dynamic simulation are generated efficiently and correctly with steady-state models.

## 1.3 Project Aims and Objectives

The aim of this project is to respond to the current state of wastewater treatment modelling and to address the deficiencies in the application of dynamic wastewater treatment models. To achieve this aim, a plant-wide steady-state design and analysis program is required. The purpose of this program is to improve the usage and understanding of steady-state WWTP models. With this program, WWTP design and analysis can be performed efficiently and effectively. Furthermore, high-level information for use in dynamic simulation is appropriately generated with steady-state models.

The program has various requirements. The various steady-state models have to be integrated with an expert-guided user-interface. This user-interface aims to create a platform of step-by-step assisted interaction and exploration of the steady-state models, and as well as a demonstration of the strength of the steady-state models. In doing so the usage and understanding of steady-state models can be improved

Commonly used WWTP plant configurations (MLE, JHB and UCT) need to be included in the program. The steady-state AS models is the centrepiece of the program. In-line with the movement towards plant-wide simulation and design, the AS models have to be linked holistically to important design and biological and non-biological unit processes. These include primary and secondary settling tanks, mechanical aeration and sludge digestion via anaerobic and anoxic-aerobic treatment systems. Additional tools and functionalities would be useful for the program, for example as a capacity estimation component and a hypothetical cost and unit process sizing function.

The program is not complete without a wastewater characterisation (WWChar) component for the characterisation of the raw WW, settled WW and primary sludge (PS). A varying quantity and level of data input makes WWChar a challenging process. The developed WWChar component must therefore be flexible, in order to allow for the characterisation of wastewater with varying data, in terms of quantity and quality.

The holistic nature of this program will allow for a complete plant-wide WWTP design to be completed within a few minutes, and for the generation of meaningful information to aid decision making. Through the interaction of the expert-guided user-interface, the program will offer designers a better foundation in WWTP modelling and a stronger understanding of the treatment processes. With this strength, designers can approach and use dynamic simulation models more efficiently and effectively.

It is envisioned that this steady-state design program can be incorporated alongside dynamic simulation software as a pre-processor for the use of dynamic models. In future editions, with a simple click of a button, the outputs from the steady-state models (such as flow rate, reactor sizes and mass fractions) can be transferred to the dynamic models where the systems' performance under dynamic loading can be evaluated.

The purpose of this project is summarised in the flow chart in Figure 1.2

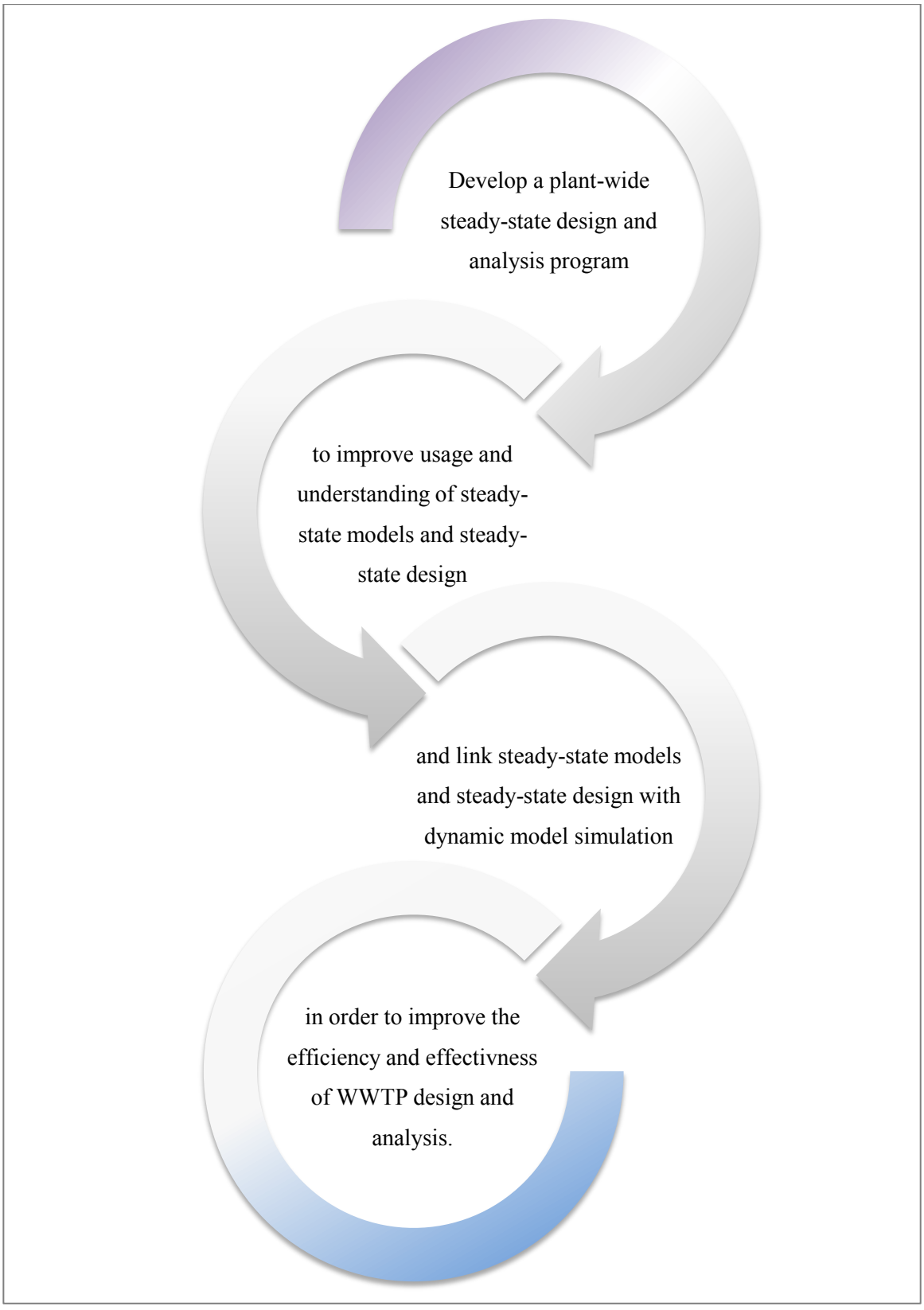



**Figure 1.2: Project objectives flow chart**

## 1.4 Thesis Structure

This thesis document consists of 10 Chapters, References, and Appendices. The introduction, detailing the background, problem, objectives, and thesis structure, is contained in Chapter 1.

Following Chapter 1, a literature review is presented in Chapter 2. Due to the nature of this project, this literature review is kept as succinct as possible and its purpose is to assimilate the various sources of information that is relevant for the models required in the plant-wide design and analysis program. The details regarding these models can be found in the original publications, summarised at the end of Chapter 2.

The design of the program is split into six parts: Program Design Part A to Part F. Each part is explained in its own chapter. In Chapter 3 Program Design Part A: Overview, a summary of the six parts is provided. This includes the purpose of each part, an overview of the information presented in each part, and the overall flow of the program design.

In Chapter 4 Program Design Part B: Program Skeleton, the technical details regarding the structure of the program is provided. Issues such as the programming language, the construction of user-interfaces, model computation, and data input are presented.

Following Chapter 4, the different design and analysis tools of the program are presented. This begins with Chapter 5 Program Design Part C: Wastewater Characterisation. Wastewater characterisation (WWChar) is an important process that is vital for the design and analysis of WWTPs; therefore, a WWChar component was developed and included in this program. Chapter 5 presents the WWChar component. The characterisation of the COD, N, P, C, and particulates (TSS, ISS) in the influent raw WW, settled WW, and PS is discussed. Issues in characterisation, the data requirements, and the different characterisation methods for different data scenarios are presented in this chapter.

With the wastewater characteristics known, the next step is the actual design and analysis of the WWTP. Chapter 6 Program Design Part D: Plant-Wide Steady-State Design, presents the various steady-state models available in the program. These steady-state models are presented in conjunction with their user-interfaces. These user-interfaces are an important aspect of the program as they allow for the interaction and exploration of the steady-state models. The focus of this chapter is how the steady-state models are used and assimilated together in order to form a plant-wide steady-state design (PWSSD). For the specific details, equations, and critiques of the models, the reader is directed to the original publications, which can be found in the references or in Chapter 2 Literature Review.

In addition to the WWChar and PWSSD, a capacity estimation (CapEst) tool was also developed. This is presented in Chapter 7 Program Design Part E: Capacity Estimation. With a set of wastewater characteristics created in the WWChar component, CapEst utilises the steady-state models in reverse to find the maximum influent average dry weather flow rate that the system can accommodate. This is a useful tool in that different bottleneck scenarios can be evaluated for a given WWTP.

Lastly, Chapter 8 Program Design Part F: Program Flow, concludes the Program Design Chapters. In Chapter 8, an overview of the entire program and the three components (WWChar, PWSSD, and CapEst) are linked together is discussed.

Following Chapter 8, the document is concluded with a discussion of the program (Chapter 9 Discussion), conclusions drawn from this project and the future work that is required for the program (Chapter 10 Conclusion).

The various sources of literature used for the development of the program and this document are presented in the References. The Appendices, which follows after, contains supplementary information for the Program Design chapters.

# 2. Literature Review

This literature review comprises of three parts, Section 2.1 to Section 2.3. The first part, Modelling Practices and Model Types, reviews the general state of WWTP modelling and aspects such as steady-state versus dynamic models, plant-wide modelling, and the currently available modelling software.

In the second part (Section 2.2), the topic of wastewater characterisation (WWChar) is reviewed. WWChar is an important process as it determines the organic load on the WWTP. Therefore, the consequence of an incorrect characterisation is that the WWTP's design capacity will be under or overestimated. This part of the literature review will review the current knowledge of wastewater characteristics and the level of detail required for WWTP design.

The third part (Section 2.3) reviews the current steady-state models. In order to develop the expert-guided plant-wide steady-state design (PWSSD) program, a firm understanding of the important parameters and the fundamental concepts of the steady-state models must be attained. This part of the literature review is an assimilation of the various steady-state models that are relevant for the PWSSD program and hence the focus of this part of the review will be the important principles and parameters that govern the steady-state models and the critical aspects to consider during the design process. The derivations, details, and development of the steady-state models can be found in the original sources. These sources are summarised at the end of this chapter.

## 2.1 Modelling Practices and Model Types

### 2.1.1 Differences between Steady-State and Dynamic Models

There are two distinct types of wastewater treatment models: steady-state, and dynamic models. Both types have the same underlying concepts but different levels of detail and structure. In the steady-state activated sludge (AS) model, the organic load is constant in terms of flow and characteristics and the system is modelled at a state of equilibrium, i.e. this implies that the excess sludge and the influent wastewater is constant in flow rate and composition (van Haandel & van der Lubbe, 2007). With this foundation, the steady-state AS model is governed by the slowest kinetic rate, and the bioprocesses linked to this rate determines the principle system design and operating parameters such as reactor volumes, sludge age, and recycle rates (Sötemann *et al.*, 2005a; Ekama & Wentzel, 2008a; Ekama, 2009). For example, the growth rate of the nitrifiers is slowest bioprocess in the AS system. Therefore, the sludge age must be long enough to ensure that the nitrifiers are not washed out of the system, i.e. exit faster than they can grow. The system volume is directly linked to the sludge age; therefore, the minimum system volume is determined by the growth rate of the nitrifiers. In contrast to the steady-state AS model, the dynamic AS models have varying flows and concentrations and thus time is required a system parameter (Ekama & Wentzel, 2008a). The state of completion of the

bioprocesses is therefore time dependent, and therefore, dynamic AS models are useful to evaluate and predict the time dependent response of the treatment system (Ekama & Wentzel, 2008a). The consequence of varying load conditions is an added model complexity and thus dynamic models are not suitable for system design and sizing. System parameters such as volume cannot be determined with dynamic AS models.

The steady-state AS models are based on the dynamic AS models, but only the slowest kinetic processes are considered and all faster processes have reached completion. Due to this simplification, the structure of the steady-state AS model comprises of simple and explicit algebraic equations (Ekama, 2009). This simplicity is advantageous in that the models can be computed easily with spreadsheet software, or even by hand, one can therefore check easily and quickly the integrity of a WWTP design. The explicit calculations force the model user to focus on the fundamentals of the models and thus knowledge gaps in the understanding of the models are easily identified (Ekama, 2009). In dynamic AS models, the modelling of the dynamic behaviour requires significantly more computational power as the models comprise of complex differential equations, which necessitate numerical integration to solve (Ekama, 2009). Depending on the software, computational strength of the computer, and the sensitivity required, the processing of dynamic models can take a few minutes to a few hours, or even days. Furthermore, in the current modelling software, a function to change the input parameters during the simulation does not exist. Therefore, if an input parameter is incorrect, the simulation has to be stopped and restarted. This can be problematic if the simulation requires a few hours. To avoid this problem, Ekama (2009) emphasises that good modelling skill, understanding, and experience is required to utilise the dynamic models effectively and correctly. If the basics cannot be managed with hand calculations, as with the steady-state models, then dynamic models should not be used (Ekama, 2009).

In order to run a dynamic simulation, a completely designed and sized AS system is required. Dynamic AS models are therefore not suitable for application as a design tool (van Haandel & van der Lubbe, 2007; Ekama, 2009). If they are used for this purpose, then the model user is easily distracted by the detailed input requirements, are driven to answer questions at a low-level of detail, and supply information that is often irrelevant for system sizing and design (Ekama, 2009). Worse, the dynamic AS models end up being used in a trial and error manner, the input parameters being tweaked until satisfactory answers are generated. This approach can lead to serious design errors (Ekama, 2009). van Haandel & van der Lubbe (2007) explain that the main objective of the dynamic AS models is to increase the knowledge of the system behaviour. Hence, for the purpose of simulation, a large number of variables and parameters are included in the models. This complexity is vital for evaluating the systems response to disturbances and control measures; however, this complexity does not allow for an analytical design solution (van Haandel & van der Lubbe, 2007). Therefore, steady-state models, instead of dynamic models, should be used for the design and sizing of the WWTP because the explicit steady-state equations allow for that. Reactor concentrations, reactor volumes, recycle ratios, mass fractions, sludge age, and waste flow rates are generated

reasonably simply and quickly and can be used as the starting conditions for dynamic simulation (Wentzel *et al*., 2006; Ekama & Wentzel, 2008a; Ekama, 2009).

Considering their ease of use, and the generation of high-level information, steady-state models are aptly suited for system design or capacity estimation. The outputs from the steady-state models can be used as inputs to the dynamic models for the evaluation of the dynamic response of the system. With this design procedure, it can be seen that steady-state models are pre-processers to the dynamic models, and that they complement the dynamic models as they generate the starting conditions required to initiate the dynamic simulation (Ekama, 2009). In addition to this, more importantly, because the steady-state models are based on the dynamic models and are therefore inherently similar, the steady-state models provide a basis for cross-checking the dynamic simulation results (Ekama, 2009).

Steady-state models are not only limited to the AS models; steady-state models are available for all major unit processes. Steady-state models can be used and are useful for the design of auxiliary unit processes, such as secondary settling tanks, thickeners and sludge digesters (van Haandel & van der Lubbe, 2007).

### 2.1.2 Available Modelling Software

Vanhooren *et al.* (2003) and Gernaey *et al.* (2004) distinguish that there are different types of WWTP modelling software. These can be either manually implemented code, general-purpose simulators, or dedicated simulators. Vanhooren *et al.* (2003) further add that the dedicated simulators either can be open or closed dedicated simulators; closed referring to propriety software, and open referring to open source software.

Manually implemented code, as described by Vanhooren *et al.* (2003), is the use of a programming language such as FORTRAN or C++ to model the wastewater treatment process. General-purpose simulators are more refined versions than manually implemented codes. These simulators are flexible; however, a major problem with them is that they require the modeller to supply the models to be used to model the specific WWTP configuration (Gernaey *et al.*, 2004). The creation of these models can be time consuming due to the coding and debugging process; this process requires a sufficiently skilled modeller, who understands the implications of each line of code (Gernaey *et al.*, 2004). Examples of general-purpose simulators include MATLAB/Simulink (Vanhooren *et al.*, 2003; Gernaey *et al.*, 2004) and ACSL (Vanhooren *et al.*, 2003). Dedicated WWTP simulators are software packages that are designed for the simulation of WWTP's. Gernaey *et al.* (2004) explains that these simulators contain a library of predefined process unit models. To simulate a specific WWTP configuration, process unit blocks and connectors are used to create the configuration, the parameters are entered for each process unit block, and the user then initiates the simulation (Gernaey *et al.*, 2004). Examples of dedicated simulators include: *BioWin*, *EFOR*, *STOAT*, *WEST*, *SIMBA*, and *GPS-X* (Vanhooren *et al.*, 2003; Gernaey *et al.*, 2004).

The simulators listed above focus on dynamic simulation and hence are marketed as dynamic software, for example *WEST* is marketed on their webpage as "*…the tool of choice for dynamic modelling and simulation of wastewater treatment plants (WWTP) and other types of water quality related systems...*" (MIKE by DHI, n.d.). These simulators have the ability to simulate a steady-state system, but they lack the capability of designing (sizing) the steady-state system or finding the capacity of an existing system. In order to initiate any form of simulation, the simulator requires an existing plant layout with the all reactors sized, the flow rates quantified, and the influent wastewater characterised. In *WEST*, to simulate a steady-state system, a constant flow with constant wastewater characteristic, and a sufficiently long time such as 100 days, is inputted into an already sized system. The simulation is then initiated and the steady-state reactor concentrations are given. These concentrations can then be used as the starting concentrations for the dynamic simulation. The simulation procedure described is essentially the steady-state/dynamic simulation process outlined by Copp (2001) in the COST "*Simulation Benchmark"* by the *IWA Respirometry Task Group* and the *European Co-operation in the field of Scientific and Technical Research (COST) 682/624 Actions.* The purpose of this simulation benchmark is to provide a standard protocol to evaluate the performance of simulation programs; it is a control strategy to ensure unbiased comparison. The dynamic simulators thus do not have a dedicated steady-state design component, and hence there is a lack of software available to design the steady-state system.

Consulting firms have setup spreadsheets to compute the steady-state models; however, there is no guarantee that these spreadsheets are correct and up-to-date with research and modelling knowledge. For firms without such a tool, the time to create one might not necessarily be available. For plant-operators, these spreadsheets can be used for analysis and capacity estimation to aid daily operation. However, like the consulting firms, time and knowledge is a factor in creating a steady-state design tool. In addition to this, a plant-wide setup might not necessarily be available; unit processes such as the activated sludge system and secondary settling tank are often designed separately, processes are treated as separate stand-alone units (van Haandel & van der Lubbe, 2007). Upstream process have a large impact on downstream processes, thus unit processes (the entire WWTP) must be designed and evaluated in an integrated manner. Furthermore, current modelling software do not have an integrated cost estimation and optimisation component. The software is simulation focused, and simulation is done very well; but the simulation software is unsuitable for design and the generation of high-level information, which has the greatest impact on decision-making. The addition of a plant-wide steady-state design program, that can fulfil the missing functionalities of the dynamic simulation software and complement the dynamic models, will be a major addition to the currently available modelling software.

From this section of the review, it is obvious that a steady-state design program needs to be developed. This program can act as a pre-processor for the dynamic simulation software, such as *WEST*. In doing so the problems in using dynamic models can be addressed and WWTP design and analyses can be more efficient. With a simple click of a button, the outputs

from the steady-state design program, such as flow rate, reactor sizes, and mass fractions, can be transferred to the dynamic models where the systems' performance under dynamic loading can be evaluated.

### 2.1.3 Plant-Wide Wastewater Treatment Models

Historically, wastewater treatment models were developed independently. This led to two distinct developments: the Activated Sludge (AS) models, e.g. ASM1, Henze *et al.*, (1987); and the Anaerobic Digestion (AD) models, e.g. ADM1 (Batstone *et al.*, 2002). Due to this isolation, these models incorporate different variables, and incompatibilities arise when coupling them. For example, carbon is not required for the AS models, but it is required to predict the carbon output and pH in the AD models (Ikumi *et al*., 2014a). The incompatibility of these models results in inefficiency and added difficulty in WWTP design – instead of computing one model with one set of input data, the designer needs to compute two models with two different sets of input data. In the realisation of this incompatibility and difficulty, attempts have been made to integrate the AS and AD models. These include the Continuity-Based Interfacing Model (CBIM, Volcke *et al.*, 2006), super-model based approach (Jones & Takács, 2004), transformation-based approach (Grau *et al.*, 2007), and lastly the plant-wide mass balance based model (Ekama *et al*., 2006a; Ekama *et al*., 2006b; Sötemann *et al*., 2006; Wentzel *et al*., 2006; Ikumi *et al*., 2014a).

The plant-wide mass balance based model approach is the most relevant for this project. With this approach, the movement of the C, H, O, N, P (and COD) materials are tracked throughout the WWTP. This is done with the aid of characterisation methods to determine the $C_XH_YO_ZN_AP_B$ elemental composition of organics, and as well as bioprocess stoichiometric equations for the various unit processes, namely, AS, AxAeD, AD, (see Ekama, 2009). Originally this was done only for C, H, O and N, but was later extended to include P by Ikumi *et al*. (2014a) and Ikumi *et al*. (2015). The crux of this approach is built on the observation that the unbiodegradable organics in the influent wastewater and the waste activated sludge from fully aerobic, N removal systems, and BEPR systems, remain unbiodegradable in anaerobic systems (Ikumi *et al*., 2014b). In the development of this approach, this continuity was realised from a semi-quantitative investigations by Wentzel *et al*. (2006), and was supported by the steady-state AD model of Sötemann *et al.* (2005) and values reported in literature, for example by O'Rourke (1968), Eckenfelder, (1980), Izzet *et al.*, (1992), and Ristow *et al.* (2005). It was concluded that, for typical South African wastewater, the unbiodegradable COD fraction in the PS obtained from the AD model, matched closely to the unbiodegradable COD fraction obtained from a mass balanced around the PST. With this conclusion, the raw WW, settled WW and primary sludge (PS) can be characterised with a mass balance around the PST and the raw WW characteristics determined using an appropriate characterisation procedure.

The plant-wide mass balance approach is useful as it allows the entire WWTP to be modelled in terms of C, H, O, N and P. Using mass balances for these elements, and as well as COD, the

influent and effluent fluxes of these materials can be tracked throughout the WWTP. This allows for the generation of very useful quantitative information; but more importantly, the continuity allows the WWTP to be modelled in a plant-wide format by simply characterising the effluent from upstream processes. Once the effluent is characterised, in terms of total COD, unbiodegradable particulates, and VFA, and $C_XH_YO_ZN_AP_B$, it can be used as direct inputs to downstream models. This is permissible because the mass balance approach provides internally consistent and externally compatible elements (Ekama *et al*., 2006b).

## 2.2 Wastewater Characterisation

Wastewater characterisation (WWChar) is an important process for the design of WWTPs. For the various steady-state and dynamic models, a common framework is the subdivision of the influent carbonaceous material, measured in terms of COD (Wentzel *et al.*, 1999).

The total influent COD is divided into two groups: biodegradable and unbiodegradable. In both groups, there exist soluble and particulate groups. For the soluble biodegradable group, the soluble COD is termed readily biodegradable COD (RBCOD). This is further subdivided into volatile fatty acids (VFA), and fermentable biodegradable COD (F-RBCOD) (Wentzel *et al.*, 1999). Knowing this division is crucial for NDBEPR activated sludge systems as the VFA and F-RBCOD respond differently in the anaerobic zones (Wentzel *et al.*, 1990). The particulate COD is termed slowly biodegradable COD (SBCOD) (Wentzel *et al.*, 1999). The division of readily biodegradable and slowly biodegradable relates to the biokinetic response of the activated sludge to COD due to the molecule size of the organic. RBCOD comprise of small molecules and thus are readily available for utilisation; SBCOD comprise of larger, more complex molecules, which require hydrolysis before it can be utilised (Dold *et al.*, 1980, 1986). The soluble unbiodegradable COD (USO) is not subdivided any further. The particulate biodegradable (BPO) and unbiodegradable (UPO) fractions can be further subdivided into settleable and non-settleable particulates, i.e. settleable BPO and UPO, and non-settleable BPO and UPO. The settleable and non-settleable division is relevant for the modelling of the PST and the solids removal. Settled wastewater comprises of mainly non-settleable particulates. Currently, there is not enough data to quantify the exact split between the settleable and non-settleable particulates, but it has been observed that unbiodegradable organics (UPO) settle out in greater proportion (65-85%) in PST than biodegradable organics (BPO, 30-45%) (Wentzel *et al*., 2006). This complicates the quantification of the composition and mass ratios ($f_{cv}$, $f_n$, $f_p$ and $f_c$) of the settleable and non-settleable particulates. Although the developed PWSSD program can accommodate different composition and mass ratios ($f_{cv}$, $f_n$, $f_p$ and $f_c$) for settleable and non-settleable unbiodegradable (UPO) and biodegradable (BPO) particulates, most literature WWChar procedures assume that settleable and non-settleable particulates have the same composition and mass ratios. Further research in this area, particularly in the behaviour of the particulates in PST, can address this knowledge gap.

In summary of this section, the degree of WWChar depends on the activated sludge system to be designed, and not only the physical, biological, and chemical processes that take place. To meet stringent effluent criteria, sophisticated activated sludge systems are required, for e.g. NDBEPR systems for N and P removal. These systems have complex models and design procedures, and hence, require more detailed wastewater characteristics.

## 2.3 Steady-State Models

A brief review of the steady-state models relevant for the development of a plant-wide steady-state design (PWSSD) program is presented in this section. Some of the important considerations, assumptions, and parameters for these models are also presented. For the details of these models, the reader is directed to the original publications.

### 2.3.1 Steady-State Activated Sludge Model

The steady-state activated sludge (AS) model by Marais & Ekama (1976) and WRC (1984) is the centrepiece of the steady-state models. A revised version of this model can be found in the *Organic Removal*, and *Nitrogen Removal* chapters 4 and 5 in the book *Biological Wastewater Treatment: Principles, Modelling, and Design* (see Ekama & Wenztel, 2008a,b).

As described by van Haandel & van der Lubbe (2007), the fundamental theory in the steady-state AS model is that it comprises of active and inactive biomass. The active biomass is composed of living bacterial organisms, which mediate metabolism of influent organic material. The inactive biomass originates from two distinct sources. The first being the influent unbiodegradable particulate organics, and the second being the continuous decay process of the active biomass. In the decay process (called endogenous respiration), a portion of the active biomass is oxidised. However, a portion of the biomass is unbiodegradable; thus, during the decay process, there is an accumulation of unbiodegradable particulates. In consideration of this theory, it is clear that the time allowed for the AS process will have an impact on the sludge mass in the system. Thus the critical parameter in the design, operation, and control of the AS system is the sludge age (SRT). SRT is the retention time of the solids in the AS system. In summary, a longer SRT results in a greater stabilisation of the influent wastewater and a lower effluent N and P nutrients concentration. However, a longer SRT means a greater mass of sludge is stored in the system, and thus for a designed reactor mixed liquor suspended solids concentration (MLSS or $X_t$), a larger reactor volume is required. For biological nutrient removal (BNR) systems, where nitrification and denitrification is used for the removal of N, the minimum SRT is primarily determined by the nitrifier specific growth rate ($\mu_{Am20}$), - corrected for temperature ($\mu_{AmT}$). The SRT must be sufficiently long so that nitrifiers are not washed out of the system, i.e. exit the system faster than they can grow.

It is important to note that the hydraulic retention time (HRT) has very little impact on the AS system design, and that wasting sludge directly from the AS reactor is much more beneficial than wasting from the secondary settling underflow. Wasting directly from the AS reactor is termed the hydraulic control of SRT as the waste activated sludge (WAS) flow rate determines the SRT of the AS system. Ekama (2010) discusses the role and benefits of hydraulic control of SRT. In addition to the SRT, there are various other important parameters that govern the design of the system, e.g. the recycle ratios (a-, s-, and r-recycle) and the minimum temperature of the AS system. Details regarding these parameters can be found in the literature.

### 2.3.2 Biological Nutrient Removal

With a specific AS system configuration, biological nutrient removal (BNR) can be stimulated, thus providing the removal N and P nutrients (nitrates and phosphates). These AS configurations are called NDBEPR systems because N and P nutrients are removed using nitrification/denitrification (ND) and biologically enhanced phosphorous removal (BEPR). Wentzel *et al.* (1990) developed the steady-state BEPR model; equations describing the P release and P uptake are provided. The details of this model and as well as a review of the current state of the BEPR model is presented by Wentzel *et al.* (2008).

In the BEPR model, the level of P removal is largely dictated by the VFA uptake by the PAOs in the anaerobic reactor. The anaerobic reactor typically receives the influent wastewater, thus the PAOs have direct access to the influent VFA. In addition to this, the OHOs mediate the conversion of F-RBCOD to VFA, which further increases the available VFA for uptake. In short, a higher uptake of VFA results in a greater production of PAOs, which in turn increases the P removal of the system. Therefore, in the BEPR model, the first and most important step is to determine the amount of VFA uptake by the PAOs. This involves calculating the split between the F-RBCOD converted to VFA for uptake by the PAOs, and the F-RBCOD not converted to VFA and utilised by the OHOs. This splitting procedure is set out by Wentzel *et al.* (2008).

The VFA uptake by the PAOs is affected by a variety of factors; primarily, these include the efficiency of the anaerobic reactor (measured by the amount of nitrate and oxygen leaked to the anaerobic reactor), the anaerobic mass fraction (its size) and the number of anaerobic compartments. In order to maximise P removal, the influx of nitrate and oxygen must be kept as low as possible, the anaerobic mass fraction must be kept sufficiently large, and more than one anaerobic compartment should be used. Creating these conditions will result in an increase in P removal. However, it is important to note that the maximum P removal is dictated by the influent total phosphorous concentration and as well as the influent cation concentrations (Ca, Mg, and K). In the P uptake process, the PAOs synthesis polyphosphate (polyP), the Mg, K and Ca cations are required to stabilise the negative polyP charge (Wentzel *et al.*, 2008). A shortage of these cations will therefore limit the synthesis of polyP and reduce P removal. Concerning the system volume, the accumulation of these cations and polyP within the PAOs

increases the ISS mass in the AS system, which in turn increase the AS reactor volume requirements. Therefore, NDBEPR systems require a significantly larger system volume than equivalent ND only systems.

For an NDBEPR model, the BEPR model is simply combined with the ND model. This is permissible because Wentzel *et al.* (1990) showed that analyses of the PAOs and non-PAOs can be separated as they act virtually independently of each other, the only link between the two groups is the interactions with VFA and F-RBCOD in the anaerobic reactor. However, in terms of the sizing of the NDBEPR system, the ND process typically fixes the SRT of the system. The nitrifiers grow at a slower rate than the PAOs, thus the minimum SRT remains determined by the growth rate of the nitrifiers as in ND only systems. This is an important consideration of the design of the AS system.

### 2.3.3 Solids-Liquid Separation

The idealised 1-Dimensional Flux Theory (1DFT) is typically used for the steady-state design of SST. This model's development and usage is described in detail by Ekama *et al.* (1997). In the 1DFT model, a solids mass balance principle is applied with the assumption that all solids exit the SST via the underflow recycle; the effluent is thus void of solids.

The purpose of the 1DFT model is to determine the minimum required SST area for safe operation and as well as the operating and minimum (critical) recycle ratios for different flow conditions (ADWF, PDWF, and PWWF). Safe SST operation occurs when the solids handling criterion 1 and 2 (SHC1 and SHC2) are met. These criterions are described by Takács & Ekama (2008). SHC1 relates to the limiting solids flux ($J_L$), which is determined by the limiting solids concentration and the settleability of the sludge. The limiting solids concentration is the bottleneck TSS concentration in the SST between the feed and underflow TSS concentrations. At this concentration, the downwards minimum flux occurs ($J_L$), which sets the maximum applied solid flux to the SST. In order for SHC1 to be satisfied, the applied flux to the SST must be less than or equal to this $J_L$, otherwise a build-up of solids in the SST will occur. SHC2 relates to the maximum overflow rate. The overflow rate of the SST is determined by the SST area and influent flow rate. This overflow rate must be less than the settling velocity of the sludge at the feed TSS concentration. If this condition cannot be satisfied then solids will exit via the effluent because the upwards velocity of the mixed liquor exceeds the downwards settling velocity at the feed point. Considering these criteria, the goal of the SST design is therefore to meet SHC1 and SHC2 for all flow conditions. Typically, because SHC2 is directly related to the hydraulic load on the SST at PWWF, the minimum SST area is determined by the SHC2 at the PWWF condition. For the ADWF and PDWF, with the required SST area determined, the SHC2 will always be satisfied. Hence, for the ADWF and PDWF, the required recycle ratios to satisfy SHC1 is the focus of these two flow conditions.

Useful design and operation charts can be generated with the 1DFT, e.g. State-Point Analysis (SPA) and the Ekama Design and Operation Chart (D&O chart). These graphical summaries are useful as they visually aid the design and operation of SSTs. During the SST design procedures, it is thus important to generate these charts in addition to the quantitative model outputs. Examples of these charts and their usage are provided by Takács & Ekama (2008).

The AS reactor particulates (TSS) concentration ($X_t$) is the feed concentration to the SST, this creates a link between the AS system volume and SST area. By combining the AS and SST model with a cost model, the $X_t$ can be optimised to determine the minimum cost of the AS-SST system. This procedure is described by Takács & Ekama (2008).

Primary settling tanks (PST) are typically coupled with a gravity thickener. Both of these systems are designed empirically, where the area and size is determined from a selected solids loading rate or maximum overflow rate, which in turn is determined from empirically based performance data. Details of sludge thickening and dewatering systems are described by the Water Environment Foundation (2005).

## 2.3.4 WAS and PS Digestion

Sludge treatment is used to stabilise primary sludge (PS) and waste activated sludge (WAS). Anaerobic digestion for PS and anoxic-aerobic digestion for WAS is typically used.

### 2.3.4.1 WAS Digestion (Anoxic-Aerobic)

The digestion (fully aerobic or anoxic-aerobic) of WAS sludge is an extension of the AS model. In this process, an electron acceptor (oxygen or nitrate) is continuously made available, but an extracellular organic substrate is not available. In this environment, a continuation of the endogenous respiration process occurs and the WAS is stabilised to a desired effluent active fraction by providing a sufficiently long retention time. The aerobic WAS digestion model is presented by Ekama *et al*. (2006b). To provide complete nitrification and denitrification (ND), an anoxic-aerobic digester can be created by using an aeration cycle, 3 hours on and 3 hours off. Doing so, as shown by Warner *et al.* (1986), allows for complete ND, and hence low ammonia and nitrate concentrations in the digester effluent. Adding intermittent aeration for denitrification has been found to not affect the endogenous respiration rates of the OHO (Warner *et al*., 1986) and PAO (Vogts & Ekama, 2012). In terms of the WAS model, the change from a completely aerobic to anoxic-aerobic digestion model therefore only requires adjustments to the oxygen demand components (FO), the oxygen utilisation rate (OUR) and the effluent N concentrations. By allowing for ND, the oxygen demand is increased by 4.57 times the flux of FSA nitrified, and decreased by 2.86 by the flux of nitrate denitrified (Ekama & Wentzel, 2008b). In terms of the OUR, the OUR is increased by 50% as the aeration system is cycled on and off because the same flux of oxygen (FO, kgO/d) still has to be supplied.

An important consideration in the WAS digestion model is the behaviour of the inorganic suspended solids (ISS). A predictive model for the ISS was developed by Ekama & Wentzel (2004). This model is included in the 2006 aerobic digestion publication by Ekama *et al*. (2006b). In the ISS model, the biomass (OHOs and PAOs) take up extra-cellular inorganic dissolved solids (IDS) as part of the biomass. When this sludge is sampled, dried, and incinerated in the VSS-TSS test procedure, this IDS precipitates as inorganic solids. Also, all the polyP in the PAO registers an ISS in the TSS-VSS test. In addition to this ISS mass, an accumulation of ISS, sourced from the influent wastewater, also occurs. Thus, the ISS mass in the reactor (AS reactor or the anoxic-aerobic digester) is related to the fixed (influent wastewater) ISS load and the ISS content of the active biomass (OHOs and PAOs) and the mass of active biomass in the digester. The behaviour of the ISS in the digester is important and this needs to be modelled in order to determine correctly the effluent particulate (TSS and VSS) fluxes (Ikumi *et al*., 2015; Vogts & Ekama, 2015)

With the predictive ISS model, and consistency of the UPO in aerobic and anaerobic environments, the research by Ekama & Wentzel (2004), Ekama *et al*. (2006a), Ekama *et al*. (2006b), Sötemann *et al*. (2006), Wentzel *et al*. (2006) and Vogts & Ekama (2012) showed that the mass balance based approach provided internally consistent and externally compatible elements. By coupling these elements, an integrated steady-state plant-wide WWTP model is produced including P, where the activated sludge system is directly linked to the WAS digestion system. While not included in the PWSSD model, Vogts & Ekama (2012) show that if lime is dosed to the anoxic-aerobic digester stabilising NDBEPR WAS, a dewatering liquor low in N and P (<0.5 mgP/L and mgN/L equivalent influent concentration) is obtained.

#### 2.3.4.2 PS Digestion (Anaerobic)

The steady-state anaerobic digestion (AD) model by Sötemann *et al.* (2005) is relevant for the steady-state design of the anaerobic digester. This steady-state AD model is a simplification of the dynamic AD model developed by Sötemann *et al.* (2005b), i.e. the integrated two-phase (aqueous-gas) mixed weak acid/base chemical, physical, and biological process kinetic model for AD of sewage sludge.

The steady-state AD model comprises of three sequential parts. The first part is kinetic component in which the %COD removal and methane production is determined from a selected retention time (SRT). The second part is a bioprocess stoichiometry component where the gas composition, alkalinity generated, and the ammonia released, is calculated from the %COD removal determined in the first part of the model. Lastly, the third part is a weak acid/base chemistry part, where the carbonate system in conjunction with the alkalinity generated and gas composition, is used to determine the pH of the digester (Sötemann *et al.*, 2005a).

In the steady-state AD model, the influent sludge feed is characterised according to its total COD, unbiodegradable COD, and VFA concentrations, and as well as its elemental C, H, O

and N composition, extended to include P by Ekama (2009). This characterisation thus conforms the steady-state AD model to the mass balanced plant-wide modelling approach, as it allows for the mass balancing of COD, C, H, O, N and P materials (Sötemann *et al.*, 2005a). With this continuity, the AD of WAS or PS, or WAS and PS mix is possible, provided that the PS only or WAS only or mixed PS and WAS sludge feed is characterised accordingly. For the AD of mixed PS and WAS, the steady-state AD model is simply used with different hydrolysis rates and biodegradable organic compositions, which are provided by Ikumi *et al*. (2014b). Furthermore with this continuity, the AS system (which is already linked to the WAS digester, SST, and PST) can be linked to the PS AD system, creating a complete plant-wide steady-state design.

## 2.3.5 Other Processes and Models

Further processes can be integrated into the plant-wide design to create a more detailed system. These processes include flow balancing, and an aeration model.

### 2.3.5.1 Flow Balancing

Flow balancing (equalisation) of the influent wastewater provides numerous advantages to the AS system. With a an average retention time of 4 to 6 hours, flow equalisation provides a reduction of more than 90% in the flow and load variations (Dold *et al.*, 1984). As a consequence of reducing the peak flow and load, equalisation of the influent wastewater flow results in a more stable AS process, a reduction in the required SST surface area, and a smaller aeration system (Dold *et al.*, 1984). A flow equalisation algorithm was developed by Dold *et al.* (1984) and tested at full-scale at Goudkoppies WWTP (150ML/d, Gauteng, RSA). In this algorithm, the outflow of the equalisation tank is optimised based on the prediction of the future 24-hour influent flow rate. This algorithm does not size the balancing tank; it maximizes the achievable flow equalization for the provided volume. In fact, there is limited literature regarding the sizing of the balancing tank. This is most likely because the sizing of the tank is rather straightforward. If the influent diurnal flow rate is known, a hydrograph that plots the cumulative flow rate versus time over a 30h period, determines the required volume of the tank

### 2.3.5.2 Aeration

The aeration system for the AS aerobic reactor and anoxic-aerobic digester is an important system. An important consideration is the relationship between the peak oxygen demand and the average oxygen demand of the AS system. For NDBEPR AS systems without flow balancing, the average oxygen demand, determined by the steady-state AS model, must be increased by a factor to account for the peak loading condition. Musvoto *et al.* (2002) provides the calculations for this peaking factor. For the design of the aeration system, various aeration

models exist. In these models the standard oxygen transfer rate (kgO/kWh), which is usually supplied by the manufacturers of the aeration equipment, is adjusted for inefficiencies due to mixing, site conditions, impurities, and aeration equipment. Bratby (n.d.) provides an aeration model that is relevant for the modelling of the mechanical surface aeration component in this program. Bubble aeration will be added to the PWSSD in future. Even if a WWTP has sufficient organic and hydraulic load capacity, its treatment capacity can be constrained below this by the aeration system.

## 2.4 Conclusion

The plant-wide steady-state design of a WWTP involves the integration of various unit processes. Currently, a plant-wide steady-state design program is not available; the majority of available software focuses on dynamic simulation. Simulation is vital for the detailed analyses of the WWTP. With the dynamic models, the system's response to varying loads and flow rate can be evaluated. However, in terms of system sizing and overall WWTP design, steady-state models are more useful in that higher-level information is generated with simple and explicit algebraic equations. This higher-level information can be used as the initial conditions for dynamic simulation; doing so will improve the efficiency and effectiveness of dynamic simulation as the higher-level information is not reliably obtained using trial and error methods with dynamic models. For the development of the plant-wide steady-state design program, the relevant steady-state models have been briefly reviewed, a summary of this literature is provided in Table 2.1. Furthermore, the important considerations for each model have been provided in this chapter. This program will utilise the principles in the mass balance based approach. With this approach, the various steady-state models for the various unit processes are linked together to form one holistic plant-wide design. The assimilation of the steady-state models into one design program will be a valuable addition to the current WWTP modelling field and WWTP designers and engineers.

**Table 2.1: Overview of the Relevant Literature on the Steady-State Models**

| System / Process | Topic / Model Component | Relevant Literature |
|---|---|---|
| Wastewater characterisation | Wastewater characterisation | Wentzel *et al.* (1999, 2006); Rössle & Pretorius (2001) |
| Activated sludge system | Organic Removal (COD) | Marais & Ekama (1976); WRC (1984); Ekama & Wentzel (2004, 2008a) |
| | Nitrogen removal (N) | Ekama & Wentzel (2008b) |
| | Phosphorous removal (P) | Wentzel *et al.* (1990, 2008) |
| WAS digestion | Anoxic-aerobic digestion | Warner *et al*. (1986) Ekama & Wentzel (2004); Ekama *et al*. (2006b); |
| WAS and PS digestion | Anaerobic digestion | Sötemann *et al.* (2005a) |
| | WAS + PS and WAS hydrolysis rates for AD | Ikumi *et al*. (2014b) |
| SST | SST 1DFT | Ekama *et al.* (1997); Takács & Ekama (2008) |
| Aeration | Aeration model | Bratby (n.d.); Warner *et al.* (1986); Musvoto *et al.* (2002) |
| Plant-wide system | Bioprocess stoichiometry for CHONP mass balancing | Ekama (2009) |

# 3. Program Design Part A: Overview

The Program Design is split into six parts (Chapters 3 to 8); this is due to its large size. Program Design serves two purposes; it is the methodology in which the program was built, and a detailed guide on how to use the program.

Program Design Part A: Overview: (Chapter 3) provides a summary of the content covered in each part of the Program Design section.

Program Design Part B: Program Skeleton (Chapter 4) covers the conceptual and structural aspects of the program. These include the coding language, program limitations and capabilities, how the models are processed and how the user interfaces are created and linked to the steady-state models. Part B aims to provide the reader with an understanding of the background routines and coding of the program. An understanding of the background activity is vital if the reader needs to add or modify models, adjust the user-interfaces, or change the components of the program (with necessary caution).

Program Design Part C: Wastewater Characterisation (or Influent Generator, Chapter 5) presents the first major component of the program. The inputs to the steady-state models, particularly the organic loads, are extremely important. Model users should have an innate understanding that “rubbish in equals rubbish out”, thus if the organic loads are incorrect then the steady-state design will be incorrect. Wastewater characterisation (WWChar) refers to the process in which the influent organic load is determined. It is often the first step in design and is often the most problematic step in design. This is because the required tests on the wastewater are not regularly performed or simply because there is no data available. The capacity of the finished WWTP design will be inadequate if the design COD, TKN, TP, TOC, and particulate (TSS, ISS) fluxes are significantly different to actual fluxes that will be experienced by the WWTP. Therefore, WWChar must be done correctly and prudently so that the WWTP can be designed as best as possible. Different WWChar methods were developed for the program so that this can be achieved. Each method is structured and tailored to a specific level of influent data availability; for example, a poor data availability scenario will rely primarily on default literature values, thus providing more generic wastewater characteristics. On the other hand, a rich data availability scenario will allow for specific inputs and hence a unique set of wastewater characteristics can be generated. The aim of each WWChar method is therefore to provide a sensible and reliable way of characterising the influent wastewater for the level of data available. Part C presents the different WWChar methods developed for the use in this program and the characterisation procedures for each method.

Program Design Part D: Plant-Wide Steady-State Design (Chapter 6) focuses on the second major component of the program. The plant-wide design philosophy centres on the concept of a holistic and integrated WWTP design. By combining this philosophy with the simplicity and strength of the steady-state models, a wealth of useful information can be

generated. Part D presents the various steady-state models available in the program, such as the activated sludge models for various WWTP configurations, solid-liquid separation models, sludge treatment models etc. Part D also presents how all the different steady-state models are combined together to form the Plant-Wide Steady-State Design (PWSSD) component. The individual steady-state models have been examined and discussed extensively by researchers and model developers, thus the analyses, critique and details of the models are not the focus of Part D. The methods in which the designer can interact with the steady-models, the important information generated by steady-state models, and how it is conveyed to the designer, are also discussed in Part D. In reading Part D, the designer can understand how the various steady-state models are pieced together to form a plant-wide design and ultimately gain an appreciation for the steady-state models.

Program Design Part E: Capacity Estimation (Chapter 7) deals with the last component of the program. In addition to the WWChar and the PWSSD components, a Capacity Estimation (CapEst) component has been developed. The CapEst component utilised the steady-state models in the PWSSD component. A capacity estimate is routine where the steady-state models are simply processed in reverse in order to find the maximum average dry weather flow that a WWTP can accommodate. Part E discusses how the CapEst procedure works, how the user can interact with the CapEst user-interface, and the information generated by the CapEst.

Program Design Part F: Program Flow (Chapter 8) concludes the Program Design section. It presents a flow chart of the entire program showing the links and transition between the different user-interfaces of the program and the various paths that the designer can take when using the program. It also presents the landing page, which is initialised when the program starts.

# 4. Program Design Part B: Program Skeleton

## 4.1 Data Input, Model Computation, and User-Interface

The skeleton of the program consists of three spheres: data input and storage, model computation, and model outputs. An overarching sphere, the expert-guided user-interface embraces all three spheres. Each sphere fulfils a specific role with certain responsibilities. The Plant-Wide Steady-State WWTP Design and Analysis Program (PWSSD) is a combination of these three spheres as illustrated in Figure 4.1.

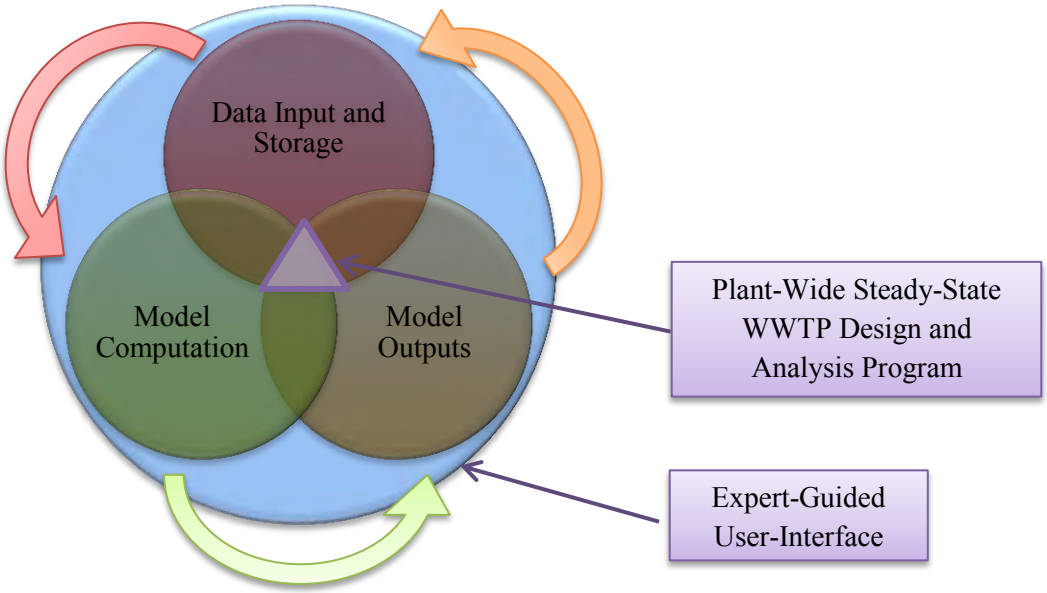



**Figure 4.1: Venn diagram illustrating the three program components**

Data input and storage refers to the manner in which the program handles data, such as the inputs to the models. The program uses different types of data, for example Booleans, strings, integers etc. Data in a sense can also be in the form of graphs or images. In the PWSSD program the data is stored in cells contained in spreadsheets, and depending on what is required from the data, it is either in the form of a variable or constant. A variable can be function or equation linked to other cells which in turn are either variables or constants. A variable is effective for data that needs to be dynamic in nature, i.e. it needs to be updated frequently, or it needs to hold a specific value depending on certain conditions. Constants are fixed values, and can be in the form of a function or equation; constants can therefore be described as fixed variables. Constants are used when it is better for the data to be fixed and independent from other cells - however, this does not explicitly mean that it can never be changed; it simply has to be changed manually. This is primarily used to improve program efficiency and integrity, for example it is better to use constants for an upstream input that affect a multitude of downstream

models; if a variable is used, and that variable is updated frequently, then every time the data is updated all downstream models will be recalculated. This can have a significant impact on the program integrity in terms computational effort and memory usage.

The model computation sphere refers to arithmetical and computational power of the program. The PWSSD program is developed in Excel/VBA* and therefore the program's computational ability is limited to the Excel/VBA environment. Excel is an extremely powerful application that has a variety of uses. It has the ability to store and manipulate large sets of data, either in traditional spreadsheets, in the VBA environment, and even from external files. The PWSSD program utilises Excel's spreadsheet capabilities to process the steady-state models. The power of the steady-state models is that they comprise explicit algebraic equations (Ekama, 2009); they do not require powerful processers or solvers to solve and hence they are perfectly suited for spreadsheets. Excel provides numerous benefits that suite the PWSSD program; however, it is not immune to problems, the pros and cons of the Excel/VBA environment is discussed further in Section 4.2 Excel and VBA.

The model outputs sphere refers to the information generated by the models. This information can be final or intermediate in nature. If it is final then the information cannot be utilised further by the program, it is presented to the model user, via the user-interface, where it can be utilised or analysed outside of the program. If it is intermediary, the model outputs form part of a new set of data inputs, which is utilised by a downstream model. This results in a circular process and hence the circular arrows on the Venn diagram in Figure 4.1, i.e. the data inputs are fed to a model, the model is computed and outputs are generated, these outputs are then utilised as inputs in a downstream model or procedure.

The user-interface encompasses all the inner spheres. It is the space where the user can interact with the models; it provides a means for the user to send commands to the software and to receive feedback from the procedures that took place. The user-interface serves variety functions: it allows for navigation between the different program components and models, it is a tool to capture input data, to provide results from the models, and as well as to provide guidance in using the program.

At the centre of the Venn diagram, all four spheres are combined together. This is in effect the PWSSD program: a graphically orientated program (tool) that allows a model user to interact, manipulate and use steady state models for the design and analysis of WWTP unit processes connected in a plant-wide manner.

* VBA = Visual Basic for Applications

## 4.2 Excel and VBA

The user-interface component was developed in Visual Basic for Applications (VBA), and the data storage and model computation components were developed using spreadsheets and VBA code. In short, the program can be described as a spreadsheet based application.

VBA is a subset of Visual Basic (VB); there are some differences between the two, but the overall structure of VBA and its functionalities are similar to VB. VB is however more powerful but also more complex, this allows for greater flexibility in program development. VB is typically used for the development of stand-alone Windows based applications. VBA on the other hand requires a host application, which in this case is Excel. A host application is an application that contains and runs an application within itself, i.e. the PWSSD program requires Excel to run, and it is not a standalone program and cannot run outside of the Excel program. VBA is therefore typically used to supplement Excel spreadsheets or projects developed in the Excel environment.

There are various advantages and disadvantages in using a host application to develop a program. The foremost advantage is that it allows the hosted program (in this case VBA) to inherit the core functions of the host application (in this case Excel); in this scenario, because Excel can work with numerous large spreadsheets and large sets of data, the PWSSD program would have the same ability. Furthermore, all the functions and tools available in Excel are also available to the PWSSD program; examples of these include graphing tools, filtering, lookup, and mathematical functions. These functions and tools might not necessarily be available if the PWSSD program was developed in VB (or in any other programming language), unless of course the code for it exists somewhere in an open source library. Another advantage of using Excel as a host is in the way tasks are executed by Excel; Excel always executes tasks in the same way, it is consistent and a stable environment, therefore the PWSSD program will have the same advantage. This consistency is extremely valuable as it helps in error debugging processes - until the error is addressed, the error will occur at the same location at the same time, every time. The principle disadvantage in using Excel is that for the intended user to run the program, Excel is required. However, the advantage of inheriting the properties and functions of the host application Excel was deemed more beneficial than the requirement of having VB run the PWSSD application.

While, the stability and consistency of Excel is great, it is not immune to problems; during testing and debugging processes compatibility issues arose when using different bit versions of Excel (but have since been resolved). The program was developed in Excel 2010 32-bit, and it ran without errors in Excel 2010 and 2013 32-bit; however attempts to start it on 64-bit Excel platforms (2010 and 2013) gave problems with the user-interfaces. The user-interfaces, which are “userforms” in VBA, caused errors and crashed the program; however, the spreadsheet components ran smoothly. It was then realised that 64-bit Excel/VBA handled memory slightly differently to the 32-bit versions. According to Microsoft, the primary difference between the 32-bit and 64-bit versions is in the way it handles memory; the 64-bit

Excel version has access to more memory and thus can handle larger sets of data. Chris Brouckaert of the Pollution Research Group (PRG) of UKZN provided adjustments to the 32-bit VBA user-interfaces that allowed the program to be run on 64-bit versions, thus allowing compatibility for both 32-bit and 64-bit (Excel 2010 and 2013 versions). However, the PWSSD program has not been tested on different regions of Excel; incompatibilities may arise if a non-English version of Excel is used. This can be addressed in future editions if required.

The choice of programming language was critical. The language, and its capabilities, had to meet the requirements of the project. The PWSSD program had to be able to store data in reliable and easily interpreted format, the program had to be able to compute the steady-state models efficiently and quickly, be easy to expand and include any future model extensions, and most importantly it required the ability to provide some form of user-interface to capture data. Due to all these consideration, the Excel/VBA environment was ultimately chosen as it satisfied all the points mentioned.

## 4.3 User-Interface Creation

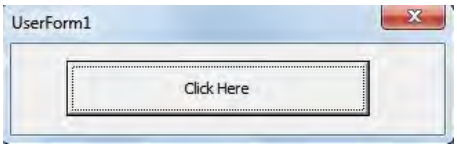
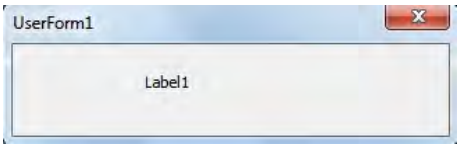
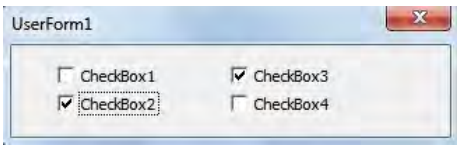
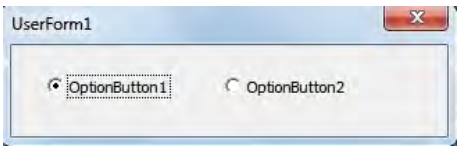
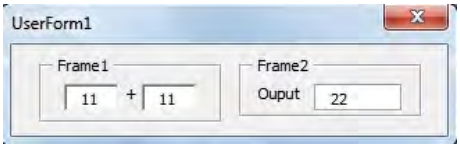
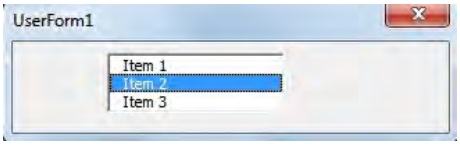
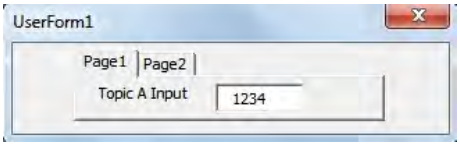
The user-interface comprises multiple controls such as textboxes, option buttons, command buttons etc. This section discusses the user-interface aspect of the PWSSD program, how it is structured and as well as provide some examples of the commonly used controls on the user-interfaces.

The user-interface consists of set of controls that allow user interaction with the program. An example is a textbox that displays or allows the user to enter alphanumeric data. Another example is a command button that initiates a specific procedure when clicked. Controls have various properties that govern their appearance and behaviour; they also contain different types of events that can be activated. When the program user activates/triggers these events, the program executes a sequence of code (called a subroutine) to perform a variety of tasks, for example to capture, select, transfer or export data, perform calculations, display messages etc. Subroutines can also be used to change the properties of the control. Properties can be aesthetic, such as its background colour and or its border colour or type; the control's visibility and physical screen location is also a property. Furthermore properties can also be related to the control's behaviour, for example if it can be selected (enabled) or not (disabled).

In order to construct a user-interface, the controls are contained in a userform, which is in a sense a control itself. Table 4.1 presents examples of the types of controls, and their primary functions and how they are used within the user-interface.

The PWSSD user-interface is primarily built using the controls presented in Table 4.1. These controls are the building blocks of the user-interface and are pieced together to provide the program user with an interactive environment. In the sections to follow, examples of the user-interfaces are presented and discussed along with the conceptual aspects to how the program was developed.

**Table 4.1: Type of user-interface controls**

| | Description/Function | Usage example | Visual Example |
|---|---|---|---|
| Userform | Window that contains other controls | A window that contains the controls to enter and transfer the inputs |  |
| Command button | A push button | When clicked the command button transfers the values in the input boxes to a spreadsheet |  |
| Textbox | A textbox that contains and allows for alphanumeric inputs | Allows the user to enter values or inputs that can be transferred to the spreadsheets |  |
| Label | A fixed text label that contain alpha-numeric value | Displays a fixed alpha-numeric value, for example the units for a textbox or the name of the textbox |  |
| Checkbox | Selection of non-exclusive options | Allows user to select any of the following options A, B, C or D |  |
| Option button | Selection of exclusive options | Select option A or option B, but not both options. |  |
| Frame | Groups controls together on a userform | Frame1contains inputs, Frame2 contains the outputs |  |
| Spin button | Increases or decreases a value by a specific amount | Clicking the spin button will increase or decrease a textbox's value by a fixed amount |  |
| List box | Displays a list of items | Displays a list of available items that can be selected by the user |  |
| Multipage | Collection of page objects, each page contains its own set of independent controls | Page 1 contains controls related to topic A, page 2 contains controls related to topic B |  |

# 5. Program Design Part C: Wastewater Characterisation

The influent wastewater (WW) needs to be characterised before the steady-state models can be used. The characteristics determine the organic load on the system, which directly affects the outputs of the models and hence the design of the system. Wastewater characterisation (WWChar) is a complicated task as the most important characteristics of the wastewater, the unbiodegradable particulate organics (UPO) COD fraction ($f_{S'up}$) and the readily biodegradable soluble organics (BSO) COD fraction ($f_{S'bs}$), are not often measured. This is a major dilemma as these parameters, which are most often guessed, have a profound impact on system performance and effluent quality. Furthermore the available wastewater data is not always the same in quantity and quality - there can be many available wastewater samples or there can be very few or none at all. This is problematic and makes developing a generalised WWChar procedure difficult. Nevertheless, the wastewater characteristics have to be determined as best as possible, the accuracy of these characteristics relies solely upon the designer (user).

A flexible WWChar component to characterise wastewater with different quantities of available influent data (data rich to data poor) was developed and included in the program. The output of this component is a wastewater profile, which is a set of diurnal characteristics that describe the flow rate, COD, TKN, TP, TOC, particulates (TSS, ISS), and TOD concentration of the raw WW, settled WW, and primary sludge (PS). An average pH and alkalinity is also included in the profile. The WWChar component is a collection of different WWChar methods that focus on different levels (quanta) of data availability. The idea behind this is that the WWChar procedure must suite the amount of data available. Four methods (and one in development), each one aligning to a different level of available influent data, have been developed and are discussed in this chapter. Each of the five influent data input methods produce the same set of wastewater characteristics, the only difference being the less and less data available, the more and more data has to be estimated/assumed from default values. The data levels range from a data rich scenario to a data poor scenario and the five WWChar methods in order of data richness are:

- Direct Input (rich data availability)
- Diurnal Flow Data (rich data availability)
- Characterisation Tree (mixed data availability)
- Grab Sample Reconciliation (poor data availability)
- Preloaded Profile (very poor data availability)

In a data rich scenario, where the designer enters very specific characteristics, very few adjustments are required for the inputs. In a data poor scenario, the inputs are more general and

focus on the "overall" characteristics of the wastewater that affect the WWTP the most (*viz*. organic load, kgCOD/d, UPO fraction $f_{S'up}$, BSO COD fraction, $f_{S'bs}$ and maximum specific growth rate of nitrifiers $\mu_{Am20}$). Between the data rich and data poor level is a "mixed" data scenario, which can lean towards the rich or poor sides depending on the type and availability of data. For this scenario, the data consists of some directly usable inputs and some preliminary inputs. The directly usable inputs can be used as is, but the preliminary inputs require some form of adjustment in order to be used. These adjustments, which are essentially preliminary calculations, are applied to the inputs based on the decisions made by the designer, for example if the available data are measurements on a grab sample at 2PM, then an adjustment is made to calculate the flow-weighted average. In this mixed data scenario, preloaded default values can be used to supplement the entered data. These default values are reasonable substitutes based on historical evidence for any missing data and hence allow for a best approximation of the characterisation procedures. Examples of preloaded defaults include the mass ratios $f_{cv}$ (gCOD/gVSS), $f_n$ (gN/gVSS), $f_p$ (gP/gVSS) and $f_c$ (gC/gVSS) of the five* different wastewater organics groups, namely: volatile fatty acids (VFA), fermentable biodegradable soluble organics (FBSO), unbiodegradable soluble organics (USO), biodegradable particulate organics (BPO) and unbiodegradable particulate organics (UPO). The inputs from the designer, combined with the preloaded default values (which can be changed if required), allow for a flexible characterisation procedure that can accommodate a variety of influent wastewater data quantity and quality scenarios.

The WWChar methods are discussed in this chapter. This chapter begins with the data rich scenarios and moves towards the poorer data scenarios. The goal of this chapter is to show how the different influent data levels are accommodated and to highlight what is necessary and what is irrelevant for each level (scenario). Following the different WWChar methods, a few sections on the navigation and flow of the WWChar component within the PWSSD program is presented.

* The PWSSD program actually has seven organic groups. The BPO and UPOs are further split into settleable and non-settleable groups, and different mass ratios can be used for them. However, to date there is too little historical evidence to define different settleable and non-settleable mass ratios, but in time, this may come to light.

## 5.1 Method 1: Direct Input

The Direct Input is the most straightforward method, it caters for a scenario where the designer has all the wastewater characteristics - the wastewater has already been fully characterised and a complete and specific set of influent wastewater characteristics can be entered. When using this method, the designer is presented with a window where a wastewater characterisation block diagram is displayed. The purpose of Direct Input is to generate the influent flow-weighted average (FWA) concentrations that will be displayed in this block diagram. Figure 5.1 shows the Direct Input window.

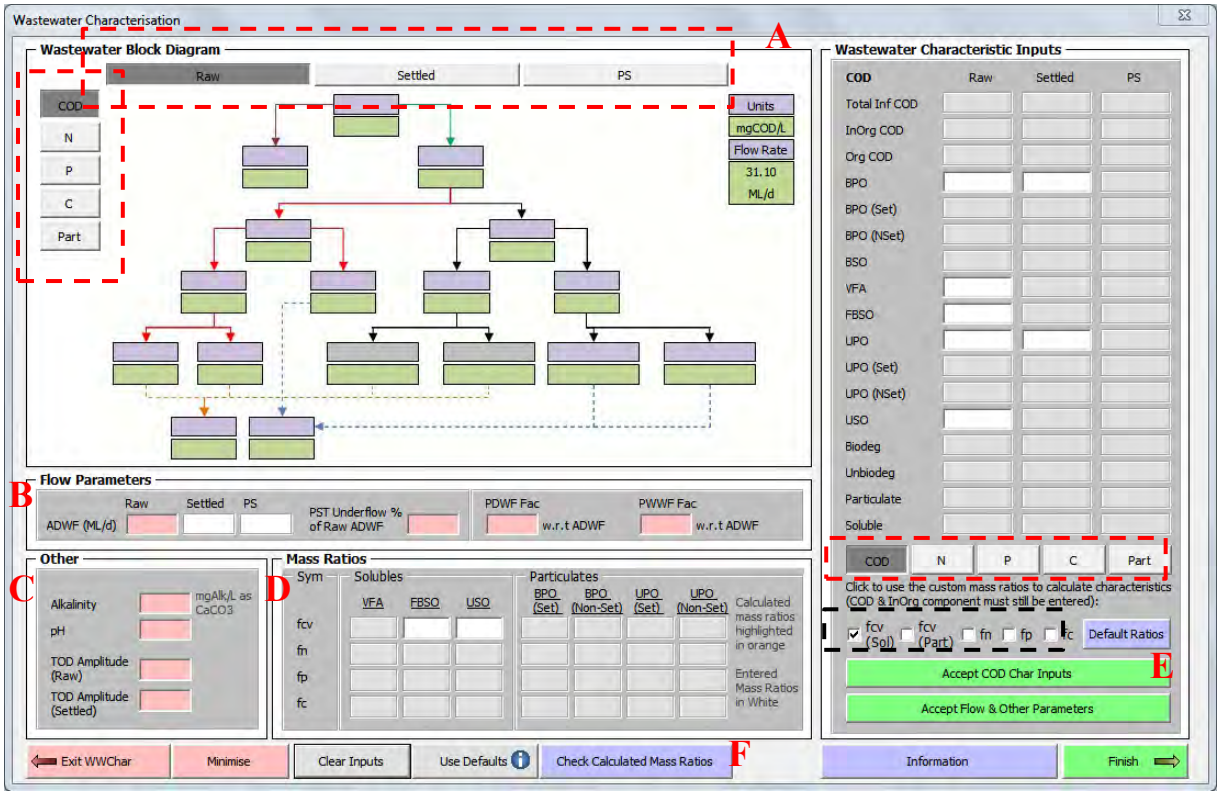



**Figure 5.1: Direct Input**

### 5.1.1 Data Requirements

On the Direct Input window, adjacent to the block diagram are the input boxes that allow the raw WW and settled WW characteristics to be entered (**A**). Characteristics that are the sum of other characteristics cannot be entered and their boxes have been disabled. For example, in order to enter the BSO COD concentration, the COD of the FBSO and the VFA must be entered separately; the BSO will be the sum of the entered FBSO and VFA. Note that for the BPO and UPO both the raw and settled WW COD concentrations are entered. The raw WW BPO is the sum of the settleable and non-settleable BPO; the settled WW BPO consists of non-settleable BPO only. The same applies for the UPO. The BPO and UPO in the PS are the

differences between the raw WW and settled WW BPO and UPO concentrations. Hence, the higher the settleable UPO and BPO COD concentrations relative to the total COD, the greater the COD removal in the PST. The PS characteristics cannot be entered, they are found by the flux difference between the raw and settled WW (which can be entered). The PS flow and all dissolved concentrations are included in the flux difference between raw and settled WW. This is to ensure a material mass balance over the primary settling tank (PST). By clicking on the *N, P, C and Part* tabs at the top left or bottom right of the screen, the organic N, P, C and Particulates (TSS, VSS and ISS) concentrations can entered in the same way as the COD.

Flow rates are required to calculate the flux difference between the raw and settled WW, i.e. the PS flow. The input boxes for raw ADWF and the PST underflow percentage of the ADWF are available below the block diagram (**B**). Associated with the ADWF are the flow factors for peak dry weather (PDWF) and peak wet weather flow (PWWF). Input boxes for other important parameters, such as alkalinity and pH are also provided (**C**). There is no diurnal flow pattern associated with this method so no adjustments are made to the concentrations that are entered, therefore the entered influent concentrations MUST be flow-weighted average (FWA) concentrations (entering the simple average influent concentrations will significantly underestimate the organic, N, P and ISS loads). The TOD (= COD + 4.57×TKN) load amplitude cannot be calculated because a 24h diurnal flow pattern is not entered for this scenario; therefore the TOD amplitude for raw and settled WW must also be entered. This amplitude has an impact on the aeration requirements for the AS system (Musvoto *et al.*, 2002). An example of the data requirements is shown in Table 5.1 and Table 5.2. The data in these tables fall within the expected data ranges of typical South African municipal WWTPs.

**Table 5.1: Direct Input: Primary data requirements**

| | Raw wastewater | | | | | Settled wastewater | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type | COD mgCOD/L | TKN mgN/L | TP mgP/L | TOC mgC/L | Part mg/L | COD mgCOD/L | TKN mgN/L | TP mgP/L | TOC mgC/L | Part mg/L |
| InOrg | - | 47.4 (FSA) | 8.8 (OP) | - | 60.1 (ISS) | - | - | - | - | 12 (ISS) |
| BPO | 650 | 12.9 | 2.4 | 200.7 | 402.7 | 375.2 | 7.7 | 1.5 | 120.7 | 242.2 |
| VFA | 60.2 | - | - | 22.5 | - | - | - | - | - | - |
| FBSO | 160 | 4.8 | 1.0 | 45.5 | - | - | - | - | - | - |
| UPO | 141.3 | 9.5 | 2.4 | 49.4 | 95.4 | 30.8 | 2.1 | 0.5 | 10.8 | 20.8 |
| USO | 50 | 1.2 | 0.0 | 16.6 | - | - | - | - | - | - |

Where:
- Raw wastewater particulates include settleable and non-settleable particulates
- Settled wastewater particulates has only non-settleable particulates

**Table 5.2: Direct Input: Secondary data requirements**

| ADWF | PST Under flow % | PDWF Fac w.r.t ADWF | PWWF Fac w.r.t PWWF | Alk mgAlk/L as $CaCO_3$ | pH | TOD Amp Raw | TOD Amp Settled |
|---|---|---|---|---|---|---|---|
| 32.1 | 0.5 | 2.0 | 1.5 | 350 | 7.0 | 1.20 | 1.20 |

The data for Direct Input can be entered in any order. To transfer the data to the characterisation model, the designer needs to click on the *Accept COD* (or *N*, *P*, *C*, *Part*) *Char Inputs* button (**E**) for each of the characteristic type (COD, N, P, C and Particulate). The flow rates and other inputs have a different accept button, which is located below the *Accept Characteristics* button (*Accept Flow & Other Parameters).* By accepting and transferring the data to the WWChar model in pieces, input checking and error flagging is made easier. From the entered influent COD, N, P, C and VSS concentrations, the mass ratios $f_{cv}$, $f_n$, $f_p$ and $f_c$ are calculated for the FBSO, BPO, USO and UPO components, where the settleable UPO and BPO and non-settleable UPO and BPO can each have different mass ratio values. These calculated mass ratios can be checked against the default mass ratios, which are historically measured values (Wentzel *et al*., 2006; Ekama, 2009). If any of these mass ratios are significantly different then they are flagged in red. To check the calculated mass ratios, the *Check Calculated Mass Ratios* button (**B**) must be clicked.

Unless negative, the flagged (marked red) mass ratios do not stop the characterisation process. However, if the designer wishes, instead of using the BSO, USO, BPO and UPO characteristics that result in flagged mass ratios, custom (or default) mass ratios can be used to calculate the FBSO, USO, BPO and UPO characteristics. In order to do this, the $f_{cv}$, $f_n$, $f_p$ or $f_c$ check boxes (indicated with the black rectangle in Figure 5.1) must be checked, and the preferred (custom) mass ratios must be entered in the mass ratios table (**D**). Then keeping the COD, free and saline ammonia (FSA) and ortho-phosphate (OP) and inorganic suspended solids (ISS) concentrations the same, new FBSO, BPO, USO and UPO OrgN, OrgP, OrgC and VSS concentrations are calculated (depending on which of the $f_{cv}$, $f_n$, $f_p$, or $f_c$ are checked), resulting in revised influent TKN, TP, TOC and VSS concentrations in the block diagrams. Thus, the custom mass ratios are used to calculate new wastewater organics concentrations keeping the COD and inorganic characteristics (FSA, OP and ISS) the same. Furthermore because the COD/VSS $f_{cv}$ mass ratio for the FBSO and USO cannot be measured, if custom $f_n$, $f_p$ or $f_c$ mass ratios are entered then the FBSO and USO $f_{cv}$ mass ratios are automatically required inputs. It is advised to select custom mass ratios in the range set within the program; no mass ratio should be flagged red, unless there is strong evidence for accepting such value.

When clicking on the accept buttons, warning boxes are displayed if there are any critical input errors occur (see Figure 5.2). The designer can cycle through the different block diagrams (COD, N, P, C, Particulates for raw WW, settled WW and PS) and the different input pages (COD, N, P, C, Particulates) by using the tab buttons provided (red rectangles). The characterisation results are only displayed when all required data is entered.

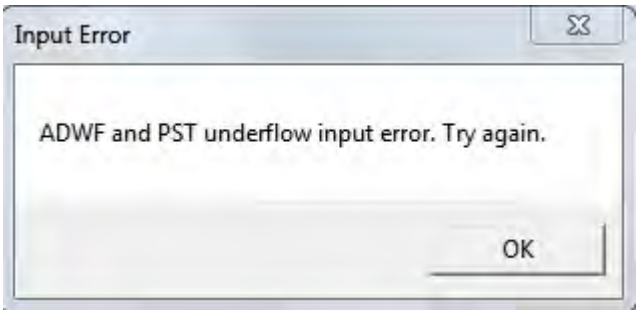



**Figure 5.2: Example of a message box indicating an input error**

### 5.1.2 Characterisation Procedure

Figure 5.3, on the next page, shows a completed Direct Input window with the data from the tables entered into the input boxes and the results from the characterisation shown in the block diagram. Using the data in Table 5.1 and Table 5.2, the characterisation procedure is straightforward. The soluble concentrations (VFA, FBSO, and USO) remain the same for the raw WW, settled WW, and PS; therefore, by entering the soluble concentration for the raw WW, the concentrations for the settled and PS are fixed to the same concentrations. The particulate concentrations in the raw WW consist of settleable and non-settleable particulates (BPO and UPO); the settled WW consists of only non-settleable particulates. Knowing both the raw and settled WW particulate concentrations, the raw WW settleable particulates concentration can be calculated. For example, in Figure 5.3 below, the entered raw WW BPO COD was 650 mgCOD/L, which consists of settleable and non-settleable BPO. The entered settled WW BPO was 380 mgCOD/L; this concentration consists of non-settleable BPO only. Therefore, the raw WW settleable BPO is simply 650 - 380 = 270 mgCOD/L.

With the raw and settled WW concentrations known, using the raw WW ADWF and the PST underflow as a percentage of the raw WW ADWF, the settled WW, and PS flow rates can be calculated. The raw and settled WW fluxes of each wastewater component can then be calculated using the concentrations and flow rates. The difference between the raw and settled WW fluxes is the PS flux, and the PS concentration is the PS flux divided by the PS flow rate. For the N, P, and particulates, the TKN, TP, and particulates (TSS, ISS) concentrations are obtained by adding the inorganic concentrations (FSA, OP and ISS) to the total organic concentrations (OrgN, OrgP and VSS). Once the concentrations are calculated, the mass ratios ($f_{cv}$, $f_n$, $f_p$ and $f_c$) are calculated automatically (**D**). Note that due to the characterisation procedure, if the entered particulate raw WW concentrations are the same as the particulate settled WW particulates concentrations, then the raw WW settleable particulates concentration will be zero and raw and settled WW will be the same. Consequently, the settleable particulates mass ratios will be incalculable as a division by zero will occur (0 mgVSS/L), thus for mass ratios that are incalculable default mass ratios are substituted in.

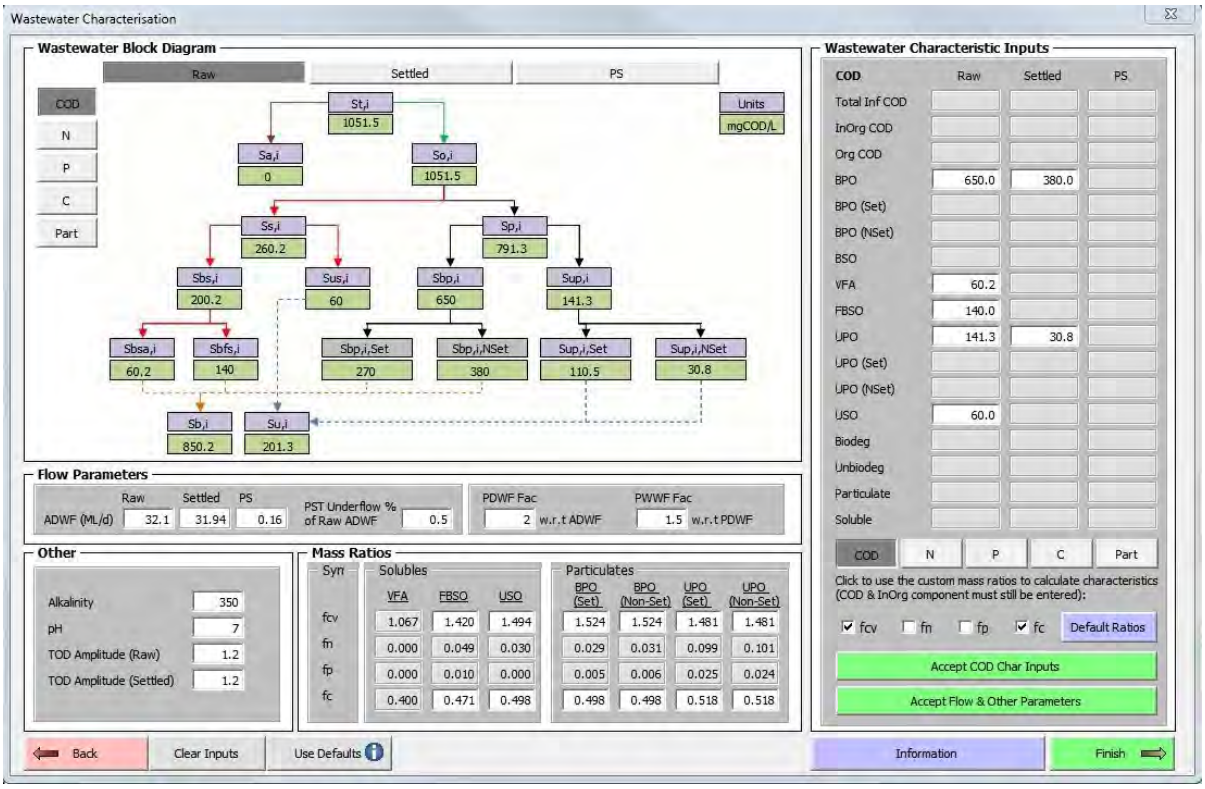



**Figure 5.3: Direct Input with entered data**

### 5.1.3 Optional Inputs

Total Organic Carbon (TOC) data is not always available to the designer. To generate the missing the data, $f_{cv}$ and $f_c$ mass ratios can be used to generate the TOC concentrations. These ratios are used to calculate the TOC concentrations of the seven different organics components (VFA, FBSO, USO, settleable BPO, non-settleable BPO, settleable UPO and non-settleable UPO). Note that because the VFA is pre-defined from its known composition ($CH_3COOH$ or $C_1H_2O_1N_0P_0$), its $f_c$ (and $f_{cv}$) mass ratio cannot be changed. Utilising these $f_{cv}$ and $f_c$ mass ratios to find the TOC concentration is in effect the same as when the mass ratios are flagged in red and custom mass ratios are entered as a substitute for the incorrect characteristics. To use custom mass ratios, check the mass ratio checkbox at the bottom right (indicated with the black rectangle in Figure 5.1), the mass ratios can then be entered in the mass ratios table.

If the mass ratios option is selected to calculate the N, P and C concentrations of the six organics components, but the designer is unsure of what mass ratios to use, default mass ratios can be loaded by clicking on the *Default Ratios* button placed next to the mass ratios check boxes. Because the raw and settled WW inorganic (ISS) concentrations are independent of the seven organics components, these have to be entered separately in the particulates (Part) menu. Default values also can be used for the secondary (*Other*) parameters: Alkalinity, pH, TOD amplitude for raw and settled WW.

### 5.1.4 Comments and Conclusion

The Direct Input method focuses on specifying ADWF, PDWF and PWWF and the raw WW and settled WW characteristics only and therefore should only be used if all the wastewater flow-weighted average COD, FSA, OP, and ISS concentrations are known. The designer enters very specific data in a systematic manner, which guides the data input to avoid errors and influent wastewater characteristic inconsistencies. If the designer does not have all these wastewater concentrations, it is recommended to use a different WWChar input method that is suitable for the level of data available. The same basic WWChar calculation procedure is used for all five methods of wastewater characteristic information input. The only difference is that if less data is available, more information needs to be assumed - from user experience or from default literature values.

## 5.2 Method 2: Diurnal Flow Data

The Diurnal Flow Data (DFData) method focuses on a data rich scenario where a dry weather diurnal flow, COD, TKN, FSA, OP and ISS concentration patterns and a PWWF are known. The majority of inputs are obtained directly from tests on wastewater samples and there are only two important decisions required from the designer: the type of diurnal data (raw WW or settled WW samples), and complete or partial flow-weighted average data. This method represents the ideal situation and generates reliable wastewater characteristics as WWChar procedure is data focused and the decisions made by the designer are data centred.

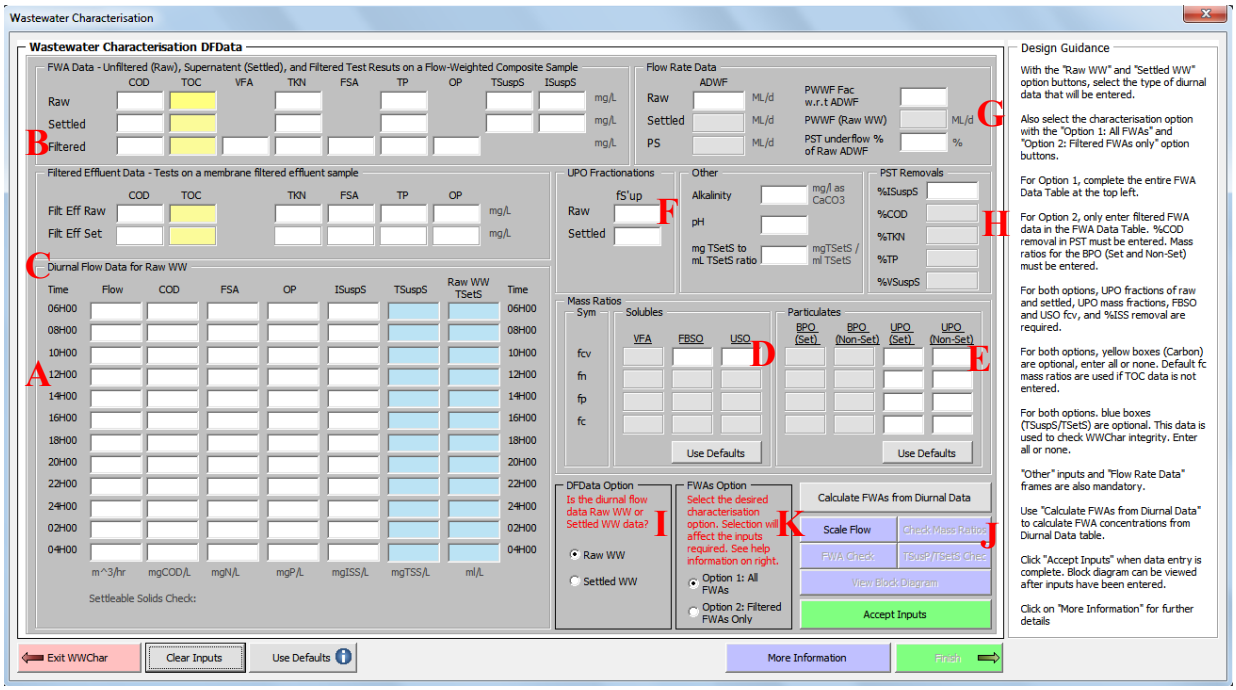



**Figure 5.4: DFData**

Figure 5.4 on the previous page, shows the DFData window. The central grey frame contains the data tables for data entry. The functions and controls relevant to DFData are located at the bottom right of the grey frame. The *Design Guidance* frame, on the right, provides a brief tutorial on using the DFData method and displays all relevant information in the characterisation and data entry processes.

### 5.2.1 Data Requirements

The list below summarises the influent data that is required for DFData. Following the list, examples of the data are shown in Tables 5.3 to 5.7. A few important points about the data requirements are also presented after the list. The data entry locations marked with the red capital letters on the DFData window (Figure 5.4) coincide with the alphabetical list below. Note that all data is required, **A** to **H**.

**A.** Raw or settled WW diurnal data from 6AM to 4AM, for flow rate, COD, FSA, OP, and ISuspS (settleable + non-settleable for raw WW, or non-settleable only for settled WW). Diurnal data for TSuspS (settleable + non-settleable BPO and UPO) and TSetS (ml/L, settleable BPO and UPO only) are optional. Raw or settled WW diurnal data is selected at **I**.

**B1.** Raw, settled and filtered COD, TKN, FSA, TP, OP, TSuspS, and ISuspS concentrations for a flow-weighted composite sample. These are the flow-weighted averages (FWA). Option **B1** is selected at **K**.

**B2.** Filtered COD, VFA, TKN, FSA, TP, and OP concentrations for a flow-weighted composite sample, and the %COD removal in the PST at **H**. Option **B2** is selected at **K**.

**C.** Filtered effluent concentrations for COD, TKN, FSA, TP, and OP.

**D.** The $f_{cv}$ mass ratios for FBSO and USO. The $f_n$, $f_p$ and $f_c$ are calculated.

**E.** $f_{cv}$, $f_n$, $f_p$ and $f_c$ for settleable and non-settleable UPO, these mass ratios do not have to be the same.

- If option **B1** is selected, $f_{cv}$, $f_n$, $f_p$ and $f_c$ for the settleable and non-settleable BPO are calculated. They are also calculated for the FBSO and USO.
- If option **B2** is selected, $f_{cv}$, $f_n$, $f_p$ and $f_c$ for the settleable and non-settleable BPO must be entered**.** They must also be entered for the FBSO and USO.

**F.** Raw and settled WW UPO fraction ($f_{S'up}$).

**G.** Raw ADWF, PST underflow % of raw ADWF, and PWWF factor (w.r.t. to ADWF); PDWF factor (w.r.t. to ADWF) determined from diurnal flow rate data (**A**).

**H.** Alkalinity, pH, TSetS ml/L to mg/L ratio, and % ISS removal in PST (and %COD removal if required)

The diurnal TSuspS and TSetS data are not actually used in the characterisation procedure as the diurnal TSuspS and TSetS concentrations are calculated from the diurnal COD and ISuspS data (**A**) and the $f_{cv}$ mass ratios for the settleable BPO and UPO and the non-settleable BPO and UPO (**E**). However if the diurnal TSuspS and TSetS data is entered, then the entered diurnal data can be used to check the calculated TSuspS and TSetS concentrations. If the calculated and actual data are significantly different then there can be problems in the entered data. This is discussed in more detail in Section 5.2.3 Optional Inputs.

The diurnal data provided in Table 5.3 are from raw WW grab samples, however the settled WW diurnal data can be used instead, the type of grab sample is designated by selection of the *Raw wastewater* or *Settled wastewater* option button at (**I**). This selection affects the characterisation procedure, which is discussed further in Section 5.2.2. The two different options for **B** are also discussed in Section 5.2.2. As with the Direct Input example, the data presented here falls within the data ranges of typical South African municipal WWTPs.

**Table 5.3: DFData inputs - Raw wastewater flow and concentrations for dry weather conditions**

| Time | Flow $m^3/hr$ | COD mg/L | FSA mgC/L | OP mgN/L | ISuspS mg/L | TSuspS mg/L | TSetS ml/L |
|---|---|---|---|---|---|---|---|
| 06h00 | 480.0 | 392.0 | 19.6 | 3.1 | 19.0 | 211.1 | 5.0 |
| 08h00 | 673.0 | 396.0 | 27.9 | 2.8 | 31.0 | 225.2 | 4.4 |
| 10h00 | 2000.0 | 746.0 | 46.1 | 6.4 | 43.5 | 408.9 | 7.9 |
| 12h00 | 2293.0 | 1026.0 | 53.8 | 9.2 | 65.0 | 567.8 | 11.0 |
| 14h00 | 1993.0 | 1156.0 | 59.7 | 10.2 | 70.5 | 636.9 | 12.3 |
| 16h00 | 1560.0 | 1184.0 | 64.0 | 10.7 | 76.0 | 656.0 | 12.7 |
| 18h00 | 1360.0 | 1306.0 | 53.3 | 11.8 | 81.0 | 721.2 | 14.0 |
| 20h00 | 1547.0 | 1212.0 | 49.1 | 10.4 | 70.5 | 664.3 | 12.8 |
| 22h00 | 1413.0 | 1119.0 | 43.9 | 9.5 | 59.5 | 607.9 | 11.7 |
| 00h00 | 1293.0 | 1072.0 | 34.1 | 8.7 | 54.0 | 579.5 | 11.1 |
| 02h00 | 907.0 | 979.0 | 32.0 | 8.4 | 48.5 | 528.4 | 10.1 |
| 04h00 | 587.0 | 653.0 | 26.0 | 5.6 | 30.0 | 349.8 | 6.7 |
| 06h00* | 480.0 | 392.0 | 19.6 | 3.1 | 19.0 | 211.1 | 5.0 |
| Simple Ave (Simpsons Rule) | 1336.6 | 932.4 | 42.5 | 8.0 | 54.2 | 511.1 | 9.9 |
| FWA (Simpsons Rule) | | 1016.3 | 47.3 | 8.8 | 60.1 | 558.0 | 10.7 |
| %Diff between Ave and FWA | | 9.0 | 10.3 | 9.2 | 9.8 | 8.4 | 9.2 |

* Extra 6AM value is required for Simpsons rule to compute averages, last 6AM same as first 6AM.

**Table 5.4: DFData inputs - Raw and settled WW concentrations for a flow-weighted composite sample**

| Tests | COD mg/L | VFA mg/L | TOC mgC/L | TKN mgN/L | FSA mgN/L | TP mgP/L | OP mgP/L | TSS mg/L | ISS mg/L |
|---|---|---|---|---|---|---|---|---|---|
| Raw wastewater | 1016 | --- | 336.8 | 75.8 | --- | 14.58 | --- | 558 | 60 |
| Settled wastewater | 656 | --- | 217.7 | 63.2 | --- | 11.76 | --- | 275 | 12 |
| Filtered | 250 | 60 | 85.8 | 53.4 | 47.4 | 9.78 | 8.82 | --- | --- |

Where:
- Entire table is required for option B1; for option B2, required data is shaded in red

**Table 5.5: DFData inputs - Membrane filtered effluent from raw AS system @ 18°C**

| Tests | COD mg/L | VFA mg/L | TOC mgC/L | TKN mgN/L | FSA mgN/L | TP mgP/L | OP mgP/L | TSS mg/L | ISS mg/L |
|---|---|---|---|---|---|---|---|---|---|
| Raw wastewater | 50 | 0 | 17.0 | 1.5 | 0.34 | 8.74 | 8.74 | --- | --- |
| Settled wastewater | 50 | 0 | 17.0 | 1.5 | 0.34 | 8.74 | 8.74 | --- | --- |

**Table 5.6: DFData inputs - mass ratios**

| Mass ratio | FBSO | USO | UPO (settleable) | UPO (non-settleable) |
|---|---|---|---|---|
| $f_{cv}$ | 1.450 | 1.500 | 1.481 | 1.481 |
| $f_n$ | / | / | 0.100 | 0.100 |
| $f_p$ | / | / | 0.025 | 0.025 |
| $f_c$ | / | / | 0.518 | 0.518 |

**Table 5.7: DFData inputs - Other data inputs**

| Input | Value |
|---|---|
| $f_{S'up}$ Raw | 0.139 |
| $f_{S'up}$ Settled | 0.047 |
| ADWF (ML/d) | 32.1 |
| PST Underflow % | 0.5 |
| Alkalinity (mg/L as $C_aCO_3$) | 300 |
| pH | 6.8 |
| %ISS removal in PST | 80 |

The data required for **A** and **B** in the DFData window (Figure 5.4) is of a high level because the data is not easily measurable; furthermore, many characterisation tests are required. The diurnal data for **A** (Table 5.3) comprises a series of grab samples collected and tested at regular (2h) intervals throughout the day, for COD, FSA, OP, ISuspS, TSuspS, and TSetS (mL/L). The diurnal data for TKN and TP is not required as this can be calculated from the FSA and OP and the mass ratios. The characterisation procedure, discussed further in Section 5.2.2, calculates the OrgN and OrgP constituents from the COD constituents with the respective $f_{cv}$, $f_n$, and $f_p$ mass ratios. The OrgN is added to the FSA, and the OrgP is added to the OP, this gives the respective TKN and TP concentrations. This fixed "addition" relationship between the OrgN, OrgP and COD is the reason why the diurnal FSA and OP concentrations are entered and not the diurnal TKN and TP concentrations. Not only are TKN and TP concentrations analytically more burdensome to measure (samples require a prior acid digestion step), using the diurnal TKN and TP concentrations can result in negative diurnal FSA and OP concentrations if the calculated OrgN or OrgP exceeds the entered TKN or TP, i.e. FSA = TKN – OrgN, and OP = TP – OrgP. However, when TKN, FSA, TP and OP are all measured, it becomes possible to calculate the $f_n$ and $f_p$ mass ratios of the organics groups. Although this is not available as the likelihood of having both measurements is low and because with both measurements, inconsistent mass ratios can occur, which greatly complicates the WWChar procedure. The WWChar procedures for the diurnal TKN and TP also apply to the diurnal TSS and TSetS (mL/L), the calculated VSS concentrations are added to the entered ISS concentration. It is thus with this procedure that diurnal TSS and TSetS data is not actually required for the DFData method. TSS and TSetS data is discussed further in Section 5.2.3 Optional Inputs.

For **B**, the flow-weighted average (FWA) concentrations for the COD, TKN, FSA, TP, OP, TSS and ISS flow-weighted average (FWA) concentrations are required (Table 5.4). To obtain FWA concentrations, a flow-weighted composite sample needs to be collected and tested. This is done by collecting (sometimes with an automatic composite sampler but usually manually) a wastewater grab sample every 2h over a 24h day, where the volume of the grab samples taken is proportional to the influent flow rate. These 12 grab samples from 6AM to 4AM are then combined and tested. So in effect, by collecting the 12 flow-weighted grab samples, which are combined and tested for **B** (Table 5.4), the diurnal COD, FSA, OP, TSS, ISS and TSetS (mL/L) concentration data required for **A** can also be generated by testing each flow-weighted grab sample before it is combined with the rest. This can save time and effort because the number of tests is reduced. Each flow-weighted grab sample is tested only for COD, FSA, OP, TSS, ISS and TSetS (mL/L). The final composite sample will then be tested for the COD, TKN, FSA, TP, OP, TSS and ISS FWA concentrations, and the filtered COD, VFA, TKN, and TP FWA concentration.

If the flow-weighted grab samples are raw WW samples, then the final composite sample can be settled in an Imhoff cone and the supernatant tested for the settled WW COD, TKN, TP, TSS, and ISS FWA concentrations. This is obviously not possible if the flow-weighted grab samples are settled WW samples because it is impossible to "unsettle" the settled WW samples.

If the samples are from settled WW, then an alternative method (option **B2**) will have to be used to generate the raw WW data from settled WW data. In this option, alternative inputs are required. These inputs are the %COD removal in the PST and the $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios for the settleable and non-settleable BPO. These inputs replace the raw and settled WW COD, TKN and TP FWAs. However, the filtered FWA concentrations must still be entered. Note that this option is not limited to only settled WW grab samples; it can also be used for raw WW grab samples. In fact, the purpose of option **B2** is to cater for the lack of FWA data, and thus the FWA table (**B**) cannot be fully completed. This is discussed further in Section 5.2.2.

FWAs are extremely important. If a non-flow-weighted composite sample is tested (i.e. where equal volume of 2-hourly grab samples are mixed and tested), the "average" concentrations will be significantly lower than the FWA concentrations. The percentage differences between the non-flow-weighted and flow-weighted samples will depend on the amplitude of the diurnal flow and COD concentration pattern. For strong diurnal patterns where the diurnal flow rate profile and the diurnal concentration profile vary significantly, this difference can be greater than 30%, which means that the organic load can be under estimated by more than 30%. In the data tables above, the diurnal flow pattern has a mild variation and concentration patterns are similar. In this case, the FWA for COD is 1016 mgCOD/L and the non-flow-weighted (simple average) concentration is 932.4 mgCOD/L, these averages give a percentage difference of only 9%. For the other parameters, FSA, OP, ISuspS, TSuspS this difference is 10.3%, 9.2%, 9.8%, and 8.4%. These percentages show that in this example, if the simple average is used, the organic load is underestimated ±10%. If the influent flow and COD concentration vary as in phase sine waves each with an amplitude of 1, the FWA COD is 50% higher than the simple average, i.e. FWA concentration = (1+ab/2) × simple average concentration, where a and b are the amplitudes of the flow and COD concentration sine waves over 24h.

If a flow-weighted composite sample cannot be collected, the FWA concentrations can be calculated, but only if the diurnal flow variation and concentration results, from the individual 12 diurnal grab samples from 6AM to 4AM for the required parameter (COD, TKN, FSA, TP, OP, TSS and ISS), are available. At each (2-hourly) sample time, the concentration parameter is multiplied by the flow rate to obtain the flux; the average of the fluxes is then calculated (area under flux vs time curve) and divided by the average flow rate. Therefore, instead of obtaining a single flow-weighted composite sample and testing it for the FWA concentrations, the FWA concentrations can be calculated from individual grab sample concentrations instead, but this requires a lot more analytical work. Whether this is more accurate or easier will be ultimately up to the judgement of the designer. However, because the diurnal data is a requirement for DFData input method, the individual grab sample results need to be entered, from which the FWA concentrations are calculated.

A function to automate the calculation of the FWA concentrations has been included. This function can be accessed by clicking on *Calculate FWAs from Diurnal Data* button (**J**).

When clicked, the FWAs for the COD, FSA, OP, and ISuspS and TSuspS are calculated using the diurnal data entered in the diurnal flow data section (**A**). If the *Calculate FWAs from Diurnal Data* function is not used, and both the diurnal grab sample concentrations and the FWAs are entered, then the entered FWAs at **B** for the COD, FSA, OP, and ISuspS must reflect the diurnal data at **A**, i.e. if the FWAs were to be calculated from the entered diurnal data at **A**, then these FWAs must match the entered FWAs at **B**. If they do not match well enough (±5%), then there is likelihood that the entered data (FWAs or the diurnal data) is incorrect. At the end of the characterisation procedure, a window displaying the calculated and entered FWAs is shown (Figure 5.5). The percentage differences (error) between the calculated and entered FWA concentrations are shown and if it greater than 5% are flagged as an error. The error does not stop the usage of the calculated FWA concentrations, but it is recommended to proceed with no errors by changing one or more of the diurnal concentrations.

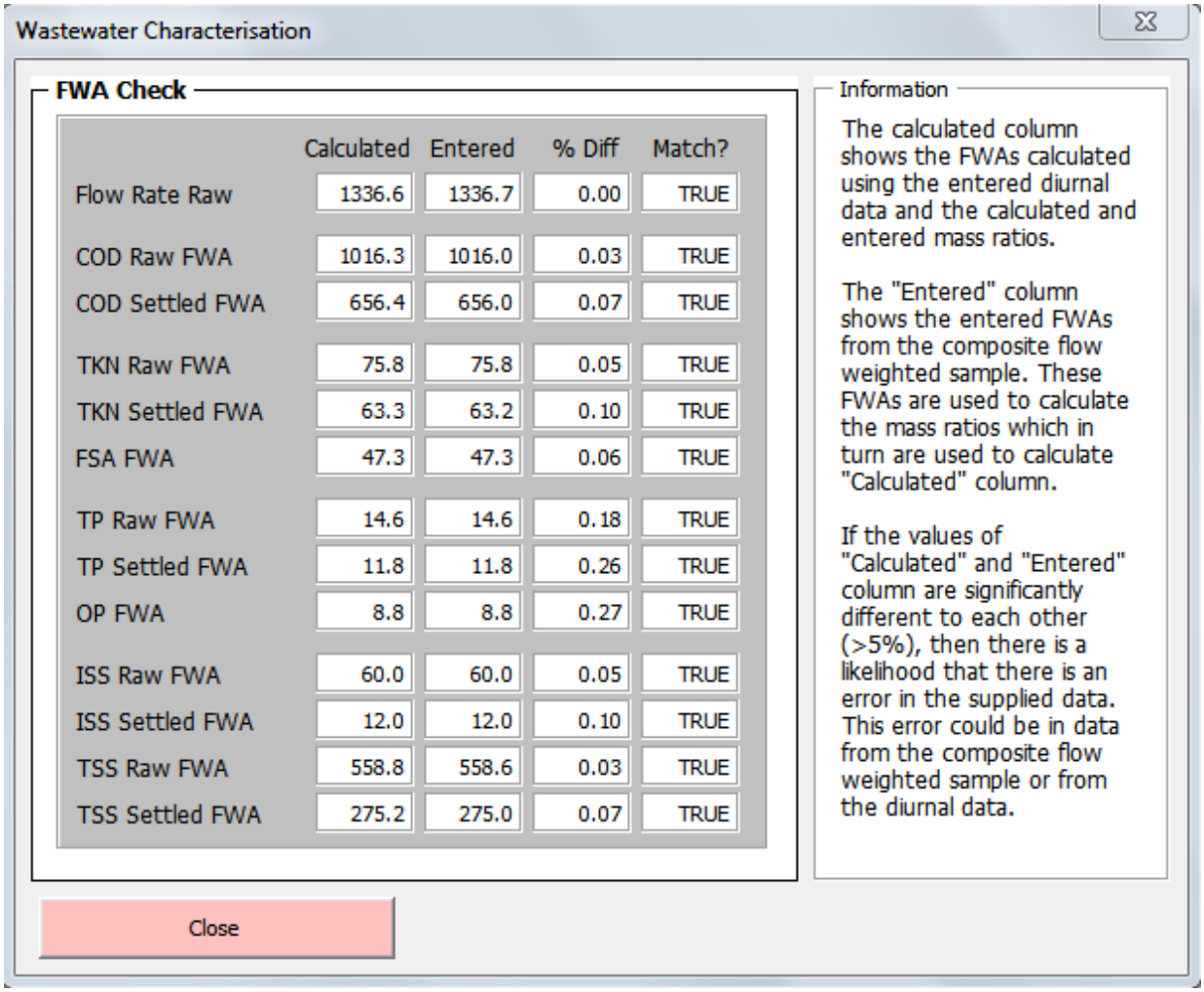



**Figure 5.5: DFData – FWA Check**

Table 5.8 summarises this section, it is the same table as Table 5.4, but the cells are shaded in different colours to the origin of the FWA data. Assuming that the grab samples are raw WW samples, the concentrations in the blue cells can be calculated from the 12 flow-weighted grab samples or it can be generated from tests on a flow-weighted composite sample. The orange cells are from the tests on the flow-weighted composite sample, and the green cells are from the tests on the Imhoff cone supernatant of the flow-weighted composite sample.

**Table 5.8: Origins of the FWA concentrations if raw WW grab samples are collected**

| Tests | COD mg/L | VFA mg/L | TOC mgC/L | TKN mgN/L | FSA mgN/L | TP mgP/L | OP mgP/L | TSS mg/L | ISS mg/L |
|---|---|---|---|---|---|---|---|---|---|
| Raw wastewater | 1016 | --- | 336.8 | 75.8 | --- | 14.58 | --- | 558 | 60 |
| Settled wastewater | 656 | --- | 217.7 | 63.2 | --- | 11.76 | --- | 275 | 12 |
| Filtered | 250 | 60 | 85.8 | 53.4 | 47.4 | 9.78 | 8.82 | --- | --- |

Where:
- Blue cells are from tests on the flow-weighted composite sample, or calculated from the 12 flow-weighted grab samples
- Orange cells are from tests on the flow-weighted composite sample
- Green cells are from tests on the Imhoff cone supernatant of the flow-weighted composite sample

Figure 5.6 below shows the DFData window with all the data from Table 5.3 to Table 5.7 entered into the respective sections. In this Figure because the diurnal data comprises of raw WW grab samples, the *Raw wastewater* option button at I was selected. Furthermore, because the FWA table at B can be fully completed with the data in Table 5.4, option **B1** was selected and thus the *Option 1: All FWAs* checkbox at **K** was also selected. FWAs for the raw COD, filtered FSA, filtered OP, raw TSS, and raw ISS at **B** were entered directly; the *Calculate FWAs from Diurnal Data* (**J**) function would have provided the same result as the data in Table 5.3 is from data set in Table 5.4. Note that if the *Settled wastewater* option button was selected then the *Calculate FWAs from Diurnal Data* (**J**) function would calculate the FWAs for the settled COD, filtered FSA, filtered OP, settled TSS and settled ISS. Alternatively, for option **B2**, the *Option 2: Filtered FWAs Only* checkbox at **K** must be selected, the FWA table (**B**) will not allow data entry in the Raw and Settled wastewater rows. The *%COD removal* input box and the $f_{cv}$, $f_n$, $f_p$, and $f_c$ input boxes for the settleable and non-settleable BPO will be available as they replace the missing raw and settled WW FWAs in the characterisation procedure. As with option B1, the $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios for the settleable and non-settleable UPO must also be entered, and as well as the $f_{cv}$ mass ratios for the FBSO and USO. Figure 5.7 shows this alternative option, the slight differences in the inputs are marked with the black rectangles.

With an understanding of the data entry options for the characterisations procedure, the characterisation procedure, which runs in the background, is presented in the next section.

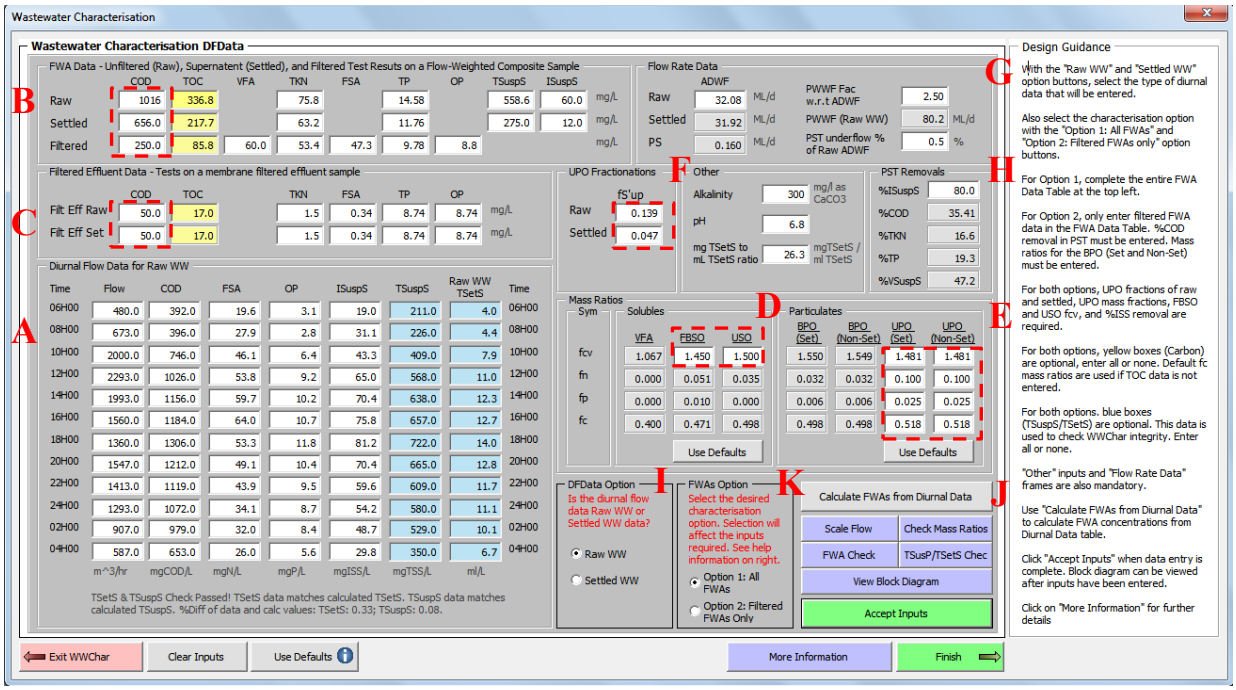



**Figure 5.6: DFData – Option B1**

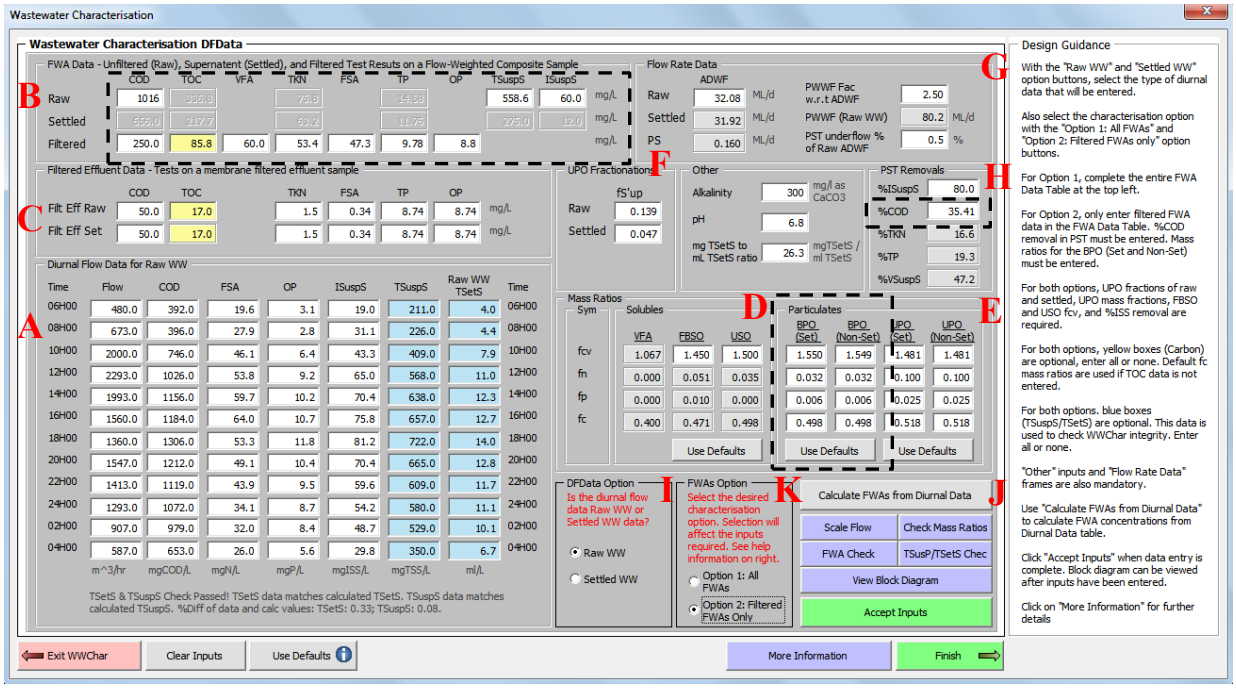



**Figure 5.7: DFData – Option B2**

## 5.2.2 Characterisation Procedure

The FWAs of the seven COD organic groups (VFA, FBSO, USO, settleable BPO and UPO and non-settleable BPO and UPO), for raw and settled WW, can be obtained with the COD characterisation parameters, *viz*. effluent COD concentration from which the influent USO fraction ($f_{S'us}$) is calculated, the UPO fractions ($f_{S'up}$) of the raw and settled WW, and the COD/VSS ($f_{cv}$) mass ratios of the settleable and non-settleable UPO. These parameters are indicated by the red rectangles in Figure 5.6.

The crux of the procedure assumes that the relative proportions and mass ratios of the seven organic groups do not change over 24h. Therefore, knowing the COD concentrations of the seven FWA organic groups, the COD concentrations of the seven organic groups at each sample time can be calculated from the total COD concentration at that sample time. Furthermore, because the seven organic groups have an OrgN, OrgP, OrgC and VSS part, the relative proportions between the OrgN, OrgP, OrgC, and VSS of the seven organic groups also remain constant. Then with the $f_{cv}$ $f_n$, $f_p$, and $f_c$ mass ratios and the COD concentrations of the seven organic groups, the total OrgN, OrgP, OrgC and VSS at each sample time can be calculated. These are then be added to their respective inorganic concentrations (FSA, OP, and ISS) to obtain the total concentrations (TKN, TP, and TSS).

The assumption that the mass ratios and the relative proportions of the organics groups with respect to the total remain constant over a 24h diurnal period simplifies the WWChar even though it probably does not reflect reality. In reality, the proportions and mass ratios do change, but modelling this will make the characterisation procedure unnecessarily complicated. Furthermore, the raw, settled, filtered, filtered effluent, raw and settled $f_{S'up}$, and $f_{cv}$ mass ratios for FBSO, USO, and settleable and non-settleable UPO will be required for each (2h) grab sample. This is practically not possible as it requires intensive testing. The assumption that the proportions and mass ratios remain constant therefore not only simplifies the characterisation process but it also reduces the input data required for characterisation.

In the characterisation procedure, the appropriate split between the settleable and non-settleable particulates is required. This is because in this program, the settleable and non-settleable particulates can have different mass ratios. This needs to be accounted for in the characterisation procedure if the designer wishes to use different mass ratios (to date there is too little historical evidence to define different mass ratios for the settleable and non-settleable UPO and BPO, but in time, this may become known). To obtain the settleable and non-settleable split, i.e. in effect the required COD removal in the PST, it is assumed that 100% of the settleable UPO and BPO (with their associated N, P, and C via the mass ratios) are removed in the PST, non-settleable UPO and BPO are not removed. Therefore, to increase the COD removal in the PST, the proportion of settleable UPO and/or BPO is increased at the expense of the non-settleable UPO and/or BPO. The same is done for the ISS. It has been found that PSTs remove greater proportions of UPO and ISS than BPO (Ekama *et al*., 2006a), i.e. ISS is removed between 70-90%, UPO between 65 to 85% and BPO between 35-55%. If this were

not the case, then the range of observed VSS/TSS ratio (0.70-0.80) and unbiodegradable COD fraction ($f_{PS'up}$, 0.60-0.70) of PS would not be obtained by the WWChar model.

In the characterisation procedure, the raw WW characteristics are computed first, and initially only the total (settleable + non-settleable) BPO and UPO particulate concentrations are known. The total UPO in raw WW is equal to the total COD multiplied by raw WW $f_{S'up}$ fraction, and the total BPO fraction is calculated from the difference between the total particulate concentration, where the latter is the total COD minus the VFA, FBSO and USO (i.e. total soluble concentration). The settled WW BPO and UPO concentrations are then calculated the same way, where the total BPO and UPO concentrations in the settled WW are assumed to comprise only non-settleable particulates. Hence, the concentration of settleable BPO and UPO in the settled WW is zero. From this assumption, the concentrations of the settleable UPO and BPO in the raw WW are given by the difference between the raw and settled WW UPO concentrations and raw and settled WW BPO concentrations respectively. The BPO and UPO particulates splitting process is demonstrated in the steps below:

1. Compute raw WW characteristics.
2. Raw wastewater settleable and non-settleable particulates (split is currently unknown).
3. Compute settled WW characteristics.
4. Assume only settleable BPO and UPO are removed in the PST.
5. Thus, total BPO in settled WW comprises of only non-settleable BPO.
6. Thus, total UPO in settled WW comprises of only non-settleable UPO.
7. Carry non-settleable BPO and non-settleable UPO in settled WW to raw WW.
8. Raw wastewater settleable BPO = total raw BPO – non-settleable BPO.
9. Raw wastewater settleable UPO = total raw UPO – non-settleable UPO.

With the COD characterisation procedure in mind, it can be seen that the FWA COD concentration for the raw WW and the settled WW is required. This is because Step 3 in the BPO and UPO particulates splitting process is independent of the raw WW characteristics, i.e. the settled WW characteristics are calculated and its non-settleable particulates concentrations are transferred to the raw WW characteristics.

The FWA COD concentration for the settled WW is specified according to the option selected (**B1** or **B2**). For option **B1**, all FWA concentrations (COD, TKN, TP, TSS, and ISS) for the raw and settled WW are entered. These FWA concentrations are used to generate the COD, N, P, and particulates concentrations of the seven organic groups. The non-entered $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios and the relative proportions of the seven organic constituents are calculated from these FWA concentrations. These proportions are assumed constant throughout the day and are used to generate the complete diurnal profile, i.e. VFA, FBSO, USO, settleable

BPO and UPO, and non-settleable BPO and UPO concentrations for COD, N, P, C, and particulates, at each time step for the raw and settled WW. Note that by entering the FWA COD concentration for the raw WW and settled WW, the %COD removal (Equation 5.1) is indirectly specified and thus the *%COD removal in PST* box at **H** is automatically completed.

**Equation 5.1: WWChar - %COD removal**

$$\%\textbf{COD removal} = [(\textbf{raw COD} - \textbf{settled COD}) / \textbf{raw COD}] \times 100\%$$

Alternatively, for option **B2**, the %COD removal is entered in the *%COD removal* input box. For this option, in the FWA table (**B**), only the filtered FWA COD, VFA, TKN, and TP concentrations are entered. The $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios for the settleable and non-settleable BPO must be entered because they cannot be calculated with option **B2**. This is in addition to the $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios for the settleable and non-settleable UPO, and the $f_{cv}$ mass ratios for the FBSO and USO. At this stage, the FWA table appears as Table 5.9, where the blue cells are calculated from the diurnal data (**A**) using the *Calculate FWAs from Diurnal Data* button (**J**); the orange cells are entered; the yellow cell is calculated with the %COD removal, which in this case is 35.4%; and the purple cells are not required. Note that this is for the raw WW diurnal data example, if settled WW diurnal data was used then the colours of the 1016 mgCOD/L and 656 mgCOD/L cells will be swapped around. If option **B1** is selected, all the data in Table 5.9 is available and hence can be entered in the FWA table (**B**).

**Table 5.9: FWA concentration inputs for Option B2**

| Tests | COD mg/L | VFA mg/L | TOC mgC/L | TKN mgN/L | FSA mgN/L | TP mgP/L | OP mgP/L | TSS mg/L | ISS mg/L |
|---|---|---|---|---|---|---|---|---|---|
| Raw wastewater | 1016 | --- | ? | ? | --- | ? | --- | 558 | 60 |
| Settled wastewater | 656 | --- | ? | ? | --- | ? | --- | ? | ? |
| Filtered | 250 | 60 | 85.8 | 53.4 | 47.4 | 9.78 | 8.82 | --- | --- |

Where:
- Blue cells calculated from diurnal data
- Orange cells are entered
- Yellowcell calculated from diurnal data entered %COD removal in PST
- Purple cells are not required

With the COD characterisation parameters known (raw, settled, and filtered FWA COD concentrations, raw and settled $f_{S'us}$ and $f_{S'up}$, and settleable and non-settleable UPO $f_{cv}$), the COD characterisation procedure to split the particulates into settleable and non-settleable parts can be performed and the FWA COD concentrations of the seven organic groups for the raw and settled WW can be calculated. The seven COD concentrations for the raw WW at each sample time are then calculated with the total COD concentrations and the relative proportions

of the seven organics. The settled WW total COD concentration at each sample time can be calculated by assuming a constant %COD removal in the PST and then reducing the total raw WW COD concentration at each sample time by that %COD removal. For option **B2**, this %COD removal is entered directly, and for **B1**, it is calculated with the entered raw WW and settled WW FWA COD concentrations. Assuming a constant %COD removal has the same effect as having all the settleable particulates (BPO and UPO) removed by the PST, i.e. the settled WW COD concentration at each sample time can also be generated by removing the settleable UPO and BPO COD concentrations from the total raw WW COD concentration at each sample time. With the total COD concentration of the settled WW at each sample time known, the COD concentrations for the five remaining organic groups (no settleable BPO and UPO) for the settled WW at each sample time can be calculated because the relative proportions of the five organics for the settled WW is also known.

With the complete diurnal COD concentration for the raw and settled WW calculated, the next step is to calculate the diurnal N, P, C and particulate concentrations. In order to do this the OrgN, OrgP and VSS components of the seven organic groups need to be calculated at each sample time; this is done differently depending on the option selected (**B1** or **B2**). For option **B1**, the entire FWA table was completed. This allows for a direct calculation of the FWA OrgN, OrgP, TOC, and VSS concentrations of each of organic groups (but zero VSS for VFA, FBSO, and USO), and as well as the non-entered $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios. Then at each sample, because the COD concentrations of the seven organic groups are known, the OrgN, OrgP, TOC and VSS concentration of each organic group can be calculated with the $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios determined from the FWAs. Lastly, at each sample time, the entered diurnal FSA, OP and ISS concentrations are then added to the total OrgN, OrgP and VSS concentrations to obtain the total concentrations (TKN, TP and TSS). If option **B2** is selected, a similar process is applied, the only difference is that the because FWA TKN, TP and TOC concentrations for both the raw and settled WW are not entered, the $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios for the settleable and non-settleable BPO cannot be calculated, hence must be entered instead. For the soluble organics (FBSO and USO), these mass ratios can be calculated because the filtered COD, VFA, TKN, and TP FWA concentrations are entered. Therefore, from this it can be seen that the critical difference in option **B1** and option **B2** is the manner in which the mass ratios for the settleable and non-settleable BPO are specified, i.e. if raw and settled WW FWA concentrations are available then the settleable and non-settleable BPO $f_{cv}$, $f_n$, $f_p$, and $f_c$ are not entered, and *vice versa*. Note that the $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios for the settleable and non-settleable UPO (which do not need to be the same), and the $f_{cv}$ mass ratios for the FBSO and USO are always entered, irrespective of the option selected.

A few points arise with this characterisation procedure. By entering a %COD removal with option **B2**, or by indirectly calculating it with option **B1**, the characterisation procedure appropriately assigns the correct settleable UPO and BPO COD concentrations in the raw WW to achieve this COD removal. The %TKN, %TP, and %VSS removals in the PST are then connected to this %COD removal. This is because the TKN, TP and VSS of the settleable UPO

and BPO are linked to the COD via the mass ratios of these two organics groups. Thus, for option **B2**, only the %COD removal in the PST can be specified and the %TKN, %TP, %VSS removals in the PST are fixed by the %COD removal. In fact, the only way the %TKN, %TP, and %VSS removals in the PST can be changed without changing the %COD removal, is by changing the mass ratios of the settleable BPO and UPO groups. Furthermore since the proportions relative to the total COD of the COD of the seven organics groups in the raw WW remains unchanged over the day, the percentage COD, TKN, TP, VSS, and ISS removal in the PST is the same over the day and equal to the average percentage COD, TKN, TP, VSS and ISS removals in the PST. The %ISS removal is independent and needs to be specified separately. For the settled WW ISS concentration, the desired ISS removal in the PST is entered in the *%ISS removal in the PST* input box (e.g. 80%). The diurnal raw WW ISuspS data will then be reduced by this percentage to generate the settled WW ISS concentrations (alternatively it is increased if the diurnal data is settled WW data). So the settled WW concentrations (COD, TKN, TP, TOC VSS and ISS) at each sample time is equal to the raw WW concentrations at each sample time multiplied by 100 minus the percentage removal in the PST divided by 100, *viz*. settled COD = raw COD x (100 - %Rem/100).

Once the raw and settled WW characteristics are determined, the PS characteristics are determined simply by the flux difference of the seven organic groups of the raw and settled WW, divided by the PS flow rate, with the settleable UPO and BPO zero in the settled WW. This flow rate is specified by the *PST underflow % of raw ADWF* input, and is taken as a constant flow rate throughout the day.

For carbon (C), because the C data is not always available, it is an optional input. However, if anaerobic digestion of PS is included in the plant wide set-up, it is recommended that TOC data is obtained and used in the characterisation. An accurate TOC characterisation will result in better predication of methane gas production ($CH_4$), gas composition ($pCO_2$), and anaerobic digester pH. If C data is entered, it is characterised in the same manner as for N and P. The handling of C for is discussed further in Section 5.2.3 Optional Inputs.

The characterisation procedure was discussed primarily for a raw WW diurnal data scenario. If settled WW instead of raw WW diurnal data was entered, the characterisation procedure remains largely the same. The mass ratios are calculated in the same manner; the only difference is that the COD removal and ISS removal part is computed in reverse, i.e. going from settled WW to raw WW, instead of raw WW to settled WW. In summary, the DFData characterisation procedure for the raw WW is as follows:

1. Calculate the FWA COD, N, P, C and particulates concentrations for the seven organic groups for the raw and settled WW.
2. If option **B1** is selected, this can be done with the FWA concentrations and the COD characterisation parameters ($f_{S'us}$, $f_{S'up}$ of the raw and settled WW, and the $f_{cv}$ mass ratios of the settleable and non-settleable UPO). If option **B2** is selected, this can be done with

the entered filtered FWA COD, VFA, TKN, and TP concentrations, the %COD removal, and the additional mass ratios for the settleable and non-settleable BPO.

3. With the total raw WW COD at each sample time, the COD concentration of the seven organic groups for the raw WW, at each sample time, is calculated using the relative COD ratios of the seven organic groups in the raw WW.
4. With the total raw WW COD at each sample time, and assuming a constant %COD removal, the settled COD concentration at each sample time is calculated.
5. With the total settled WW COD at each sample time, the COD concentration of the five remaining organic groups in the settled WW (no settleable BPO and UPO) are calculated using the relative COD ratios of the five organic groups in the settled WW.
6. Using the $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios, the OrgN, OrgP and particulates concentrations for the seven organic groups for the raw and the five for the settled WW at each sample time are calculated.
7. With the entered diurnal inorganic concentrations (FSA, OP, and ISS), the TKN, TP, and TSS is calculated at each sample time.
8. With the diurnal raw and settled WW characteristics, the PS is characterised by the flux difference of seven organic groups in the raw WW and settled WW.

### 5.2.3 Optional Inputs

TOC data is not always available due to the difficulty and equipment required in TOC measurement; hence, it is an optional input. The TOC data are not required by the activated sludge models, which are COD based, unless the $CO_2$ gas evolution from the AS reactors needs to be known. However, for the anaerobic digestion (AD) of PS, C should be known, as the TOC characteristics will design of the anaerobic digester (in terms of $CH_4$, $pCO_2$, and AD pH). The TOC characteristics can be generated using default (or entered) $f_c$ mass ratios for the six organic groups (except VFA). The characterisation procedure is identical to the N and P.

If TOC data is available, the designer enters the TOC data in yellow input boxes, see Figure 5.6. Yellow boxes are used to show that they are optional and can be omitted if the data is not available. Option **B1** and option **B2** also apply to the TOC data entry. If option **B1** is selected, then the FWA TOC concentrations can be entered in **B**. These concentrations, along with the default (or entered) $f_c$ mass ratio for the settleable and non-settleable UPO, and the filtered effluent TOC concentration, allow for the FWA TOC concentrations of the seven organic groups to be calculated. The remaining $f_c$ mass ratios can then calculated because the FWA VSS concentrations are also known. Alternatively, for Option **B2**, the filtered FWA TOC concentration and all the $f_c$ mass ratios, except for the VFA, are entered. The FWA TOC concentrations of the seven organic groups are calculated with the $f_c$ mass ratios and the seven COD concentrations. With the seven FWA TOC concentrations and all the $f_c$ mass ratios

known, the rest of the diurnal TOC concentrations can be generated. The option of partially entering TOC data is not accommodated. All the required TOC data, for the selected input option (**B1** or **B2**), must be entered. If this requirement cannot be satisfied, then partial TOC data must not be entered. In a partial data scenario, default values can be mixed in with the entered data to characterise the wastewater; Method 3: Characterisation Tree caters for this type of scenario; hence, that method should be used if the data set is incomplete.

The diurnal data for total suspended solids (TSuspS or TSS) and total settleable solids (TSetS in ml/L) are also optional inputs. Diurnal TSS and TSetS data is not required to characterise the wastewater. However, due to the simplicity of measuring with an Imhoff cone, TSuspS and TSetS data can easily be collected at 2 hourly intervals over a 24h day; therefore it was necessary to include this data input as an option. The TSuspS and TSetS data is not used to characterise the wastewater but it is used to check the integrity of the COD and particulates (TSS, ISS) characterisation. The calculated total settleable solids (settleable BPO + settleable UPO + settleable ISS) at each sample time is checked with the diurnal the TSetS data (ml/L × 26.3* mgTSetS/L). A percentage difference is calculated for each sample time and an average of these percentages is calculated. The same is done for the calculated TSuspS (VSuspS + ISuspS) and the entered TSS data. If the averages of the percentage differences are greater than 5% then there is a possible error in the diurnal data. When the *Accept Inputs* button is clicked, the characterisation procedure will run and this integrity check will be automatically executed, a message box will show the results of the this check. Figure 5.8 shows this message box informing the user that the entered TSuspS and TSetS match the calculated TSuspS and TSetS.

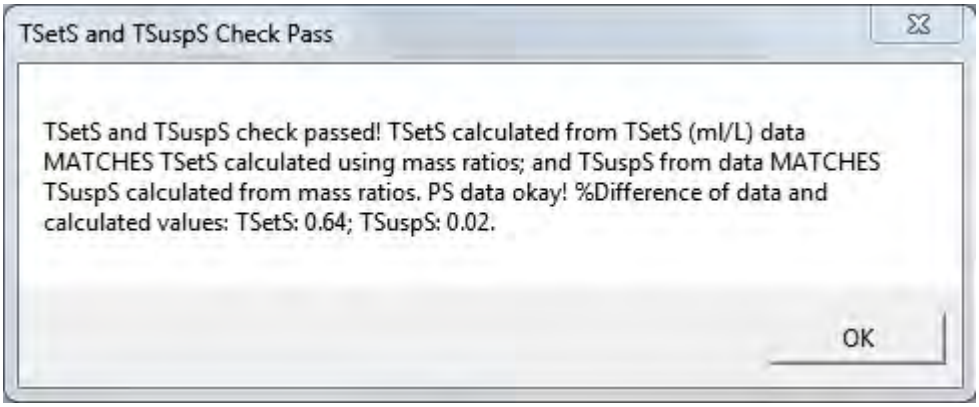
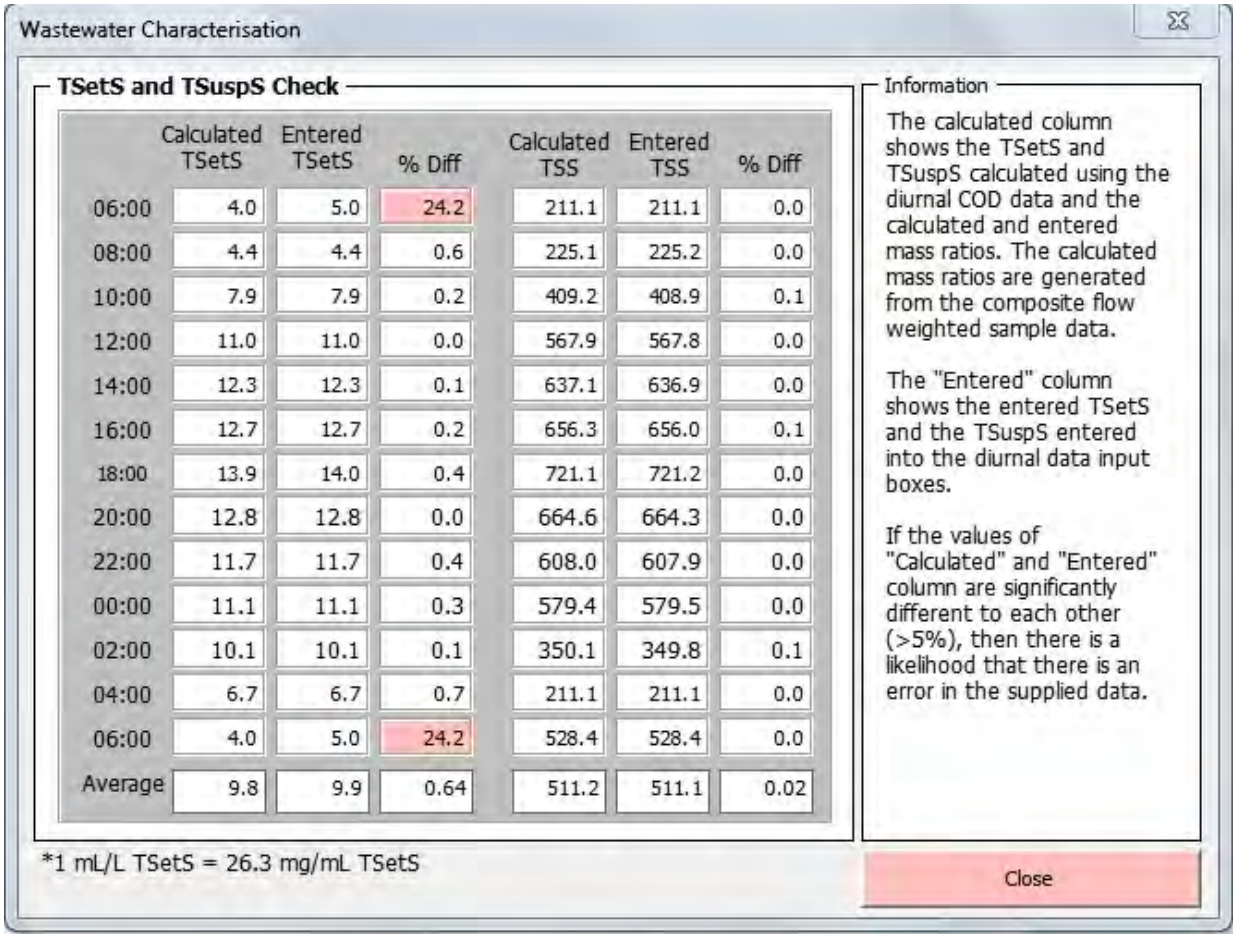



**Figure 5.8: DFData – TSetS and TSuspS data check message box**

* This is an input option and the input box for it is located in the *Other* section; 26.3 mgTSetS/L is the default value but any measured value can be entered.

A more detailed window showing the percentage differences for the calculated and entered TSuspS and TSetS, for each sample time, can be viewed. Differences greater than 5% are highlighted in red; for the data used in this example, it can be seen that the TSetS data at 6AM is incorrect, however because the flow rate is low at this time, it has a small impact on the characterisation – the overall percentage difference of the calculated and entered TSetS is 0.64%. This window can be accessed by clicking on the *TSuspS/TSetS Check* button. Figure 5.9 shows this window. Like the TOC data, because TSS and TSetS is not a requirement for characterisation, their input boxes on the main *DFData* window is displayed differently – in this case they are shaded in light blue (see Figure 5.4, Figure 5.6, or Figure 5.7). Also like the TOC data, the designer must either: (i) enter TSS and TSetS data or (ii) enter none at all.




| | Calculated TSetS | Entered TSetS | % Diff | Calculated TSS | Entered TSS | % Diff |
|---|---|---|---|---|---|---|
| 06:00 | 4.0 | 5.0 | 24.2 | 211.1 | 211.1 | 0.0 |
| 08:00 | 4.4 | 4.4 | 0.6 | 225.1 | 225.2 | 0.0 |
| 10:00 | 7.9 | 7.9 | 0.2 | 409.2 | 408.9 | 0.1 |
| 12:00 | 11.0 | 11.0 | 0.0 | 567.9 | 567.8 | 0.0 |
| 14:00 | 12.3 | 12.3 | 0.1 | 637.1 | 636.9 | 0.0 |
| 16:00 | 12.7 | 12.7 | 0.2 | 656.3 | 656.0 | 0.1 |
| 18:00 | 13.9 | 14.0 | 0.4 | 721.1 | 721.2 | 0.0 |
| 20:00 | 12.8 | 12.8 | 0.0 | 664.6 | 664.3 | 0.0 |
| 22:00 | 11.7 | 11.7 | 0.4 | 608.0 | 607.9 | 0.0 |
| 00:00 | 11.1 | 11.1 | 0.3 | 579.4 | 579.5 | 0.0 |
| 02:00 | 10.1 | 10.1 | 0.1 | 350.1 | 349.8 | 0.1 |
| 04:00 | 6.7 | 6.7 | 0.7 | 211.1 | 211.1 | 0.0 |
| 06:00 | 4.0 | 5.0 | 24.2 | 528.4 | 528.4 | 0.0 |
| Average | 9.8 | 9.9 | 0.64 | 511.2 | 511.1 | 0.02 |

**Figure 5.9: DFData – Calculated and Entered TSuspS/TSetS Check window**

### 5.2.4 Comments and Conclusion

DFData is data centred approach to WWChar that represents an ideal data quantity scenario. The data requirements for DFData are not easily obtainable; particularly the 2-hourly grab samples over 24h because they are often: 1) unweighted, 2) inconsistently taken, and 3) not tested for all the required parameters. Unweighted samples are problematic because a flow-weighted composite sample cannot be obtained and tested for FWA concentrations. With a simple average concentration, the material loads (COD, TKN, TP, TOC and particulates) can be severely underestimated, with consequent knock-on effects on WWTP sizing and effluent quality (performance) estimation. By measuring (accurately) the influent flow rate over a 24h day, together with 2-hourly 1-litre sample collection, a flow-weighted composite can be calculated, which will significantly improve the accuracy of the organic load estimation and WWChar. For the other two points 2) and 3) above, the missing data can be obtained from interpolation or reconciliation methods, but it is best when regular (2-hourly) samples are collected and tested for more parameters. Like the Direct Input method, the characterisation procedure is rigid in the sense that specific data is required and if any of this data is missing, the characterisation procedure cannot be performed. However, a few missing pieces of information should not stop the designer from using this method. For example, the filtered effluent concentrations can be estimated (guessed) if they are not known, and option B2 can be used if FWA data is not fully available. The accuracy of characterisation results, obtained with missing data, will be up to the discretion of the designer. If too much data is missing then it is recommended to use the WWChar Tree method, where flexibility in the inputs and characterisation process is allowed.

## 5.3 Method 3: Characterisation Tree

In practice, the designer often encounters a mixed level of data availability. This is problematic particularly if the quantity and quality of the data available is poor. With variable data and with the many different scenarios possible, the question to the designer is what data is relevant, what data is not relevant, and what can be used, but with some adjustments. Developing a method to characterise wastewater with a mixed level of data was therefore challenging.

In a mixed data scenario, the characterisation procedure needs to be flexible to allow for a variety of inputs, but at the same time have a form of structure so that the wastewater can be characterised in a consistent and reasonable manner. This structure is necessary because without it, the designer can use any type of data, indiscriminately and without any discernment, in the characterisation procedure. Depending on the data entered, whether it is right or wrong, of importance or not, inconsistencies and significant errors can arise, resulting in meaningless outputs. Alternatively, the designer cannot complete the characterisation procedure because the available data is irrelevant for characterisation. Therefore, WWChar requires a strong sense of engineering judgement and experience with WWTP design and operation. Furthermore, without some structure, there is likelihood that the all inputs are given the same level of importance, which is not valid because some wastewater characteristics have a much greater influence in the activated sludge plant than others. If the same level of importance is given to each parameter then minor parameters receive unnecessary attention, an example is the influent USO COD concentration, which is irrelevant in determining the activated sludge (AS) system capacity. However, for the influent VFA and FBSO concentration, because the anaerobic uptake of VFA and FBSO largely determines the quantity of P removal in biological phosphorous removal systems, it is crucial to know the influent VFA and FBSO concentration. Thus, the designer should spend less time on the inconsequential wastewater characteristics, as literature values or estimates can be used, and focus on the characteristics that have a direct and substantial impact on the AS system performance. In a plant-wide design sense, this principle applies not only to the activated sludge system but also to the entire WWTP. Data that is not relevant for the AS system, but is important for other unit processes, should not be neglected. One particular example is the TOC characteristics, which is vital for the modelling of the PS anaerobic digesters, but is unimportant for the AS system.

In an attempt to address the problems encountered with a mixed level of data scenario, the Wastewater Characterisation Tree (WWChar Tree) method was developed. This method allows flexibility in the data input and allows the designer to utilise default characteristics or inputs if data is missing. More importantly, this method organises the inputs according to what is important and what is optional, and provides information to why and when it is important. Doing so assigns the relevant amount of focus to the important inputs, so that meaningful characterisation results, applicable for the system design, are obtained. This method's user-interface, data requirements, and WWChar procedure are discussed further.

### 5.3.1 WWChar Tree Window

Figure 5.10 shows the WWChar Tree window. The WWChar Tree consists of three frames: 1) *Data Inputs* (**A**), 2) *Characterisation Results* (**B**), and 3) *Design Guidance* (**C**). The *Data Inputs* frame contains multiple pages; each page contains the inputs and selection options for the WWChar Tree. The enlargement in Figure 5.10 shows these pages in order. Subsequent pages are only available if the designer has completed the previous pages. Furthermore, when going forward, the designer cannot skip pages and must navigate them in the order provided. The data requirements and a breakdown of the pages is provided in Sections 5.3.2 and 5.3.3. The *Characterisation Results* frame contains the FWA concentrations calculated from the input data. The characteristics are organised into multiple pages, one for each characteristic group (*COD, N, P, C, Part, TOD, Other, Flow*). The characterisation results for that characteristic group will only be displayed if the inputs, relevant to that group's characterisation procedure, are entered. When the characterisation process is complete, the FWA concentrations can be displayed in a block diagram format by clicking the *View Characteristics In Block Diagram* at **D**. The *Characterisation Results* frame also displays the calculated and entered $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios (**E**). The *Design Guidance* frame is located at the bottom left, and is the primary location where the information about the characterisation procedure is displayed. The data requirements and the characterisation procedure is discussed further in the next sections.

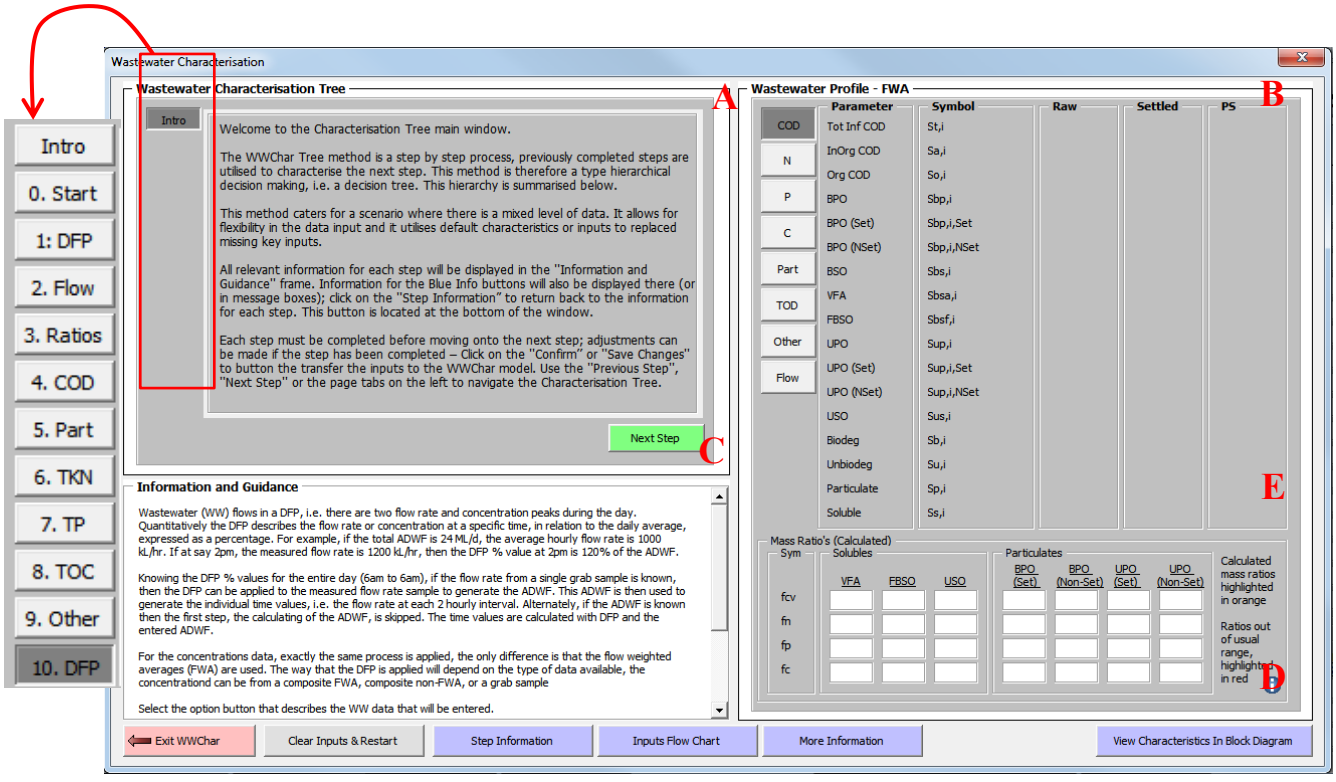



**Figure 5.10: WWChar Tree**

### 5.3.2 Data Requirements

The data requirements for the WWChar Tree are flexible in that the designer can enter different combinations of data. However, it is important to note that there are inputs that are crucial for the WWChar procedure and are thus mandatory. Without these inputs, the wastewater cannot be characterised. However, for some of these mandatory inputs, if the designer does not enter them, the program will automatically substitute preloaded defaults into the WWChar procedure. It is important to note that these preloaded defaults are literature values based on historically measured data (within the South African wastewater context). These values might not reflect the wastewater characteristics of the WWTP considered for the design and analysis. Therefore, they should always be used with caution.

The WWChar Tree method is a systematic process, where previously completed steps are utilised to execute the next step. Therefore, this method is a type of hierarchical decision-making procedure, i.e. a decision tree. The data requirements for each WWChar Tree step and characteristic group are best summarised in flowcharts (Figure 5.11 to Figure 5.18). For each flow chart, the inputs are organised into crucial and optional inputs. For certain inputs, (crucial or optional) the designer can have a selection of input options; in each flowchart, these inputs are indicated by the headings in the rectangular blocks. The different steps for the WWChar Tree and the flow charts linked to them, in the order of the tabs on the WWChar Tree window (Figure 5.10), are:

| | | |
|---|---|---|
| *Intro* | Introduction | |
| *0. Start* | Diurnal flow pattern (DFP) application | ➔ Figure 5.11 |
| *1. DFP* | Preliminary DFP selection/creation | |
| *2. Flow* | Raw/Settled/PS Flow rates | ➔ Figure 5.12 |
| *3. Ratios* | Estimated mass ratios ($f_{cv}$, $f_n$, $f_p$, $f_c$) | |
| *4. COD* | COD inputs | ➔ Figure 5.13 |
| *5. Part* | Particulate inputs | ➔ Figure 5.14 |
| *6. TK*) | TKN inputs | ➔ Figure 5.15 |
| *7. TP* | TP inputs | ➔ Figure 5.16 |
| *8. TO* | TOC inputs | ➔ Figure 5.17 |
| *9. Other* | Other inputs | ➔ Figure 5.18 |
| *10. DFP* | DFP adjustment and finalisation | |

The data inputs for each WWChar Tree input page and how they are utilised in the characterisation procedure, are discussed in Section 5.3.3 after the WWChar Tree flow charts.

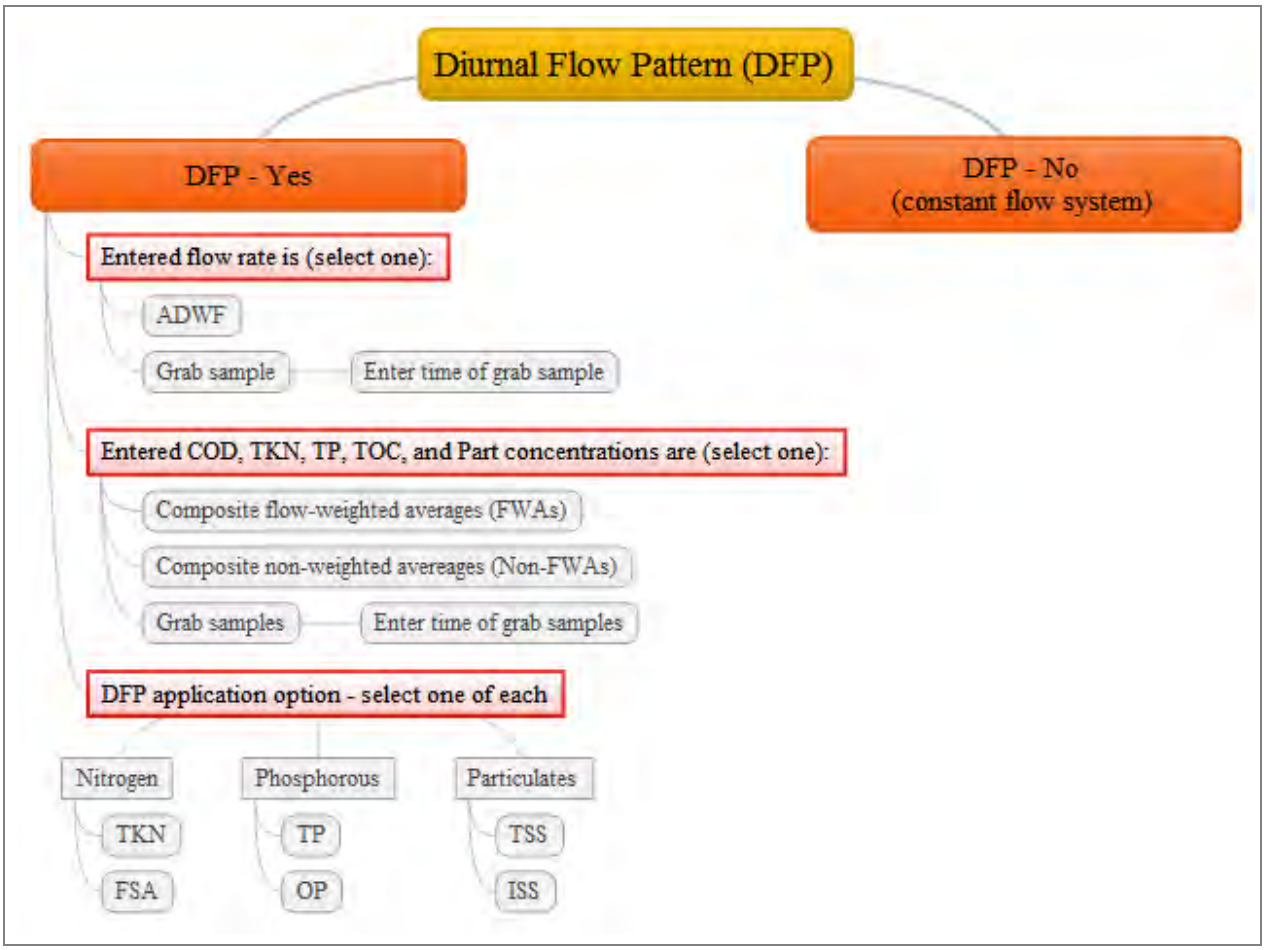



**Figure 5.11: WWChar Tree – Input flow chart for Diurnal Flow Pattern**

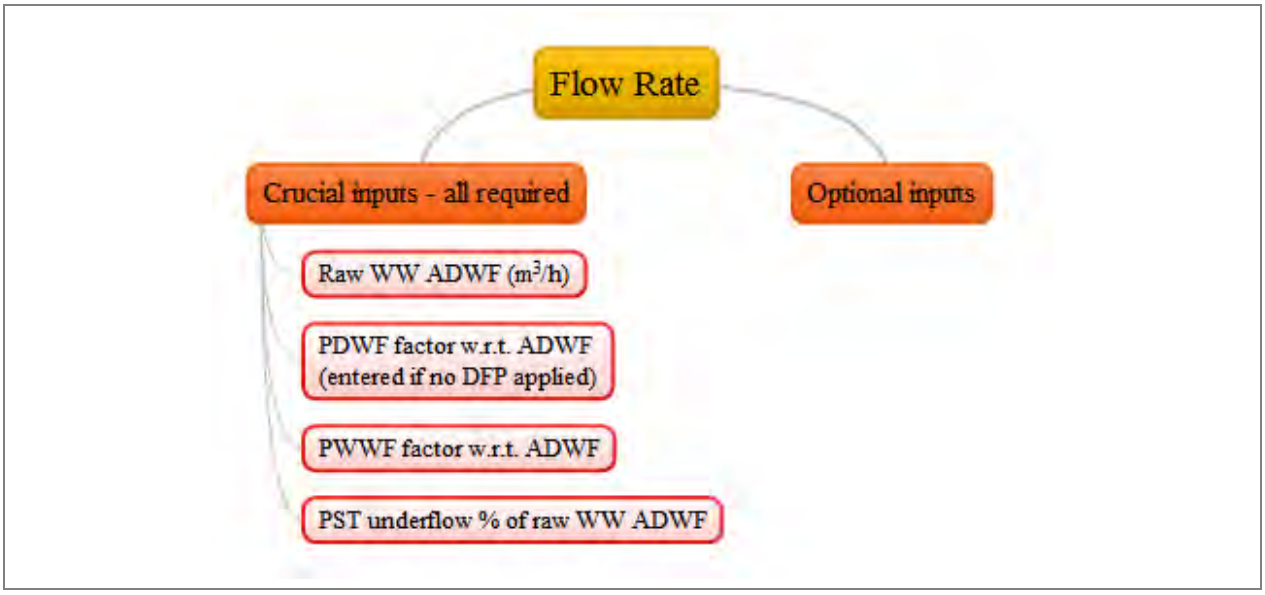



**Figure 5.12: WWChar Tree – Input flow chart for Flow Rate**

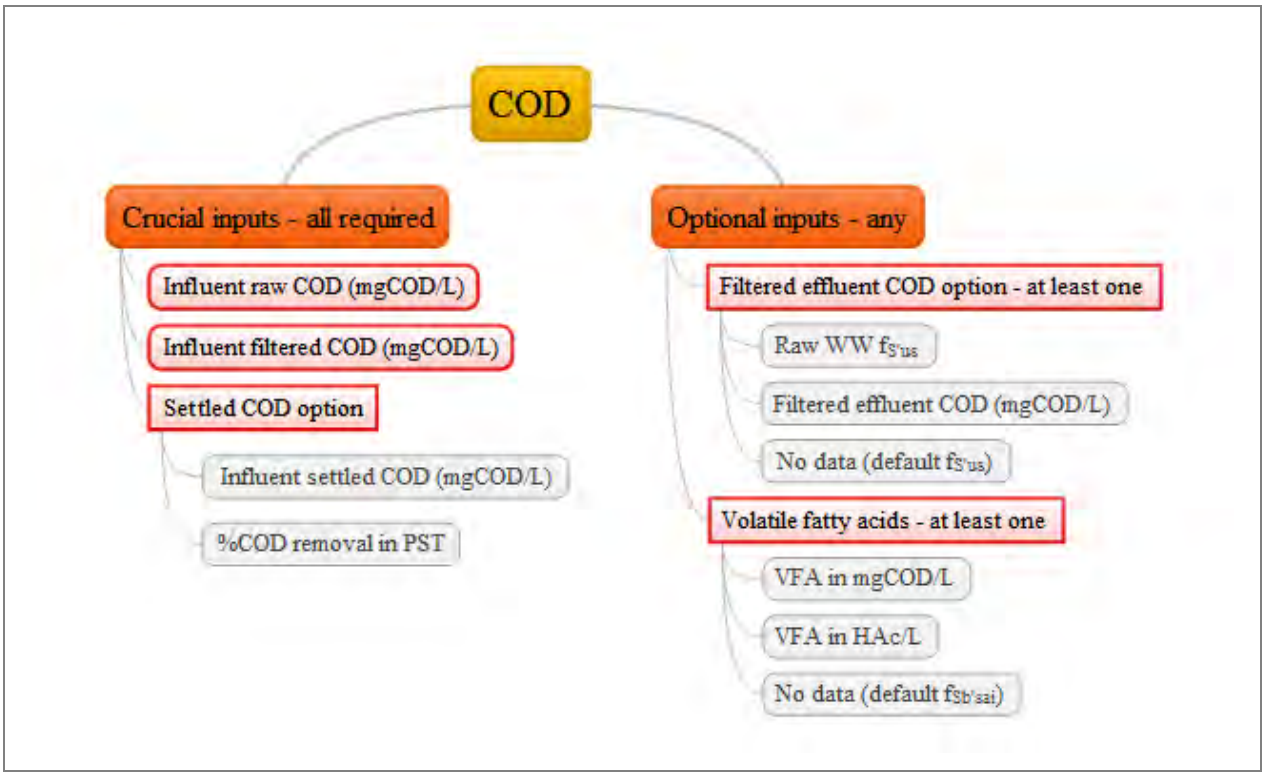



**Figure 5.13: WWChar Tree – Input flow chart for COD**

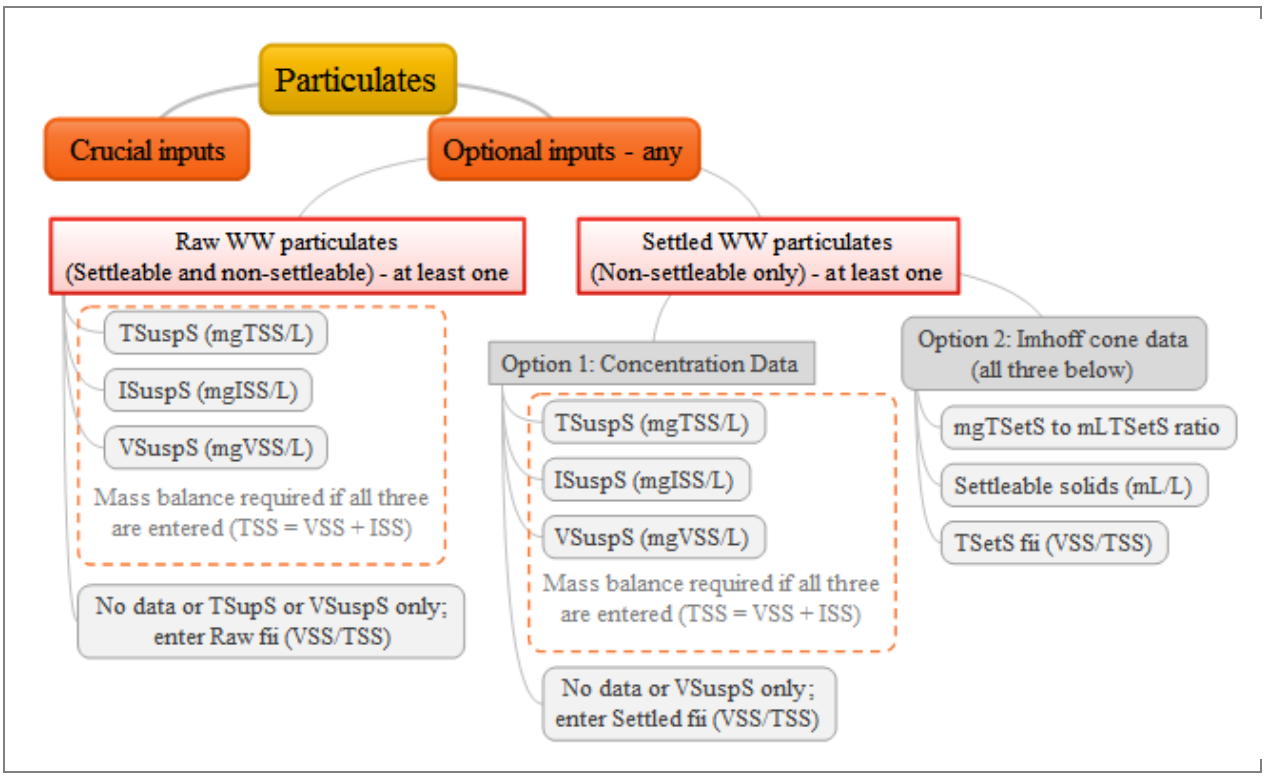



**Figure 5.14: WWChar Tree – Input flow chart for Particulates**

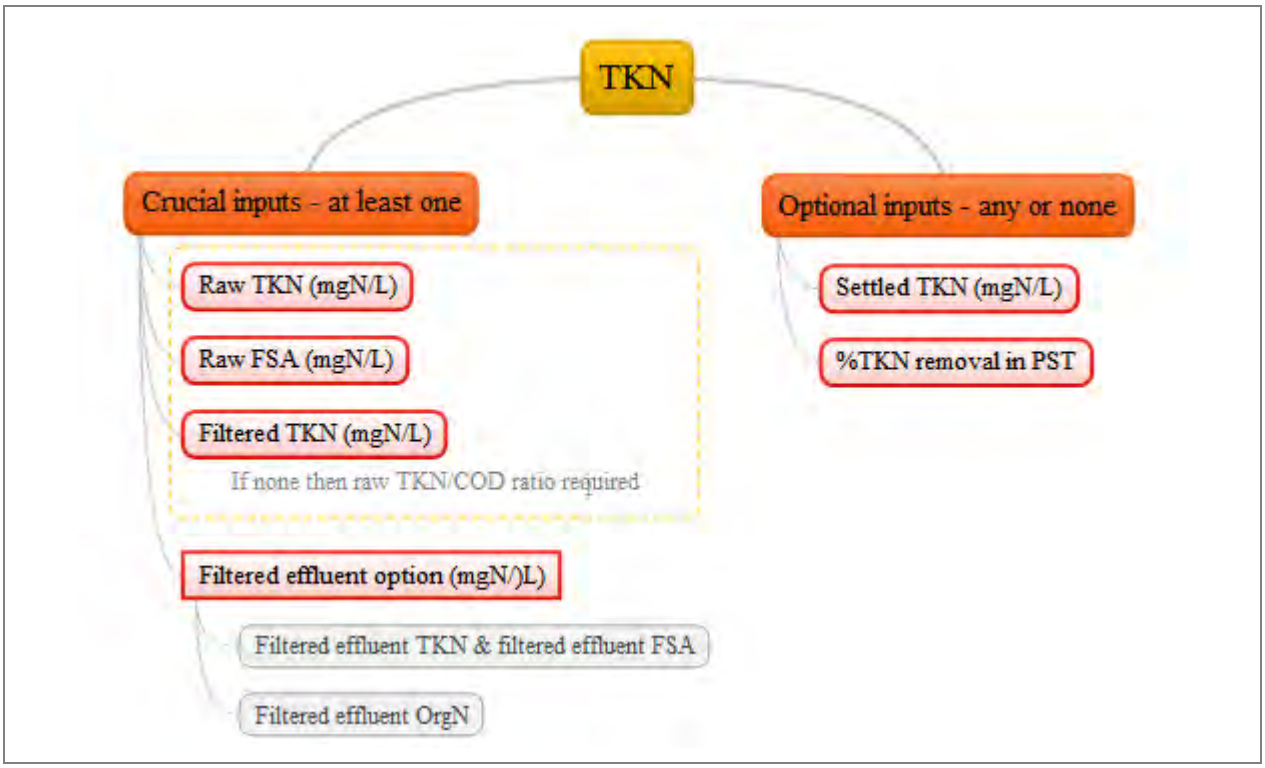



**Figure 5.15: WWChar Tree – Input flow chart for TKN**

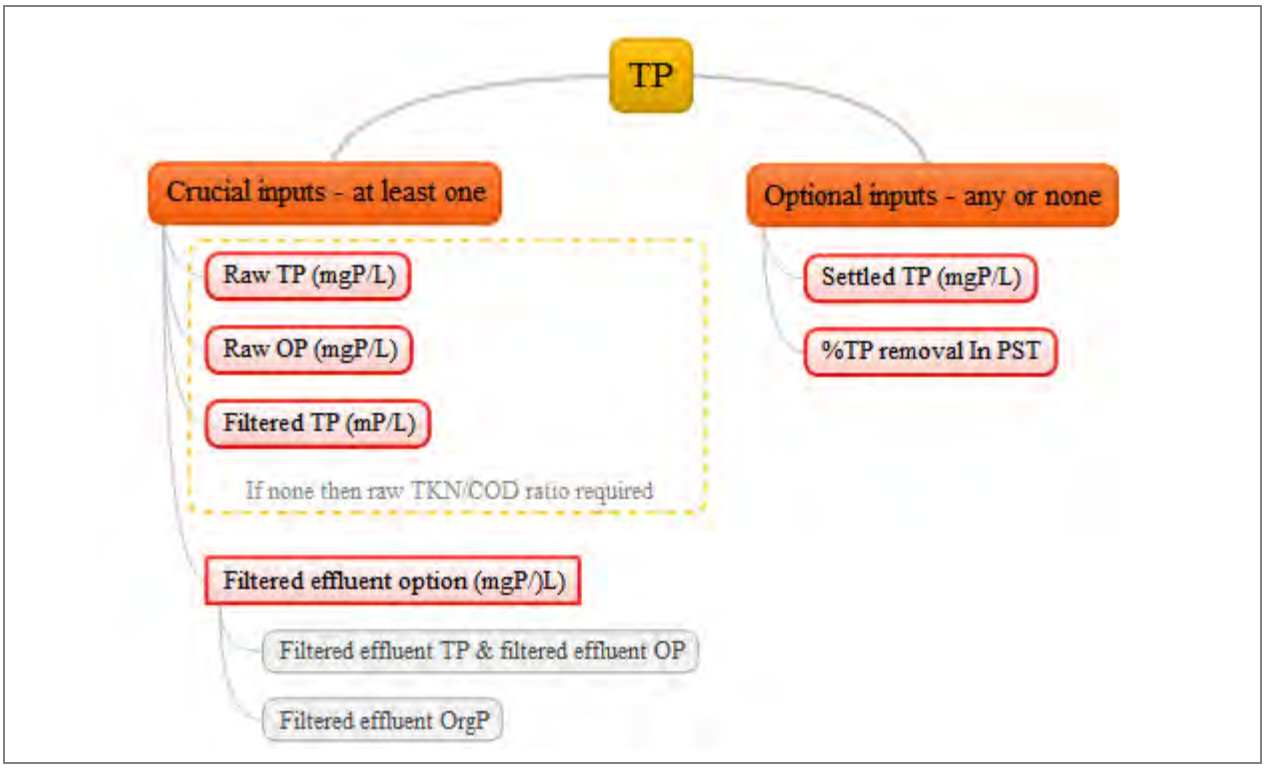



**Figure 5.16: WWChar Tree – Input flow chart for TP**

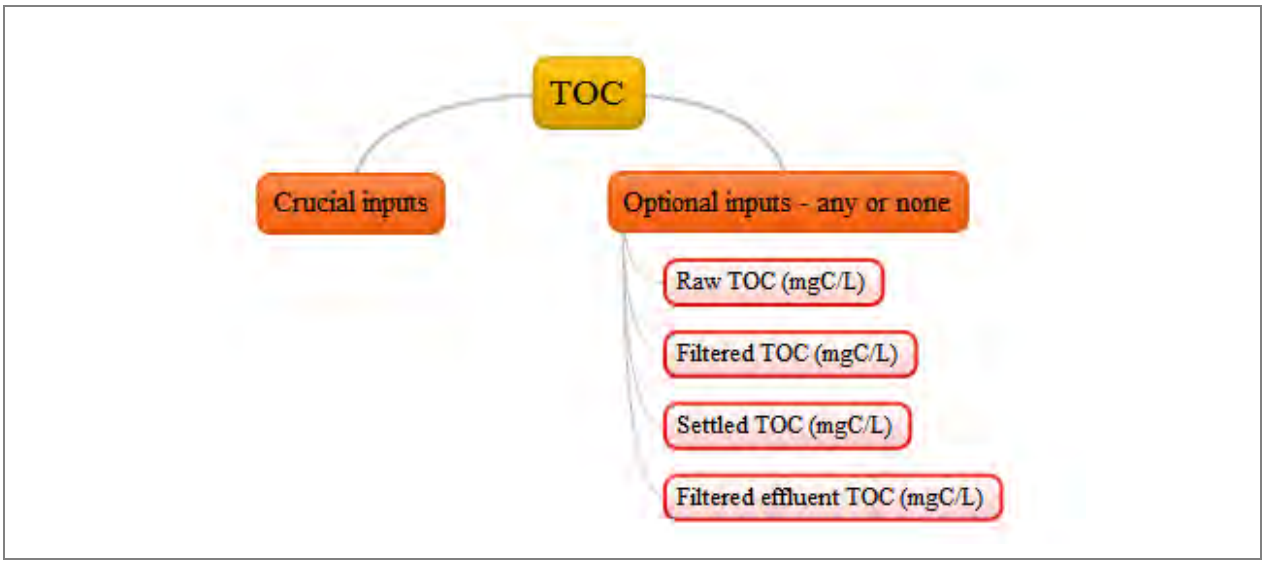



**Figure 5.17: WWChar Tree – Input flow chart for TOC**

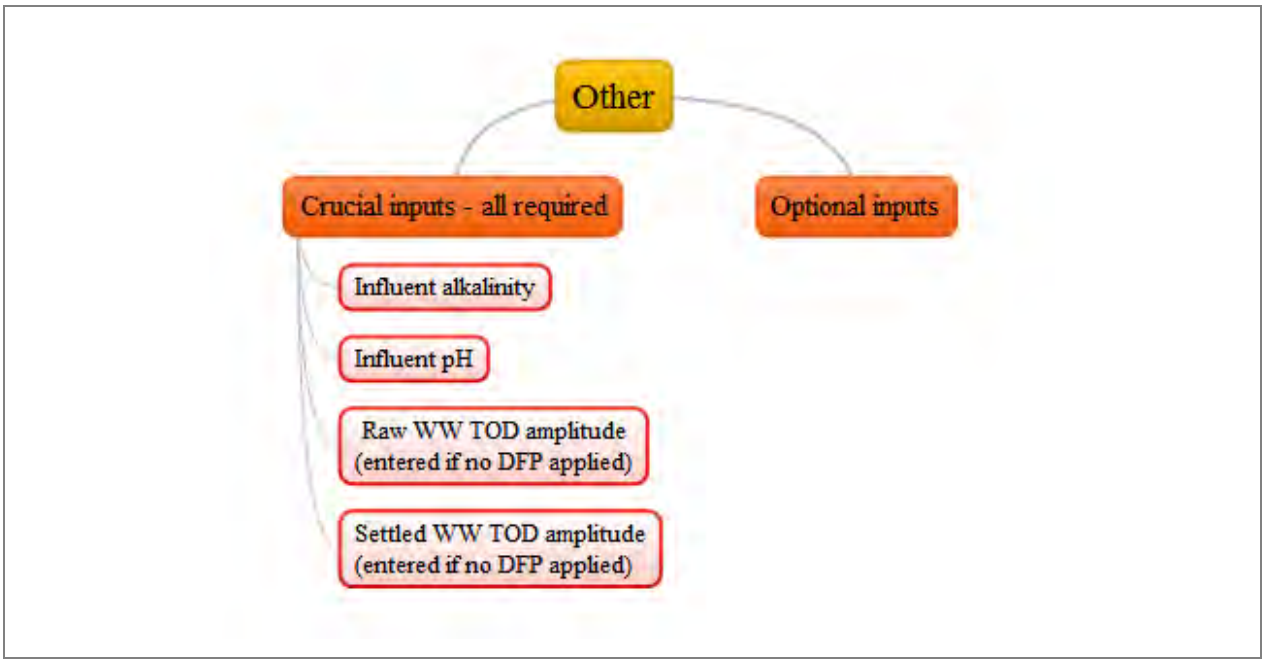



**Figure 5.18: WWChar Tree – Input flow chart for Other**

### 5.3.3 Characterisation Procedure

The WWChar Tree characterisation procedure has a few similarities to the DFData characterisation procedure. In the DFData characterisation procedure, the primary objective is to characterise the COD concentration of the seven organic components for the FWA and at each sample time. Then with the $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios, which are entered or determined from the N, P, C and particulates inputs, the total OrgN, OrgP, TOC, and VSS concentrations at

each sample time is calculated. These organic concentrations, added to their inorganic counterparts, give the total concentration at each sample time. The WWChar Tree characterisation procedure has a similar structure in that the primary objective is to characterise the COD concentrations first. At the beginning of the characterisation procedure, the designer estimates all the mass ratios (except for VFA). Then with the N, P, C and particulates inputs, the procedure will attempt to characterise fully the OrgN, OrgP, TOC and VSS concentrations and their respective mass ratios. If required, the procedure will insert the estimated mass ratios into the calculations to substitute for any missing inputs. The mass ratios that can be calculated from the inputs will then replace the mass ratios estimated in the beginning of the procedure. For the inorganic counterparts, these cannot be calculated from the mass ratios and thus must be entered directly. If the designer does not enter them directly, then reasonable assumptions in the form of characteristic ratios, e.g. TKN/COD, TP/COD, VSS/TSS, are required.

Complementing the characterisation of the organic and inorganic concentrations is the profiling of the diurnal flow pattern (DFP). DFData (Section 5.2) introduced aspects of this where Table 5.3 showed that the simple average concentration obtained from a composite non-weighted sample, underestimated the organic load by 10%. For other sets of data, depending on the amplitude of the diurnal variation of the flow and concentration, this percentage can exceed 30%. In most cases, the daily wastewater flow has two peaks, morning and evening. Depending on the type of wastewater sample and the time that it is collected, the calculated concentrations might require adjustments to obtain FWA concentrations. The significance, and as well as accuracy of the adjustment will depend on the type of wastewater sample collected. There are three possible sample types: 1) composite flow-weighted, 2) composite non-weighted, or 3) grab sample. The first two have already been introduced; the third type, a grab sample, is simply a sample of the WW taken at any time during the day. Flow weighting the grab sample has no effect on the measured concentrations. In general, a rule of thumb is that a composite flow-weighted sample is better than a composite non-weighted sample, which in turn is better than a grab sample. The adjustments to a grab sample are much more significant than to a composite non-weighted sample; a composite flow-weighted sample will have no adjustments. The greater the adjustments made to the calculated characteristics, the greater the risk of deviation to the actual wastewater characteristics (this is because more assumptions are made). Therefore, depending on the type of data selected and the sample time of the data, the DFP is utilised in different ways. For example if the data is from a grab sample at 2PM, then the concentrations calculated for the 2PM data must be reduced in order to obtain the FWA concentrations. This is because at 2PM, the DFP is likely to be at its peak; if unadjusted concentrations were used then the organic load will be overestimated. The same adjustments can be applied to the flow rate data.

With these aspects in mind, the characterisation procedure is discussed. The *Intro* page in the WWChar Tree window only introduces the WWChar Tree method; the actual characterisation procedure only starts from the second page, *0. Start*.

### 5.3.3.1 DFP Application - 0. Start

Figure 5.19 shows the *0. Start* page. The designer has the choice of applying or not applying a DFP to the wastewater characteristics. If a DFP is applied to the characteristics then the flow rate and concentrations will have a diurnal variation, the product of the average flow rate (ADWF) and FWA COD concentration will determine the organic load to the WWTP. This DFP can be selected from a list of preloaded diurnal patterns or it can be a custom DFP created by the designer. To apply a DFP, the *Yes* option button must be clicked. As discussed previously, the characterisation procedure applies the DFP differently depending on the type of wastewater sample: composite flow-weighted, composite non-weighted, or grab sample. Hence, when *Yes* is selected, the options relating to the wastewater sample type are available to the designer. There are two categories of inputs available, one for the flow rate data (left frame) and one for the wastewater sample concentration data (right frame). For the example in this characterisation procedure, a DFP will be applied to the wastewater data, hence *Yes* is selected.

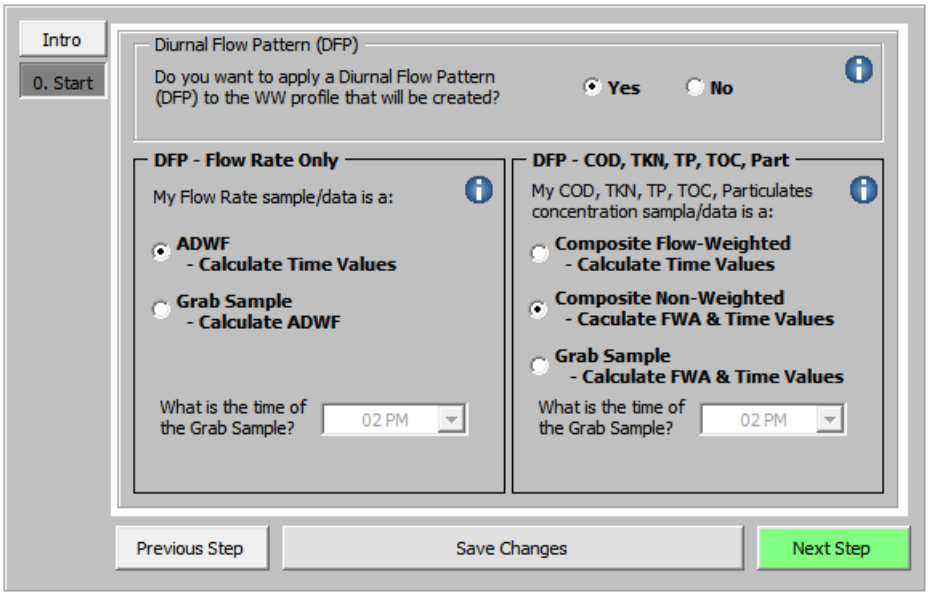



**Figure 5.19: WWChar Tree – Input page 0. Start**

For the flow rate DFP, if the designer knows the ADWF for the WWTP, then the designer must select the *ADWF* option. The consequence of this is that the DFP for the flow rate, which the designer will create or select in the next step, will disaggregate the entered ADWF into 2h interval time values. The average of these time values will then be the ADWF that is entered. So in effect, by selecting the *ADWF* option, which is shown in Figure 5.19, the designer is directly specifying the ADWF to be used in the WWTP design. Alternatively, the *Grab Sample* option can be selected. With this option, to determine the ADWF, the entered flow rate is

increased or decreased depending on the flow rate DFP and the flow sample time selected for the "grab" flow sample. The sample time input will be made available if this option is selected.

For the concentration data (COD, TKN, TP, TOC, and Particulates), the same options as for the flow rate apply, however, an additional option is available. Note that only one flow rate and one influent concentration for COD, N, P, C and particulates are entered for each of these options.

The first option for the concentration data is the *Composite Flow-Weighted* option, which is identical to the *ADWF* option for the flow rate data. If this is selected, then no adjustments are made to the concentrations calculated from the entered concentrations because the entered concentrations are the FWA concentrations. The DFP will disaggregate the FWA concentrations in to the time values using also the flow rate DFP.

The second option, which is the new option, is the *Composite Non-Weighted* option. For this selection, the concentration data are from a composite simple average sample, i.e. the volume for the grab samples that make the composite sample are not proportional to the influent flow rate. Hence, the concentrations calculated from the entered concentrations are the simple average concentrations. The selected/created DFP for the flow rate and the entered simple average COD, TKN, TP, TOC and particulates (VSS, TSS) concentrations will be used to calculate the percentage difference between the simple average concentrations and the FWA concentrations; from this, the simple average concentrations are increased by that percentage difference to obtain the FWA concentrations.

Lastly, the third option is the *Grab Sample* option. This is the same as for the flow rate, and if selected, a sample time is required. The concentrations calculated by the entered concentration data will be for the sample time selected. The selected/created DFP for flow and concentrations are used to calculate the FWA concentrations.

If the designer does not want a DFP, *No* is selected. For this selection, no diurnal adjustments will be made to the input data, i.e. the flow rate entered and the concentrations calculated from the entered wastewater concentration data will be taken as FWA concentrations. The created wastewater profile (flow rate and concentrations) will have no DFP associated with it and thus it is imperative the designer enters FWA concentrations for the concentration data input boxes. As shown in the DFData section with the data provided, the simple average concentration underestimates the organic load by ±10%, depending on the intensity and differences in the flow and concentration DFPs, this can be much higher (±30%). The *No* DFP option is typically selected for a constant flow system, for example, a system that has a balancing tank. However, it is important to note that because a DFP is not created for the wastewater profile, the balancing tank model cannot be used because there is no diurnal flow rate to equalise. Therefore, if a balancing tank is required in the plant-wide setup, a diurnally varying raw WW needs to be characterised, instead of a balanced wastewater that exits the balancing tank. In doing so, the problem of not being able to add a balancing tank to the plant-wide design is circumvented. If the designer has no information about the DFP, but is certain

on the characteristics that exit the balancing tank, then select the *ADWF* and *Composite Flow-Weighted* options and create or select a reasonable DFP for the design This way the entered flow rates and concentrations will not be adjusted by the DFP.

The *Composite Non-Weighted* option, as indicated in Figure 5.19, will be the option used for the characterisation procedure example for this WWChar method. In order to demonstrate this option, composite non-weighted (simple average) concentrations are required. These concentrations can be obtained (or estimated) from the data provided in the DFData method (Tables 5.1 to 5.7). In the DFData method, the composite non-weighted concentrations for the total COD, FSA, OP, and ISS were calculated as 932.4 mgCOD/L, 42.5mgFSA-N/L, 8.0 mgOP-P/L, and 54.2 mgISS/L. These composite non-weighted concentrations are ±10% less than the FWA concentrations. Thus for all other characteristics (FBSO, USO, VFA etc.), their composite non-weighted concentrations can be estimated by reducing their FWA concentrations (calculated with the DFData method, summarised in Appendix A) by ±10%. This adjustment is done manually, outside of the program, and is not applicable for all wastewater data. In fact, if this option is selected by the designer, the designer should enter composite non-weighted concentrations and not calculate it from FWA concentrations. If the latter is done, the designer will be unnecessarily complicating the WWChar process because the WWChar Tree method will adjust the composite non-weighted concentrations to obtain the FWA concentrations, i.e. the characterisation will be going in circles. It is thus important to reiterate that the ±10% adjustment to the FWA concentrations (obtained from the DFData method) is only done here to simulate the data required for a WWChar example with the *Composite Non-Weighted* option selected.

#### 5.3.3.2 Preliminary DFP Selection/Creation - 1. DFP

Following the DFP application step, a preliminary DFP must be selected or created for the flow rate, COD, N, P, and ISS. However, before this can be done the designer must select the *Confidence Parameter* (TKN or FSA, TP or OP, and TSS or ISS) for the creation of DFP for the N, P, and ISS. The DFP for C is the same as for the COD. For the selection of the *Confidence Parameter*, this is done on the *1. DFP* page shown in Figure 5.20. This *Confidence Parameter* affects how the DFP is applied to the N, P, and particulate characteristics.

With the inputs to the WWChar Tree, the characterisation procedure calculates the COD concentrations of the seven organic groups. Then with the N, P, and particulates inputs, and as well as the $f_{cv}$, $f_n$, and $f_p$ mass ratios, the total OrgN, OrgP and VSS concentrations are calculated. Once these characteristics are known, the $f_{cv}$, $f_n$ and $f_p$ mass ratios are revised. It is assumed that the mass ratios do not change throughout the day, therefore the diurnal COD concentration fixes the diurnal OrgN, OrgP and VSS concentrations. However, the diurnal COD concentration does not fix the diurnal total and diurnal inorganic concentrations (TKN and FSA, TP and OP, and TSS and ISS). Therefore, a separate DFP is required for the total (TKN, TP, and TSS) and inorganic (FSA, OP, and ISS) concentrations. However, because a

mass balance between total (TKN, TP, TSS), inorganic (FSA, OP, ISS) and organic (OrgN, OrgP and VSS) concentrations must be satisfied at all times, i.e. TKN = FSA + OrgN, TP = OP + OrgP, and TSS = ISS + VSS, only one DFP is allowed for each of the N, P or particulates, either for the total concentrations or the inorganic concentrations. The selected type is the *Confidence Parameter*. The unselected type will be calculated via a difference in the mass balance. For example, if the FSA is selected as the *Confidence Parameter*, then the DFP is applied to the FSA to generate the diurnal FSA concentrations. The OrgN at each sample time, which is fixed by the $f_{cv}$ and $f_n$ mass ratios and diurnal COD concentrations of the seven organic groups, is added to the diurnal FSA concentrations in order to obtain the diurnal TKN concentrations. Alternatively, if TKN is selected as the *Confidence Parameter*, the DFP is applied to the TKN concentration calculated from the N inputs. A diurnal TKN concentration is obtained and the diurnal FSA concentration is calculated by subtracting the diurnal OrgN concentrations from the diurnal TKN concentrations. Note that this can result in negative concentrations at certain sample times, therefore the DFP created here is only a preliminary one, and must be revised when all inputs have been entered.

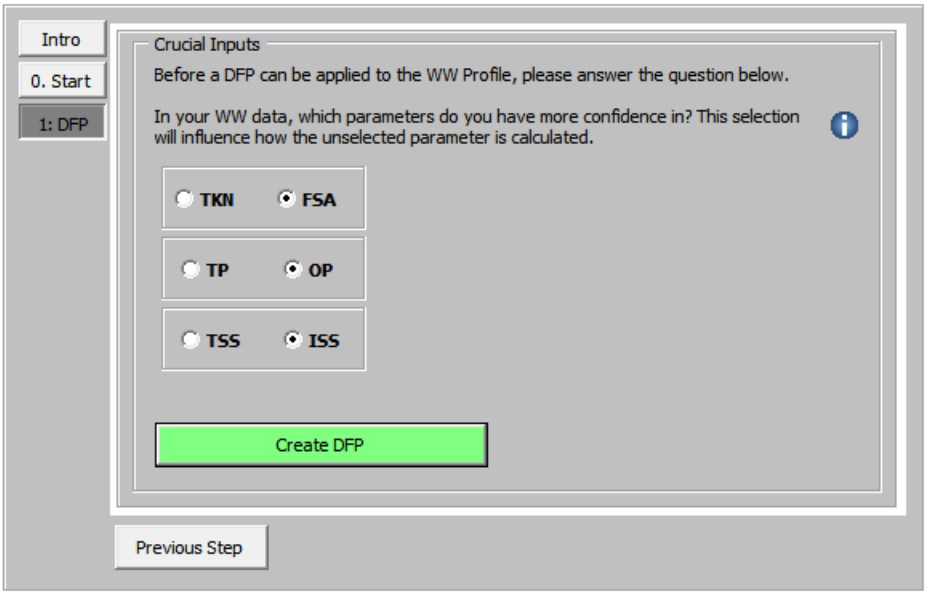



**Figure 5.20: WWChar Tree – Input page 1. DFP (Confidence Parameter)**

Once the designer selects all the *Confidence Parameters*, the DFP can be selected or created by clicking on the *Create DFP* button. The DFP Selection/Creation window will be displayed along with a graph controls window. On the graph controls window, the designer can select a preloaded DFP, create a custom DFP by entering percentages or concentrations, and refine the DFP by increasing or decreasing the intensity of the flow or concentration at each sample time. Figure 5.21 shows the DFP Selection/Creation Window.

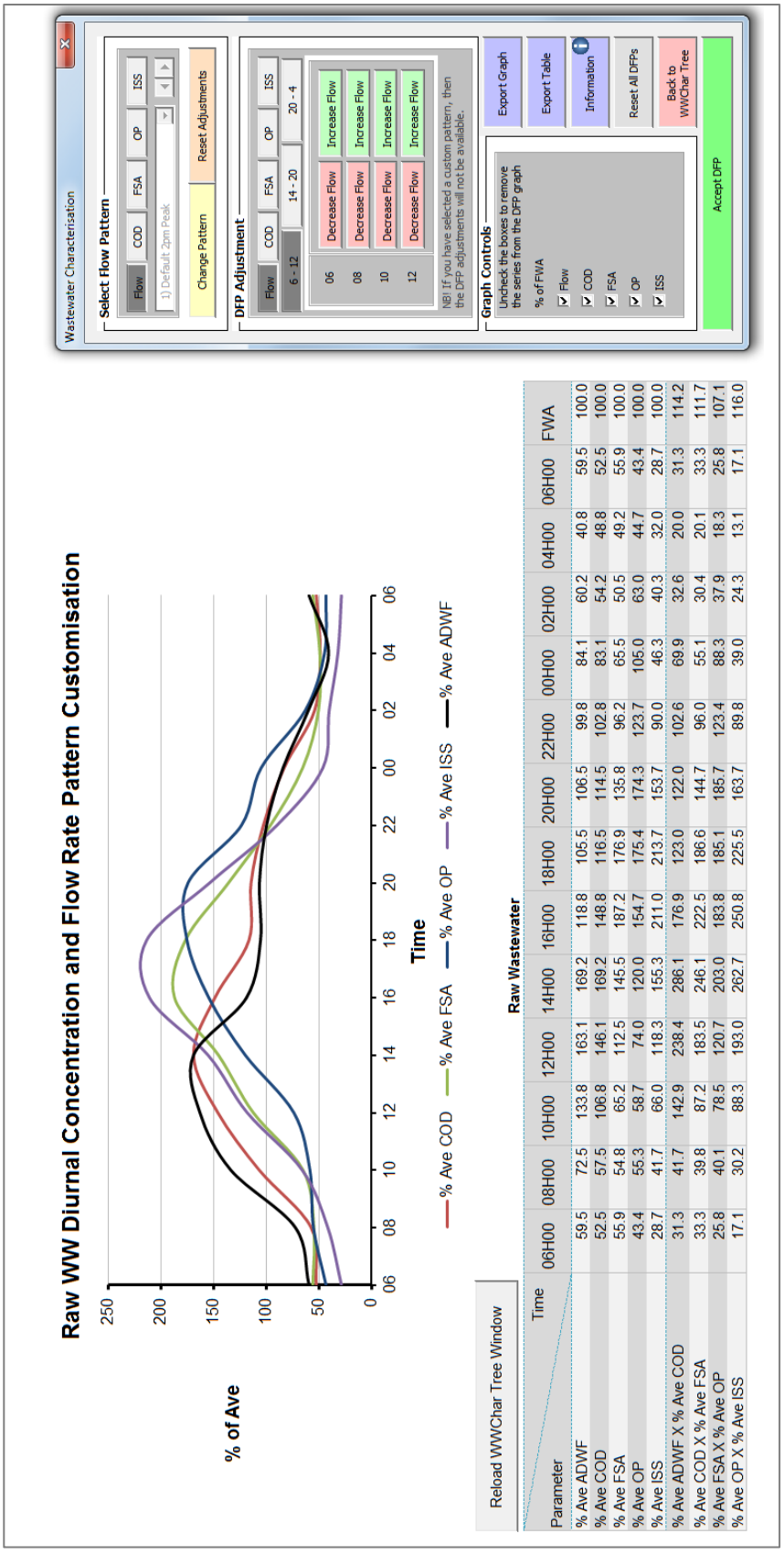



**Figure 5.21: WWChar Tree – Input page 1. DFP (Selection/Creation)**

The DFP shown in Figure 5.21 was created for the characterisation example in this section. It was based on the DFP in the DFData section but it is not identical. The only similarities being that the flow rate, COD, FSA, OP, and ISS DFPs follow the same shape and have similar DFP peak times. A comparison of the "randomly" created DFP for the WWChar Tree and the DFData's DFP is provided in Appendix A: Comparison of DFData and WWChar Tree DFPs.

The DFP consists of percentages that describe the relationship between the sample time concentrations (and flow rates) and the simple average concentrations (and flow rates), i.e. the percentage of the average (%Ave). When selecting/creating a DFP, the %Ave values are adjusted. The product the %Ave ADFW and the %Ave Concentration can also be computed, which is essentially the %Flux at each sample time. Knowing these percentages, if a concentration (or flow rate) for any sample time is known (i.e. a grab sample), the percentages can be used to calculate the simple average and the FWA concentration (or flow rate). Alternatively, if the simple average or FWA concentration is known, then the sample time concentrations (or flow rate) can be calculated. Using Table 5.10 below, this concept is easier explained. The DFP as shown in Table 5.10 is the same DFP as shown in Figure 5.21; it is simply the numerical counterpart of the DFP graph (which is the table below the DFP graph in Figure 5.21). Note that Table 5.10 only shows the DFP for the flow rate and COD, the complete table includes the percentages for the TKN or FSA, TP or OP and TSS or ISS, depending on the options selected for the *Confidence Parameter*. Furthermore, the two right most columns in Table 5.10, Flow Rate ($m^3$/h) and COD concentration (mgCOD/L), are not yet known because the flow rate or concentration data has not yet been entered. Those columns are generated later, but they are included here as they are relevant for the discussion of the DFP.

**Table 5.10: Flow Rate and COD DFP**

| | %Ave ADWF | %Ave COD | %Ave ADWF × %Ave COD | Flow Rate ($m^3$/h) | COD Concentration (mgCOD/L) |
|---|---|---|---|---|---|
| 06H00 | 63.5 | 92.3 | 58.6 | 761.7 | 937.3 |
| 08H00 | 79.5 | 86.2 | 68.5 | 953.5 | 876.2 |
| 10H00 | 135.8 | 139.5 | 189.4 | 1 629.1 | 1 417.7 |
| 12H00 | 159.1 | 170.9 | 271.8 | 1 909.0 | 1 735.9 |
| 14H00 | 167.1 | 172.9 | 288.9 | 2 005.1 | 1 756.3 |
| 16H00 | 129.8 | 104.6 | 135.7 | 1 557.5 | 1 062.4 |
| 18H00 | 107.5 | 73.3 | 78.7 | 1 289.7 | 744.3 |
| 20H00 | 108.5 | 90.2 | 97.9 | 1 301.5 | 916.8 |
| 22H00 | 91.8 | 98.5 | 90.4 | 1 101.1 | 1 001.2 |
| 00H00 | 76.1 | 76.9 | 58.5 | 913.0 | 780.9 |
| 02H00 | 47.1 | 46.9 | 22.1 | 565.1 | 476.2 |
| 04H00 | 40.8 | 59.6 | 24.3 | 489.5 | 605.2 |
| 06H00 | 63.5 | 92.3 | 58.6 | 761.7 | 937.3 |
| Simpsons AVE | 100.0 | 100.0 | 113.4 | 1 200.0 | 1 016.00 |
| - The flow rate and COD concentration columns are not yet actually known hence are not displayed in Figure 5.21. Those values are only generated after the COD inputs. | | | | FWA | 1152.3 |

For each sample time, the %Ave describes the ratio between the flow rate (or concentration) at that sample time and the daily simple average. For example, at 6AM the %Ave of the ADWF is 63.5%, then if the ADWF is 28.8 ML/d (equating to 1200 $m^3$/h), at 6AM the flow rate will be:

**Equation 5.2: WWChar - %Ave for a specific sample time**

$$\text{Flow Rate at 2PM} = 1200\frac{\text{m}^3}{\text{h}} \times \frac{167.1\%}{100\%} = 2005.1\ \frac{\text{m}^3}{\text{h}}$$

It is importance to note that, the Simpsons average of the %Ave values must always be equal to 100%. This is because a mass balance must be obtained, if the %Ave values do not provide a Simpsons average of 100% then the total daily flow rate will be greater than 28.8 ML/d, which is not permissible because 28.8 ML/d is the specified ADWF flow rate. The same principle is applied to the COD, TKN/FSA, TP/OP, and TSS/ISS. For the %Ave ADWF × %Ave COD column, the %Ave ADWF × %Ave COD at each sample time is simply the product of the %Ave ADWF and %Ave Concentration divided by 100%. For the 6AM COD example, this is:

**Equation 5.3: WWChar - %Ave ADWF × %Ave COD**

$$\text{6AM FWA to Ave \% Difference } = 167.10\%\ \text{Ave ADWF} \times \frac{172.9\%\ \text{Ave COD}}{100\%} = 288.9\%$$

Each sample time %Ave ADWF × %Ave COD is not actually useful; however, the Simpsons average of the entire %Ave ADWF × %Ave COD is meaningful. In this case it is 113.4%, which indicates that the FWA COD concentration is higher than the simple average COD concentration by 13.4% (= 113.4% - 100%). With an understanding of these percentages, the numerical background on the application of DFP can be seen. For example, if the grab sample at 2pm has a COD concentration of 1735.92 mgCOD/L, then from the DFP, to obtain the FWA COD concentration, the following calculation is performed:

**Equation 5.4: WWChar - FWA concentration from grab sample**

$$\text{FWA COD concentration} = 1735.9\frac{\text{mgCOD}}{\text{L}} \times \left(\frac{100\%}{172.9\%}\right) \times \left(\frac{113.4\%}{100\%}\right) = 1152.3\frac{\text{mgCOD}}{\text{L}}$$

Alternatively, if the composite non-weighted COD concentration is entered, i.e. the simple average concentration, which in this case is 1016.0 mgCOD/L. The adjustment to obtain the FWA will then be:

**Equation 5.5: WWChar - FWA concentration from composite non-weighted sample**

$$\text{FWA COD concentration} = 1016.0\frac{\text{mgCOD}}{\text{L}} \times \left(\frac{113.4\%}{100\%}\right) = 1152.3\frac{\text{mgCOD}}{\text{L}}$$

### 5.3.3.3 Raw/Settled/PS Flow rates - 2. Flow

The raw WW flow rate and the PST underflow percentage of the raw ADWF are two critical inputs. The flow rate DFP, selected or created in the previous step is only applied to the raw WW ADWF. This generates the 2h flow rates for the influent raw WW. The raw WW ADWF is multiplied by the PST underflow percentage to determine the PS flow rate, which is assumed constant through the day. The PS flow rate is then subtracted from the 2-hourly raw WW flow rates to determine the diurnal settled WW flow rates. The PDWF factor cannot be entered, as this is determined from the flow rate DFP created in the previous step. However, if no DFP is applied then the designer must enter the PDWF. The designer must always enter the PWWF to ADWF factor irrespective of the DFP options.

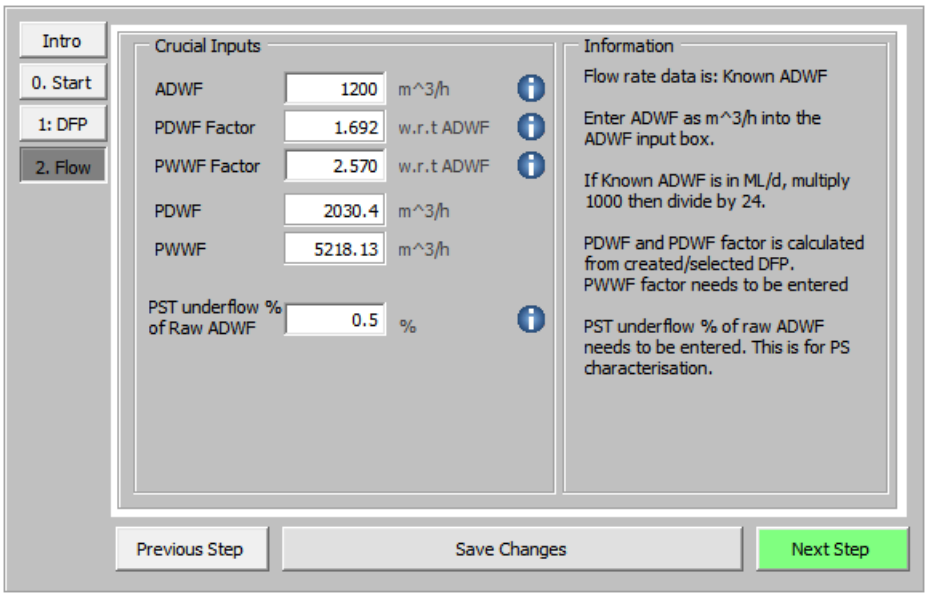



**Figure 5.22: WWChar Tree – Input page 2. Flow**

### 5.3.3.4 Estimated Mass Ratios - 3. Ratios

The estimated mass ratios ($f_{cv}$, $f_n$, $f_p$ and $f_c$) are critical inputs for the characterisation procedure. The designer enters these mass ratios on the *3. Ratios* input page, shown in Figure 5.23. Default mass ratios can be used by clicking on the respective *Use Defaults* button for the soluble, biodegradable particulate, and unbiodegradable particulate organic groups. With the *Calculate $f_{cv}$, $f_n$, $f_p$, and $f_c$ from $C_xH_yO_zN_aP_b$ composition* button, the designer can specify the stoichiometric composition of each organic group (except VFA) and calculate the mass ratios from that composition. Once the estimated mass ratios are defined, these mass ratios will be used to calculate any missing COD, N, P, C and VSS concentrations. Mass ratios that can be calculated from the entered COD, N, P, C and particulates inputs, will replace the estimated mass ratios. Note that the UPO mass ratios, for the settleable and non-settleable, are always

defined (see Wentzel *et al*., 2006) and not calculated in any of the characterisation procedures. All estimated and calculated mass ratios are displayed to the designer on the *Characterisation Results* section (see **E** on Figure 5.10). The calculated mass ratios are highlighted in orange, whereas the estimated mass ratios are in white. The mass ratios (calculated or estimated) that do not conform to the historically measured mass ratios are highlighted in red. This indicates that there is a problem with the COD, N, P, C, or particulates concentration inputs. The location of the problem will depend on the type of mass ratio highlighted; red $f_{cv}$ means COD and particulates input problem, red $f_n$ means N inputs problem, red $f_p$ means P inputs problem, $f_c$ means C inputs problem. Note that because the $f_n$, $f_p$, and $f_c$ mass ratios are also dependent on the $f_{cv}$ mass ratios, a problem with $f_n$, $f_p$, and $f_c$, can also arise if there are problems with the COD and particulates inputs.

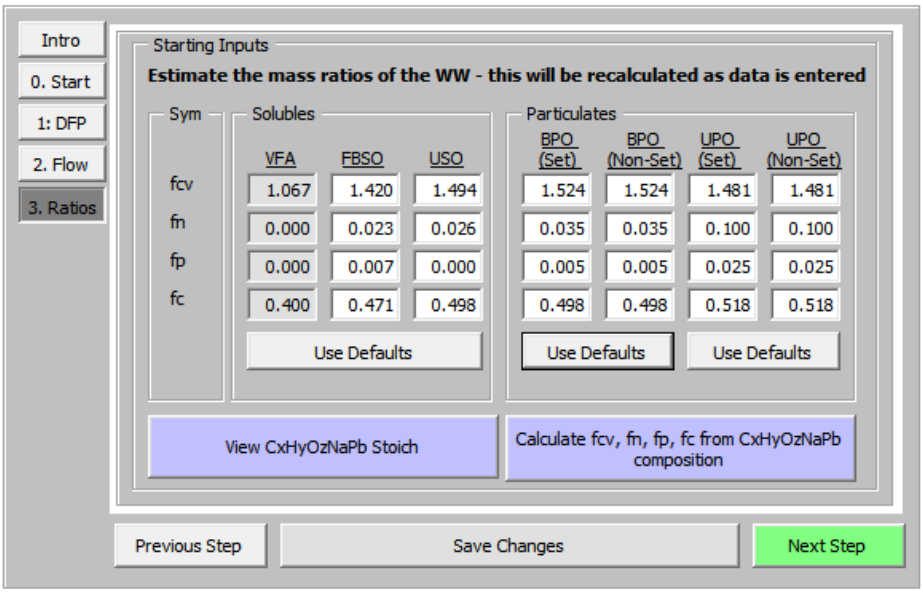



**Figure 5.23: WWChar Tree – Input page 3. Ratios**

### 5.3.3.5 COD Inputs - 4. COD

Figure 5.24 shows the page for the COD inputs (*4. COD*). On this page, the influent raw WW COD and filtered COD concentrations are mandatory. In order to obtain the settled WW concentrations, the settled WW COD concentration or the %COD removal in the PST is required. As with the DFData method, it is assumed that the %COD removal by the PST is constant over the 24h day. In addition to the raw, settled and filtered concentrations, two of three UPO fractions (symbolised as $f_{S'up}$ for raw and settled WW, and $f_{PS'up}$ for PS) are required. Any combination of UPO COD fraction can be selected. A mass balance calculates the unselected UPO fraction, e.g. if $f_{S'up}$ for raw and settled WW are given, then $f_{PS'up}$ is calculated from Equation 5.6.

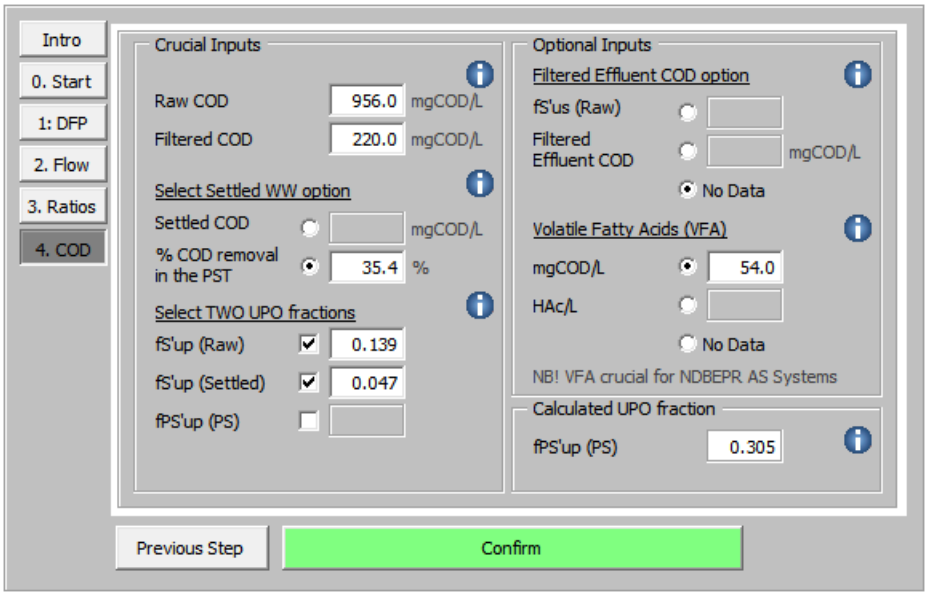



**Figure 5.24: WWChar Tree – Input page 4. COD**

**Equation 5.6: WWChar - UPO fraction mass balance**

$$f_{PS'up} = \frac{\left[\text{Raw } f_{S'up} \times \text{Raw } S_{ti} \times 1\right] - \left[\text{Settled } f_{S'up} \times \text{Settled } S_{ti} \times \left(1 - \frac{\%\text{PST Underflow}}{100}\right)\right]}{\left[\text{Raw } S_{ti} \times 1\right] - \left[\text{Settled } S_{ti} \times \left(1 - \frac{\%\text{PST Underflow}}{100}\right)\right]}$$

The data set for the DFData (Section 5.2) was used for the WWChar Tree. However, because in step *0. Start*, the wastewater sample type was selected as a composite non-weighted sample (i.e. the designer entered the simple average concentrations), to simulate this, the FWA concentration data from the DFData Table 5.4 were manually reduced by ±10%. This is because the calculations, shown in the DFData Table 5.3, indicated that the simple average concentrations were ±10% lower than the FWA concentrations. Hence, as shown in Figure 5.24, the influent raw COD concentration, filtered COD, and VFA concentrations are 956, 220, and 54 mgCOD/L respectively (the FWA concentrations in the DFData data set, Table 5.4, are 1016, 250, and 60 mgCOD/L). The same principle is applied to all the N, P, C, and particulate concentrations.

For the COD inputs, if *No Data* is selected for the filtered effluent COD (USO) input, then a default USO fraction w.r.t to the total raw COD ($f_{S'us}$) of 0.050 is substituted into the COD data. Likewise, for the VFA input, if *No Data* is selected for the VFA, a default VFA fraction w.r.t total raw COD ($f_{S'bsai}$) of 0.045 is substituted into the COD data. These fractions provide 50 mgCOD/L (USO) and 45 mgCOD/L (VFA) for every 1000 mgCOD/L (raw COD). For the VFA, if data is available, it can be entered as mgCOD/L or as mgHAc/L (milligrams of

acetate per litre). Both cannot be entered at the same time as consistency in the inputs needs to be ensured. The same applies to the USO input (either $f_{S'us}$ or in mgCOD/L), and the settled WW COD (either in mgCOD/L or %COD removal). Mutually exclusive options are designated with the round option buttons, the square checkboxes allow for multiple selections.

With the entered COD inputs, or the substituted USO/VFA inputs, the COD characterisation procedure for the raw and settled WW is as follows. The raw WW total concentration is calculated with the entered total influent raw COD and raw $f_{S'up}$, this provides the total UPO (settleable + non-settleable) concentration. The FBSO concentration can be calculated by subtracting the USO and VFA concentration from the entered filtered COD concentration. The total BPO (settleable + non-settleable) is the last unknown concentration; hence, it is calculated by subtracting the filtered concentration (VFA + FBSO + USO) and the total UPO concentration from the total influent raw COD concentration.

In order to determine the settleable and non-settleable split of the BPO and UPO, the settled WW COD concentrations must be characterised. As with the DFData, and all other WWChar methods, the settled WW contains only non-settleable BPO and UPO. Therefore, if the BPO and UPO concentrations in the settled WW are known, they can be subtracted from the raw WW total BPO and UPO concentrations in order to determine the settleable BPO and UPO concentration. For the settled WW, the total COD concentration is either entered directly or calculated with the %COD removal in the PST. The settled WW UPO concentration is then the product of the settled WW COD concentration and the settled $f_{S'up}$. In the settled WW, the soluble concentrations are the same as for the raw WW; therefore, the settled WW BPO concentration is the settled WW total COD concentration less the settled WW UPO concentration, and soluble (VFA + FBSO + USO) concentration.

Once the settleable and non-settleable BPO particulate concentrations are calculated, the settleable BPO $f_{cv}$ and non-settleable BPO $f_{cv}$ can be revised if their respective VSS concentrations are known. Whether or not the VSS concentrations are known, depends on the inputs given in the particulates input page (*5. Part*).

#### 5.3.3.6 Particulates Inputs - 5. Part

Figure 5.25 shows the page for the COD inputs (*5. Part*). For the particulates the inputs are separated into raw WW and settled WW inputs, and for both wastewater types, the input options are: TSS, ISS, VSS, $f_{ii}$ (VSS/TSS ratio), and No Data. In addition to this, for the settled WW particulates inputs, the option of entering Imhoff cone data is available.

Like in the COD characterisation procedure, the raw WW particulates are characterised first. With the $f_{cv}$ mass ratios and COD concentration for the settleable and non-settleable UPO, the settleable and non-settleable UPO VSS concentration is calculated. The settleable BPO is also calculated by the $f_{cv}$ mass ratio and settleable BPO COD concentration. The next calculation step is determined by the raw WW particulate inputs (raw WW TSS, ISS, and

VSS). If the raw WW VSS concentration can be calculated from the inputs then the non-settleable BPO is the only unknown VSS concentration and hence can be calculated. If the raw WW VSS concentration cannot be calculated from the raw WW particulate inputs, then the non-settleable BPO $f_{cv}$ mass ratio and COD concentration determines the non-settleable BPO VSS concentration. Then for the raw WW TSS and ISS, if any one of these are known, then with the VSS concentration, the other can be calculated. If the raw WW TSS or ISS is not entered, the $f_{ii}$ (VSS/TSS) ratio is required. This will determine the raw WW TSS concentration, which then can give the raw WW ISS concentration.

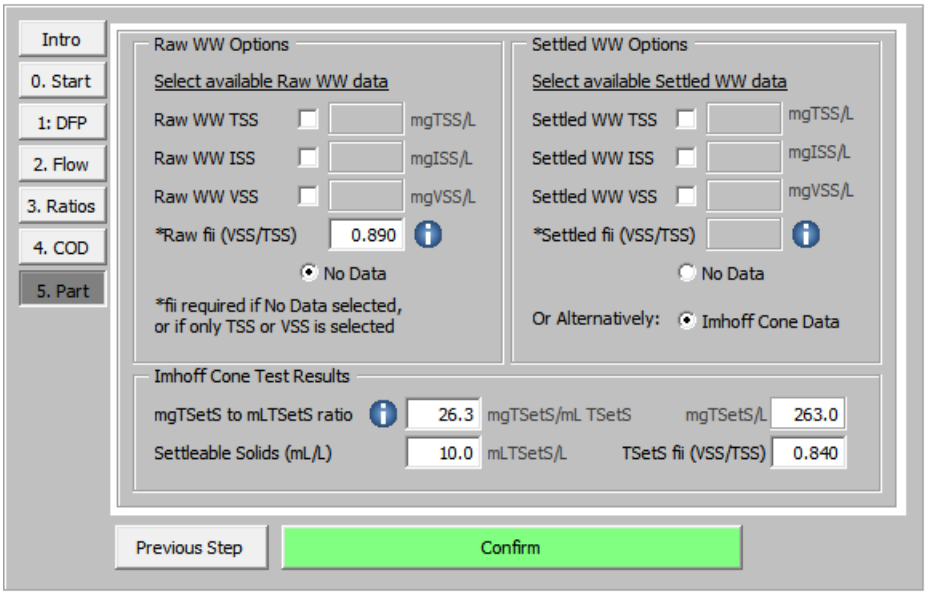



**Figure 5.25: WWChar Tree – Input page 5. Part**

The settled WW particulates characterisation follows the raw WW particulates characterisation. The non-settleable BPO and UPO VSS concentrations are transferred to the settled WW. This will give the settled WW VSS concentration. If the settled WW TSS concentration is entered, then the settled WW ISS concentration can be calculated; alternatively, the settled WW TSS is calculated if the settled WW ISS concentration is entered. If the settled WW TSS or ISS is not entered, then the settled WW $f_{ii}$ (VSS/TSS) is required. If however, the settled WW VSS concentration is entered, then only the non-settleable UPO VSS concentration calculated from the raw WW step is transferred to the settled WW. The non-settleable BPO will then be calculated via the difference between the entered settled WW VSS and the non-settleable UPO VSS concentration from the raw WW step. This calculated non-settleable BPO is transferred back to the raw WW particulates and revises the settleable and non-settleable BPO split in the raw WW. Alternatively if Imhoff cone data is entered, the mgTSetS to mlTSetS ratio, the settleable solids (mL/L) and the TSetS $f_{ii}$ ratio determines the TSetS, VSetS (settleable BPO + settleable UPO), and ISetS concentrations. These TSetS, VSetS, and ISetS concentrations,

which are assumed to be all removed in the PST, are subtracted from the raw WW TSS, ISS, and VSS concentrations to give the settled WW TSS, ISS, and VSS concentrations. The settled WW non-settleable UPO concentration is the same as in the raw WW, and so the non-settleable BPO concentration is recalculated. Once all the particulates are characterised, the $f_{cv}$ mass ratios are revised. The particulates characterisation procedure is done with a calculation table in the background, this has been simplified and shown on in Table 5.11 and Table 5.12. MR indicates the concentrations calculated with the $f_{cv}$ mass ratio and COD concentration, ENT is entered data, the FII is calculated with the entered $f_{ii}$ ratio, DIF indicates the concentrations calculated via difference, and SUM indicates a calculation via summation. The characterisation option, as selected and shown in Figure 5.25 is highlighted with the red border in the tables.

**Table 5.11: WWChar Tree - 5. Part (Calculations Table Raw wastewater)**

| | Raw wastewater Particulates Input Options | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Raw TSS | Yes | No | No | No | Yes | Yes | Yes | No | |
| Raw ISS | No | Yes | No | Yes | Yes | No | Yes | No | |
| Raw VSS | No | No | Yes | Yes | No | Yes | Yes | No | |
| Raw $f_{ii}$ | No | No | Yes | No | No | No | No | Yes | |
| Raw TSS | ENT | DIF | FII | SUM | ENT | ENT | ENT | FII | **(6)** |
| Raw ISS | DIF | ENT | DIF | ENT | ENT | DIF | ENT | DIF | **(7)** |
| Raw VSS | SUM | SUM | ENT | ENT | DIF | ENT | ENT | SUM | **(5)** |
| BPO VSS | | | | | | | | | |
| Settleable | MR | MR | MR | MR | MR | MR | MR | MR | **(3)** |
| Non-Settleable | MR | MR | DIF | DIF | DIF | DIF | DIF | MR | **(4)** |
| UPO VSS | | | | | | | | | |
| Settleable | MR | MR | MR | MR | MR | MR | MR | MR | **(1)** |
| Non-Settleable | MR | MR | MR | MR | MR | MR | MR | MR | **(2r)** |

Where:

- MR = calculated from $f_{cv}$ mass ratio and COD concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation
- FII = calculated with fii (VSS/TSS) ratio

**Table 5.12: WWChar Tree - 5. Part (Calculations Table Settled wastewater)**

| | Settled wastewater Particulates Input Options | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Set WW TSS | Yes | No | No | No | Yes | Yes | Yes | No | No | |
| Set WW ISS | No | Yes | No | Yes | Yes | No | Yes | No | No | |
| Set WW VSS | No | No | Yes | Yes | No | Yes | Yes | No | No | |
| Set WW $f_{ii}$ | No | No | Yes | No | No | No | No | Yes | No | |
| Imhoff Cone | No | No | No | No | No | No | No | No | Yes | |
| Set WW TSS | ENT | DIF | FII | SUM | ENT | ENT | ENT | FII | DIF | **(8)** |
| Set WW ISS | DIF | ENT | DIF | ENT | ENT | DIF | ENT | DIF | DIF | **(9)** |
| Set WW VSS | SUM | SUM | ENT | ENT | DIF | ENT | ENT | SUM | DIF | **(10)** |
| BPO VSS | | | | | | | | | | |
| Settleable | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Non-Settleable | MR | MR | DIF | DIF | DIF | DIF | DIF | MR | DIF | **(4s)** |
| UPO VSS | | | | | | | | | | |
| Settleable | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Non-Settleable | MR | MR | MR | MR | MR | MR | MR | MR | MR | **(2s)** |

- If the non-settleable BPO VSS is calculated here, then the settleable and non-settleable BPO VSS in the raw WW calculation is revised with the non-settleable BPO VSS calculated here.

An explanation of the characterisation procedure for the inputs as shown in Figure 5.25, with the red-bordered column in Table 5.11 and Table 5.12 is provided. For the raw WW, items (1), (2r), (3) and (4) are calculated with the COD concentrations and $f_{cv}$ mass ratios. Item (5) is the sum of (1), (2r), (3) and (4). Item (6) is calculated using (5) and the $f_{ii}$ ratio. Item (7) is the difference between (5) and (6). For the settled WW, item (2s) is the same as (2r). Imhoff cone data determines TSetS, ISetS, and VSuspS concentrations, thus (8) = (6) – TSetS, (9) = (7) – ISetS, and (10) = (5) – VSuspS. Then (4s) = (10) – (2s). Now (3) and (4) are revised: (4) = (4s), (3) = (5) – (4) – (1) – (2r). The mass ratios are then recalculated. The settleable and non-settleable BPO $f_{cv}$ mass ratios were used to calculate (3) and (4), but (3) and (4) were revised in the settled WW part, thus the recalculated settleable and non-settleable BPO $f_{cv}$ mass ratios will be different to the estimated mass ratios specified in the mass ratios input page (*3. Ratios*). For the settleable and non-settleable UPO $f_{cv}$ mass ratios, there are no changes because the (1), (2r), and (2s) were calculated with the mass ratios but were not revised at any stage.

### 5.3.3.7 TKN - 6. TKN

Figure 5.26 shows the TKN inputs page (*6. TKN*). The structure in characterising the TKN is largely the same as for the particulates characterisation, the only additional consideration is the soluble concentrations (FSA, VFA = 0 mgN/L, FBSO, and USO). Like the COD inputs, page the TKN inputs page is separated into two sections: *Crucial Inputs* and *Optional Inputs*.

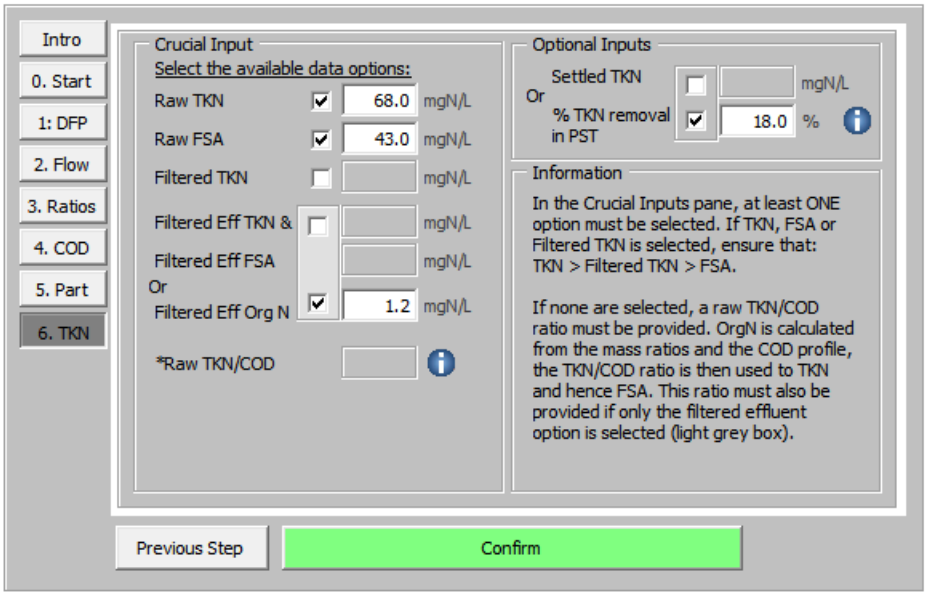



**Figure 5.26: WWChar Tree – Input page 6. TKN**

For the crucial inputs, the designer can select between raw TKN, FSA, filtered TKN, filtered effluent TKN and FSA, or filtered effluent OrgN. If none of the first three options are selected, (raw TKN, FSA, or filtered TKN) then only the total OrgN can be calculated, and thus a raw TKN/COD ratio must be supplied in order to calculate the raw TKN and FSA. Similar to the particulates characterisation process, the settleable and non-settleable UPO OrgN concentrations are determined from their $f_n$ mass ratios and VSS concentrations. The non-settleable UPO OrgN concentration is also transferred to the settled WW OrgN characteristics. When selecting the crucial inputs, it is imperative that the raw TKN > filtered TKN > FSA, otherwise negative N concentrations will occur. In the example provided in the Figure 5.26, the options selected were raw TKN, FSA, and filtered effluent OrgN. The concentrations entered for those inputs were obtained from the FWA concentrations in the DFData data set, but reduced by ±10%.

For the optional inputs, the settled TKN or the %TKN removal in the PST can be specified. In this characterisation example, the latter was selected with an input of 18%. Note that in the DFData method, only the %COD removal in the PST can be specified, the %TKN (and %TP, %TOC, and %VSS) removal in the PST is fixed by the %COD removal (which fixes the settleable UPO and BPO COD) and the specified (fixed) mass ratios. However, in the WWChar Tree method, the characterisation procedure is slightly different in that the specified mass ratios are only estimates, and any data inputs (such as the %TKN removal) that allow the mass ratios to be calculated will revise the specified (estimated) mass ratios. Therefore, in this method, the %TKN (and %TP, %TOC, and %VSS) removals in the PST are not fixed by the %COD removal and hence can be specified separately. If the %TKN removal is entered, the calculated or entered raw TKN will be reduced by this percentage to determine the settled WW TKN concentration. From there, the non-settleable BPO OrgN concentration is determined, which then allows the settleable BPO OrgN concentration to be determined from the total (settleable non-settleable) raw BPO OrgN concentration. The same procedure is applied if the settled TKN is entered; in selecting this option, the %TKN removal in the PST is indirectly specified. The N characterisation procedure, like the particulates characterisation procedure, is hosted in a calculation table that runs in the background. A simplified version of this table is provided in the Appendix B: Characterisation Tables and Methods for WWChar Tree.

#### 5.3.3.8 TP Inputs - 7. TP

Figure 5.27 shows the TP inputs page (*7. TP*). The structure in characterising the TP is identical to the TKN characterisation procedure. There are also two input sections: *Crucial Inputs* and *Optional Inputs*. Care must be taken when entering the crucial inputs, TP > filtered TP > OP. This characterisation table is also available in Appendix B.

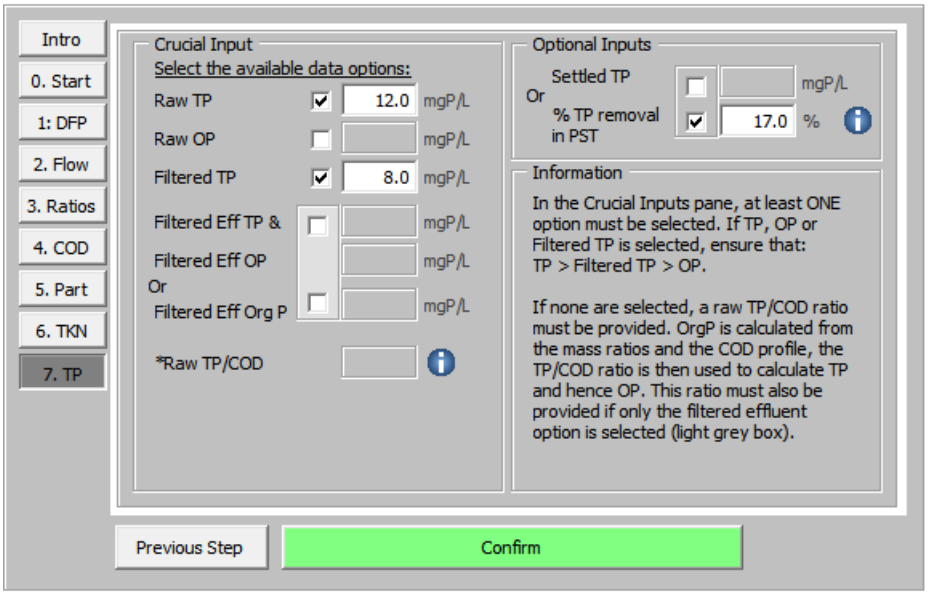



**Figure 5.27: WWChar Tree – Input page 7. TP**

### 5.3.3.9 TOC Inputs - 8. TOC

Figure 5.28 shows the TOC inputs page (*8. TOC*). The structure in characterising the TOC is similar to the TKN and TP characterisation procedure, the only difference is that the soluble inorganic component (FSA, OP) is replaced by the VFA. All TOC inputs are optional because TOC data is not always available. As with the TKN and TP inputs, when entering the TOC inputs, the following condition must always be met: raw TOC > settled TOC > filtered TOC > filtered effluent TOC. This characterisation table is also available in Appendix B.

### 5.3.3.10 Other Inputs - 9. Other

The *9. Other* input page follows the TOC inputs page and it contains all the non-connected but necessary inputs, namely: influent alkalinity (mgAlk/L as $CaCO_3$), pH, and TOD wave amplitude. The TOD wave amplitude is necessary for the aeration model to calculate the peak OUR requirements from the average OUR. The value of this parameter is influenced by the diurnal COD and TKN concentrations; therefore, if no DFP for flow, COD and TKN are determined, then the TOD wave amplitude must be entered because there is no information to calculate it. However, if DFP flow, COD and TKN are determined, then the TOD load wave amplitude is calculated for the designer. *9. Other* is shown in Figure 5.29.

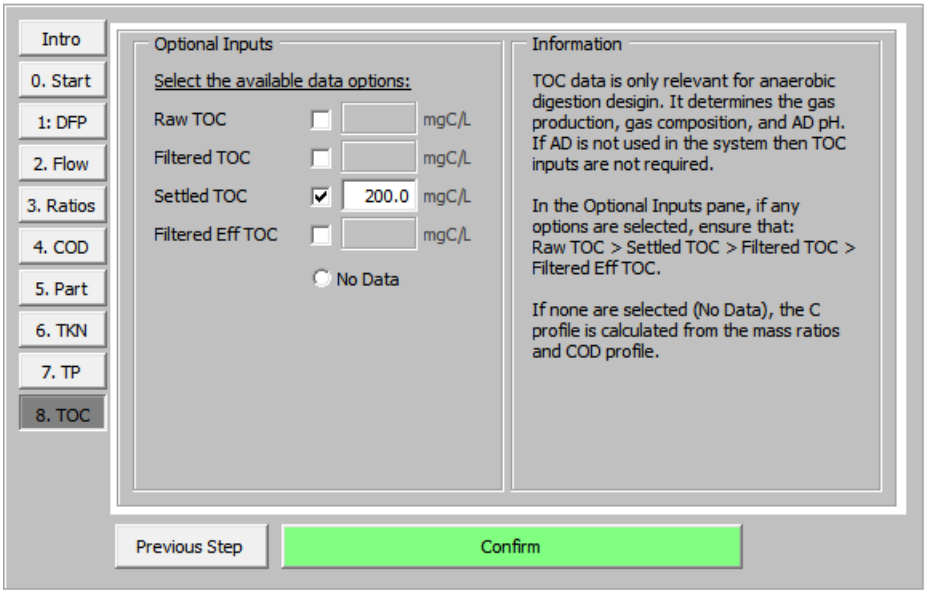



**Figure 5.28: WWChar Tree – Input page 8. TOC**

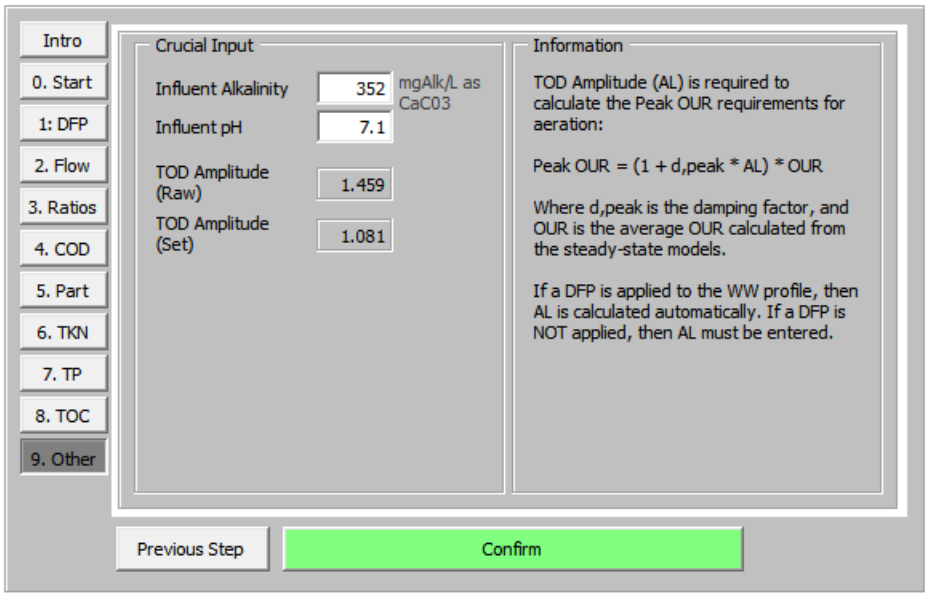



**Figure 5.29: WWChar Tree – Input page 9. Other**

### 5.3.3.11 DFP Adjustment and Finalisation - 10. DFP

Once all inputs are finalised, the DFP must be re-evaluated, particularly if the *Confidence Parameter* was selected as TKN, TP, or TSS. This is because in generating the diurnal concentrations, the organic concentrations (OrgN, OrgP, and VSS) are subtracted from the total concentrations. At any given sample time, the OrgN, OrgP, and VSS concentration is connected to the COD concentration via the $f_{cv}$, $f_n$, and $f_p$ mass ratios. Thus if the TKN:COD, TP:COD, and TSS:COD ratios at that sample time is out of proportion, then the associated

OrgN, OrgP and VSS concentrations can be larger than the TKN, TP, and TSS concentrations. This will results in negative inorganic (FSA, OP, or ISS) concentrations – which is not allowed. In this situation, the COD concentration at that sample time, which is determined by the COD DFP intensity at that sample time, is overestimated; or, the DFP for the TKN, TP, or TSS is underestimated. If the designer is certain that the DFP is correct, then the error lies with the inputs to the WWChar Tree characterisation procedure. To re-evaluate the DFP, the designer must click on the *Re-evaluate DFP* button, the DFP readjustment takes place on the same window as the preliminary DFP selection/creation window, see Section 5.3.3.2.

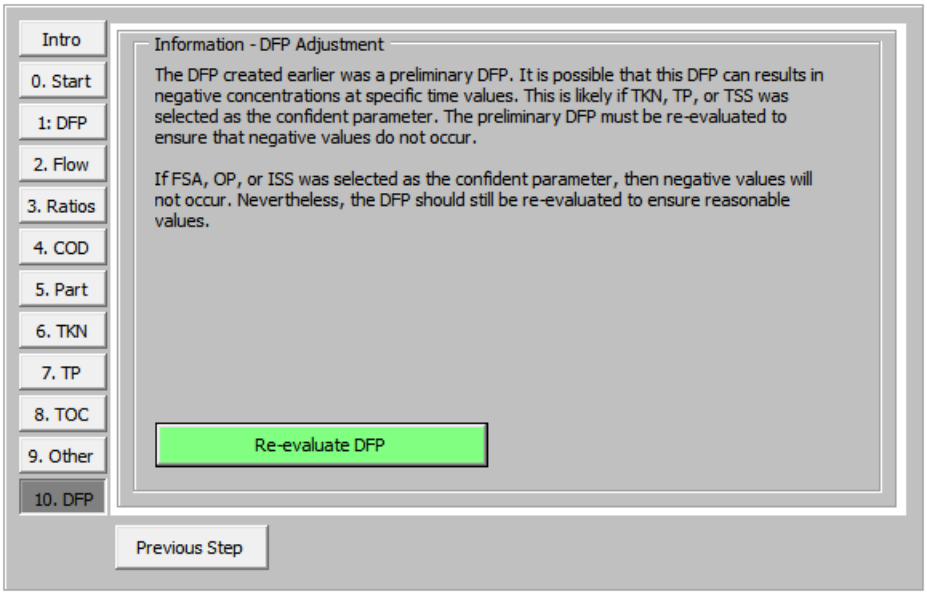



**Figure 5.30: WWChar Tree – Input page 10. DFP**

### 5.3.3.12 Characterisation Results

Figure 5.31 shows the *Characterisation Results* section displays the FWA concentrations for the created wastewater profile. The designer can toggle the different characteristic groups by using the tab buttons on the left. Note that the symbol notation displayed for the characteristics are in the UCT notation, however, by hovering over the symbols, the IWA notation as defined by (Corominas *et al*., 2010) can be viewed. At the bottom of the FWA concentrations are the revised $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios.

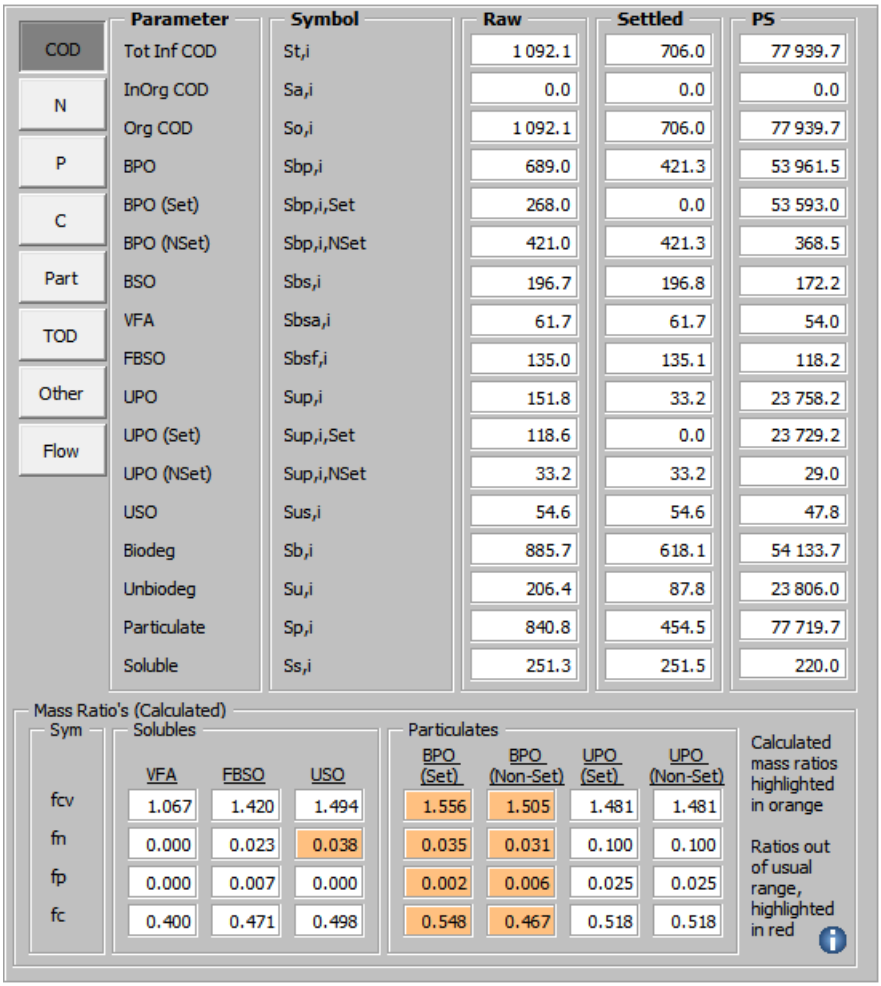



**Figure 5.31: WWChar Tree – Characterisation results**

With the WWChar Tree complete, the WWChar Tree FWA concentrations can be compared to the DFData concentrations. The WWChar Tree was processed with very little data compared to the DFData section, all the inputs, as shown in the WWChar Tree input pages (Figure 5.19 to Figure 5.29) are summarised in the Table 5.13 below. Furthermore, when it was processed, the FWA data obtained from the DFData section was scaled down by ±10% (done externally from the program) to simulate a data scenario where the concentration data is obtained from a composite non-weighted sample. In addition to this, the DFP created for this section's characterisation example was a rough estimate and by no means identical to the actual DFP in the DFData section. The only similarities are that they have similar flow rate, COD, FSA, OP and ISS peak times. In this characterisation example, the selected input options for the different characteristic groups were also chosen at random. Nevertheless, even with these irregular inputs, Table 5.14 on the next page shows that decent estimate of the wastewater characteristics were obtained, which matched relatively closely to the characteristics obtained in the DFData section that utilised the full data set. However, there were discrepancies with the non-settleable BPO VSS concentrations, which were also indicated by the non-settleable BPO $f_{cv}$ mass ratio

in Figure 5.31. This had a knock-on effect on all the non-settleable BPO characteristics. The ISS concentration also did not match closely; this is because the WWChar Tree ISS DFP was higher in comparison to the DFData's ISS DFP. However, the rest of the characteristics, particularly the important ones such as total COD, UPO COD, FSA and OP, were relatively close to the DFData characteristics.

**Table 5.13: Composite non-weighted concentrations and inputs used for WWChar Tree**

| COD | Entered Value | Units | Part | Entered Value | Units |
|---|---|---|---|---|---|
| Raw COD | 956.0 | mgCOD/L | $f_{ii}$ | 0.890 | VSS/TSS |
| Filtered COD | 220.0 | mgCOD/L | mgTSetS/mlTSetS | 26.3 | mg/ml |
| %COD Rem | 35.4 | % | Settleable Solids | 10 | mL/L |
| fS'up (raw) | 0.139 | | TSetS $f_{ii}$ | 0.840 | VSS/TSS |
| fS'up (settled) | 0.047 | | | | |
| VFA | 54.0 | mgCOD/L | | | |
| N | Entered Value | Units | P | Entered Value | Units |
| Raw TKN | 68.0 | mgN/L | Raw TP | 12.0 | mgP/L |
| FSA | 43.0 | mgN/L | Filtered TP | 8 | mgP/L |
| Filtered effluent OrgN | 1.2 | mgN/L | %TP Rem | | % |
| %TKN Rem | 18.0 | % | | | |
| C | Entered Value | Units | Flow | Entered Value | Units |
| Settled TOC | 200 | mgC/L | ADWF | 1200 | $m^3/h$ |
| | | | PST Underflow % | 0.5 | |
| Other | Entered Value | Units | | | |
| Alkalinity | 352 | mgAlk/L | | | |
| pH | 7.1 | | | | |

**Table 5.14: Comparison DFData and WWChar Tree of FWA characterisation results**

| | COD mg/L | | VFA mg/L | | TOC mg/L | | TKN mg/L | | FSA mg/L | | TP mg/L | | OP mg/L | | TSS mg/L | | VSS mg/L | | ISS mg/L | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DF Data | Tree | DF Data | Tree | DF Data | Tree | DF Data | Tree | DF Data | Tree | DF Data | Tree | DF Data | Tree | DF Data | Tree | DFData | Tree | DF Data | Tree |
| Raw WW | 1016.0 | 1092.1 | | | 335.2 | 365.4 | 75.6 | 76.6 | | | 14.6 | 13.2 | | | 558.6 | 624.2 | | | 60 | 69.6 |
| Settled WW | 656.0 | 706.0 | | | 216.2 | 228.6 | 63.2 | 62.6 | | | 11.8 | 10.9 | | | 275.0 | 323.2 | | | 12 | 20.8 |
| Filtered | 250.0 | 251.3 | 60.0 | 61.7 | 85.8 | 86.1 | 53.4 | 51.6 | 47.3 | 48.1 | 9.8 | 8.6 | 8.8 | 8.0 | | | | | | |
| USO | 50 | 54.6 | | | 16.6 | 18.2 | 1.2 | 1.4 | | | 0.0 | 0.0 | | | | | DFData | Tree | | |
| Settleable BPO | 249.7 | 268.0 | | | 80.3 | 94.4 | | 6.0 | | | 1.0 | 0.3 | | | | | 161.1 | 172.3 | | |
| Non-settleable BPO | 375.3 | 461.0 | | | 120.7 | 130.8 | | 8.8 | | | 1.5 | 1.7 | | | | | 242.3 | 279.8 | | |
| Settleable UPO | 110.4 | 118.7 | | | 38.6 | 41.5 | | 8.0 | | | 1.9 | 2.0 | | | | | 74.6 | 80.1 | | |
| Non-settleable UPO | 30.8 | 33.2 | | | 10.8 | 11.6 | | 2.2 | | | 0.5 | 0.6 | | | | | 20.8 | 22.4 | | |

### 5.3.4 Comments and Conclusion

The WWChar Tree is highly flexible characterisation method in that multiple input options are available. The characterisation tables (See Section 5.3.3.6 Particulates Inputs - 5. Part and Appendix B: Characterisation Tables and Methods for WWChar Tree) contain the characterisation procedure for all the options available. These tables only deal with one characteristic group at a time (COD, N, P, C, or particulates), thus allowing for reasonable amount of the permutations for the available input options. If all characteristic groups were considered in one attempt, then an infinite number of permutations are available. Thus in doing the characterisation procedure in stages, the permutations within each stage are more manageable. It is important to note that characterisation procedure for each stage and permutation is purely theoretical, centred on mass balances and reasonable assumptions. Furthermore, all the permutations have an almost identical structure where the settleable and non-settleable UPO is always calculated from mass ratios and the BPO is most often calculated via a difference. However, this structure might not necessarily be the best for each permutation; with further understanding of wastewater characteristics, particularly the composition and settling behaviour of settleable and non-settleable BPO and UPO particulates, these permutations can be revised thus having a unique tailored characterisation procedure that bests reflect reality. In order to adjust the characterisation procedure for each permutation, one simply has to edit the respective characterisation table.

The wastewater characteristics shown in Table 5.14 were close to the wastewater characteristics obtained in the “more demanding” DFData method, even though the inputs were irregular and roughly estimated. However, it is extremely important to note the WWChar Tree characterisation results might not always be accurate, especially if grab samples are the source of the wastewater concentration data. In this scenario, the characterisation results will be highly dependent on the DFP selected or created by the designer. The WWChar Tree example was processed with some foresight into what characteristics should be obtained. In practice, this foresight is not available; hence, as stated at the beginning of this section, “the wastewater characteristics have to be determined as best as possible, the accuracy of these characteristics relies solely upon the designer (user)”. The WWChar Tree cannot make the inputs more accurate or more correct, but it can provide results for the designer to make a judgment on their accuracy and correctness. Nevertheless, with these limitations, the WWChar Tree is a useful characterisation method in that a variety of inputs can be used, and wastewater characteristics, best conforming to the most reliable inputs, are generated.

## 5.4 Method 4: Grab Sample Reconciliation

The Grab Sample Reconciliation method is not yet available in the program. The idea for this characterisation method is to reconcile, with the aid of a graph, irregularly taken grab samples during the day – irregular in the sense that the grab sample data set is incomplete, i.e. not all 12 2-hourly interval grab samples are available, but at least one is available.

The reconciliation process is a "match the dots" process where, like the WWChar Tree, the more data supplied, the better the accuracy of the characterisation. The irregular grab sample data (flow rate in $m^3/h$ and concentrations in mg/L), is plotted on a graph with the X-axis as the sample time, and the Y-axis as the grab sample data. The designer then selects a DFP for the flow rate that best matches the pattern of the flow rate data from the irregular grab samples. At each sample time, the DFP has a specific %Ave value (intensity). Using this intensity and the flow rate data at each data point, the simple average flow rate (ADWF) is determined. The same is done for the COD, TKN or FSA, TP or OP, and TSS or ISS. A DFP for each concentration group is selected. At this point, with DFPs for the flow rate and concentration groups are available; therefore, the percentage difference between the simple average concentrations and the FWA concentrations is known. Using this information, the FWA concentration can be calculated by increasing the simple average concentrations by that percentage difference.

Now because the DFP is only an estimate and not the actual DFP of the wastewater, the calculated ADWF and the FWA concentrations at each data point will not match. The reconciliation process then takes place, with the aim to have all data points providing the same (or similar) ADWF and average concentrations. The reconciliation process involves the designer adjusting the DFPs with a series of buttons that allow the DFPs to increase or decrease in intensity. Each sample time is connected to the adjacent sample times; thus, if the designer increases or decreases the DFP intensity at a specific sample time (e.g. 2PM), the intensity of the DFP at the adjacent sample times (12PM and 4PM) increases or decreases accordingly - but not as much as the central sample time (2PM). To aid the reconciliation process, the designer also estimates the ADWF and FWA concentrations. This is used to calculate the missing data points. At these points, using the intensity of the DFP, the grab sample data is calculated using the ADWF and FWA concentration estimates. The estimated ADWF and FWA concentrations and the calculated ADWF and FWA concentrations are also plotted on the graph. The reconciliation process ends when the estimated and calculated average data points are a straight line. When this occurs, the estimated average concentrations are almost equal to the calculated averages, and the DFPs are reconciled. An example of this graph is provided in Figure 5.32. To make the reconciliation process easier and the reconciliation graph clearer, each characteristic group can be reconciled separately; Figure 5.32 only shows the COD reconciliation.

After the above-mentioned process, the designer then proceeds to the WWChar Tree method, however, the DFP creation/selection step is not required. The wastewater can then be characterised with any available wastewater data.

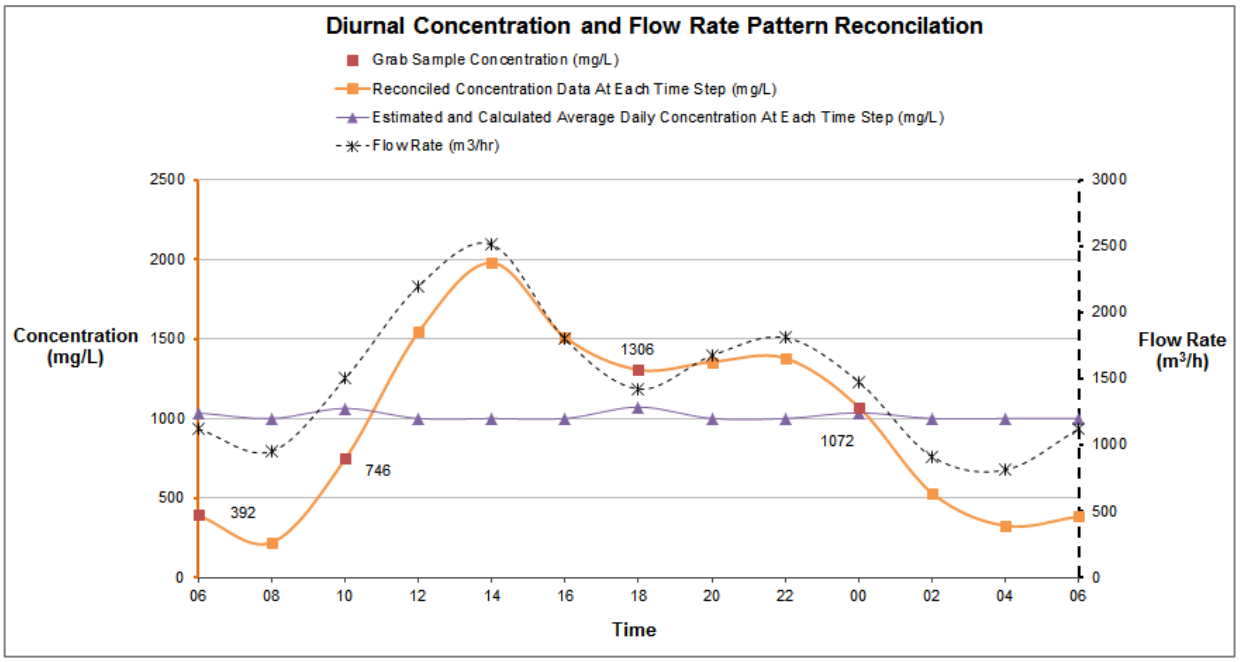



**Figure 5.32: Grab Sample Reconciliation Graph**

COD reconciliation steps (after flow rate has been reconciled), with reference to Figure 5.32:

1. Enter COD concentrations (red square/s)
2. Select COD DFP (orange line)
3. At data points (red squares), DFP intensity and entered COD concentration determines average daily concentration (purple triangles) at that data point
4. Enter estimated FWA COD concentration
5. Estimated FWA COD concentration determines the rest of the purple triangles
6. Connect all purple triangles (purple line)
7. Adjust DFP until purple line is flat

The above steps are a summary of the reconciliation process for the concentration groups. The exact same process is followed for the flow rate. Note that Figure is a completed reconciliation process, when starting the reconciliation the reconciliation graph will not look as neat as the one presented. The above example was processed with the DFData diurnal data set (Table 5.3) with only the 6AM, 10AM, 6PM, and 12AM data flow rate and COD data. A comparison of the results is provided in Table 5.15 on the next page; the entered data points are marked with ENT. Table 5.15 shows that the Grab Sample Reconciliation can generate a reasonable estimate of the diurnal flow rate and concentrations, in the above example the reconciliation overestimated the FWA COD concentration by 17%, and underestimated the ADWF by 9%.

**Table 5.15: Comparison between the reconciled data (Grab Sample Reconciliation) and the actual data (DFData) for the flow rate and COD**

| | Flow $m^3/hr$ | | COD mg/L | |
|---|---|---|---|---|
| Time | Reconciled | DFData | Reconciled | DFData |
| 06h00 (ENT) | 480.0 | 480.0 | 392.0 | 392.0 |
| 08h00 | 741.1 | 673.0 | 221.2 | 396.0 |
| 10h00 (ENT) | 2 000.0 | 2000.0 | 746.0 | 746.0 |
| 12h00 | 2 007.3 | 2293.0 | 1 543.7 | 1026.0 |
| 14h00 | 1 886.5 | 1993.0 | 1 979.3 | 1156.0 |
| 16h00 | 1 229.3 | 1560.0 | 1 510.5 | 1184.0 |
| 18h00 (ENT) | 1 360.0 | 1360.0 | 1 306.0 | 1306.0 |
| 20h00 | 1 322.1 | 1547.0 | 1 355.2 | 1212.0 |
| 22h00 | 1 374.1 | 1413.0 | 1 378.5 | 1119.0 |
| 00h00 (ENT) | 1 293.0 | 1293.0 | 1 072.0 | 1072.0 |
| 02h00 | 857.7 | 907.0 | 531.4 | 979.0 |
| 04h00 | 382.1 | 587.0 | 325.8 | 653.0 |
| 06h00 | 480.0 | 480.0 | 383.4 | 392.0 |
| Simple Average (With Simpsons Rule) | 1 217.1 | 1336.6 | 1 021.4 | 932.4 |
| FWA (With Simpsons Rule) | | | 1 189.4 | 1016.3 |

It is important to remember that the accuracy of this estimate will depend on the judgement of the designer. However, a greater factor is the amount of the data supplied for the reconciliation. In general, the more sample times available, the easier the reconciliations. Furthermore, the regularity of the sample time must not be overlooked. The reconciliation will be very inaccurate if the sample times are too far apart or too close together, for example 6AM and 6PM or 6AM and 8AM. In such situations, there is a limited indication of the shape and intensity of DFP. Therefore, grab samples that are evenly spaced out (even if there are not many samples available) provide for better reconciliation, e.g. 8AM, 12AM, and 4PM.

In summary, the Grab Sample Reconciliation method is a method that can cater for very poor data scenarios where only a few grab samples are available. Using this data, DFPs for the various characteristic groups can be generated, at which then will allow the designer to use the WWChar Tree method to populate the wastewater characteristics. This method is still a work in progress, as it needs to be tested further before it can be developed and coded into the program Depending on the how effective this method is after testing, it could rank higher than WWChar Tree in terms of data level requirements.

## 5.5 Method 5: Preloaded Profile

The Preloaded Profile method caters for a data poor scenario. In this scenario, the designer has no access to useful wastewater data; WWChar is thus difficult. The decisions that the designer makes in the method focuses on the wastewater characteristics that have the most significant impact on the size and design of the treatment system. Figure 5.33 shows the Preloaded Profile window, and Figure 5.34 is an enlargement of the inputs frame.

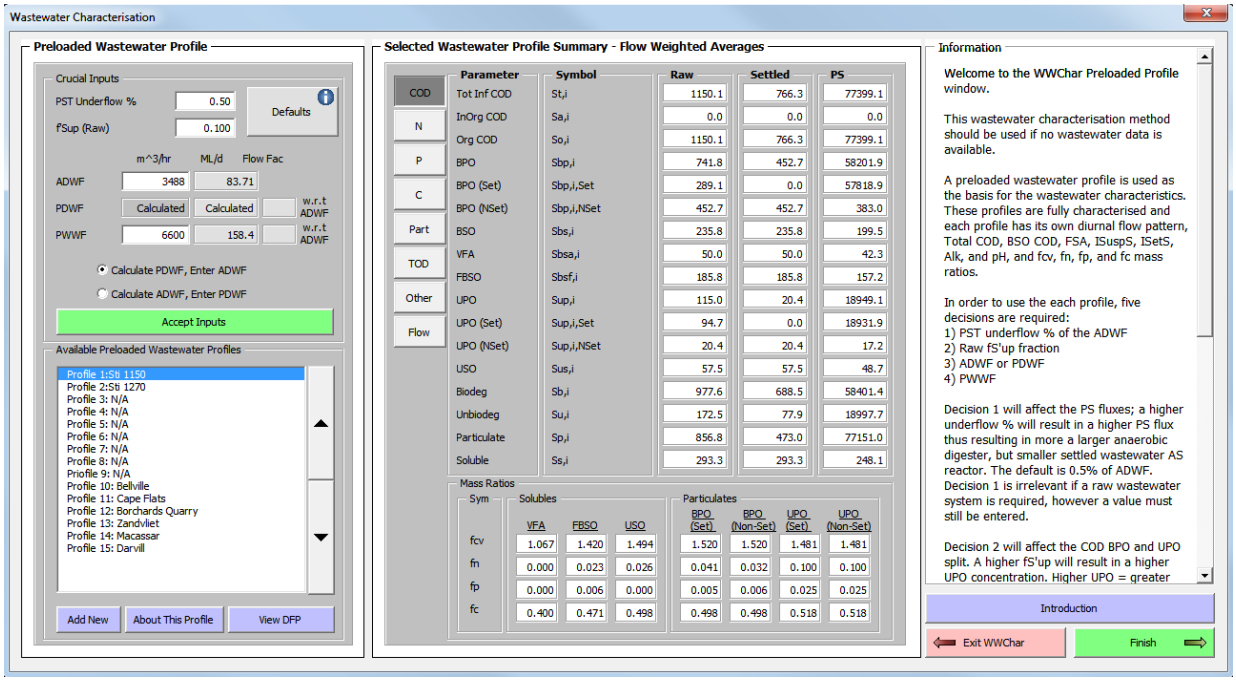



**Figure 5.33: Preloaded Profile**

### 5.5.1 Data Requirements

In the Preloaded Profile method, the designer is presented with preloaded wastewater profiles that have generalised wastewater characteristics for different WWTP types, for example, a profile for a small WWTP treating a strong diurnal variation or a large WWTP treating wastewater with a mild diurnal flow variation but high N & P concentrations. Profiles for a few named WWTPs in Cape Town where the WW characteristics were measured, are also provided. The wastewater profile selected by the designer determines the wastewater characteristics and the diurnal flow pattern. The only inputs required are the PST underflow percentage of raw ADWF, the $f_{S'up}$ for the raw WW, ADWF or PDWF, and the PWWF.

Both the ADWF and the PDWF cannot be entered; this is because the diurnal flow pattern associated with each Preloaded Profile is fixed. If both are entered then the diurnal flow pattern will not match the entered flow rates, therefore allowance for only one of them was made. If the ADWF is entered then the PDWF must be calculated; alternatively, if the PDWF is

entered then the ADWF is calculated. The decision to enter the ADWF or PDWF is made using the option buttons: *Enter ADWF, Calculate PDWF* and *Enter PDWF, Calculate ADWF*. However, because the steady-state models use the ADWF to determine the organic load, it is recommended to enter the ADWF instead of the PDWF. The PDFW is primarily utilised for the design of the operating SST recycle ratios. The PWWF determines the SST area, which in most cases is the bottleneck in terms of system capacity. Therefore, focus should be placed on selecting an appropriate ADWF and PWWF.

Information about the profile can be viewed by clicking the *About This Profile* button. The diurnal flow patterns for each profile can be viewed by clicking on the *View DFP*. Figure 5.35 shows this window where the flow pattern can be viewed. When viewing the flow pattern, the graph control window allows for toggling of the graph data.

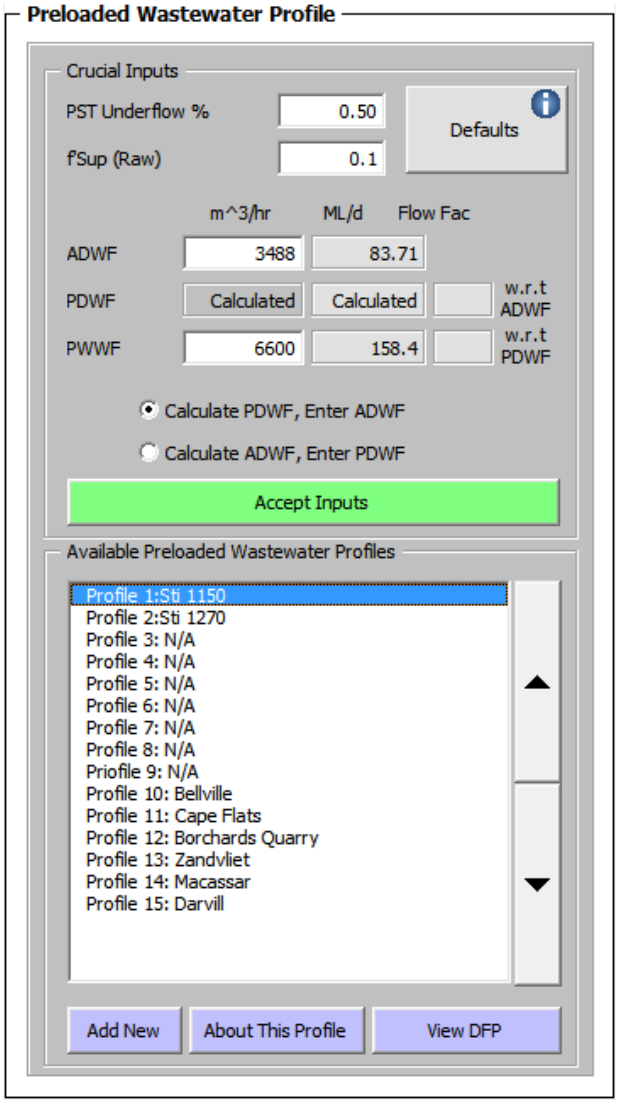



**Figure 5.34: Preloaded Profile inputs frame**

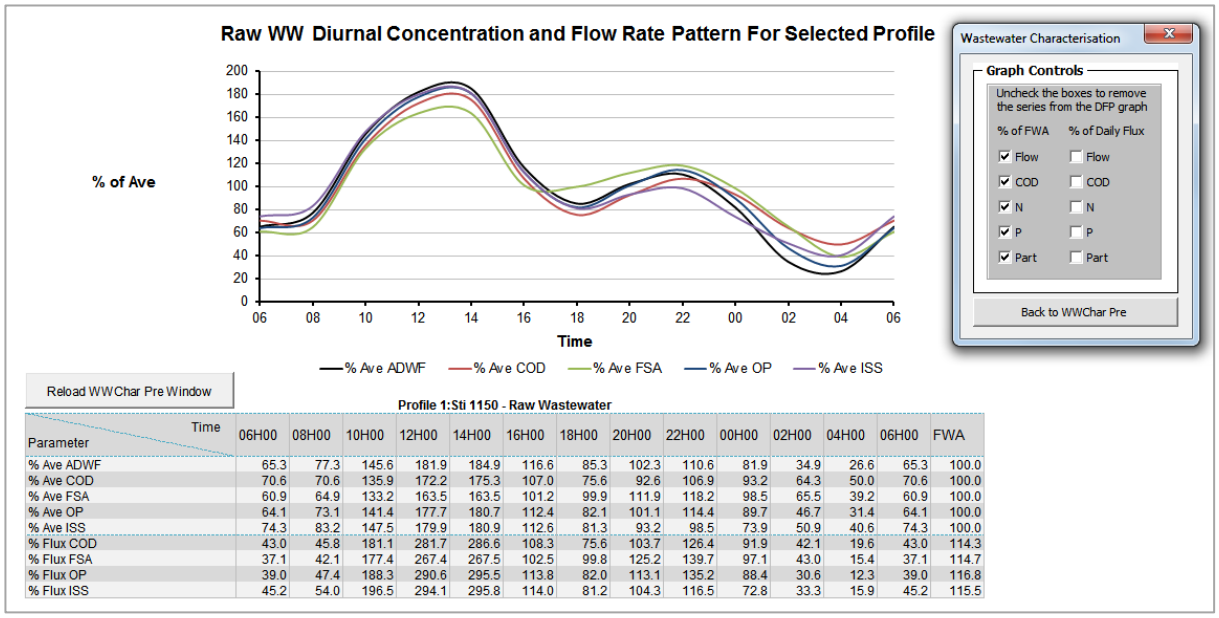
Currently the available profiles for this method are scarce, as the author has no access to a large database. However, in time additional profiles will be added, as data is made available. The amount of profiles that can be added is limited to the memory capabilities of Excel; however, in reality, this will not be reached as this memory size is sufficiently large.

## 5.5.2 Characterisation Procedure

For the raw WW, each profile has a fixed total COD concentration and soluble COD concentration, the total particulate COD concentration is the difference between the two. The selected $f_{S'up}$ fractions determine the ratio between BPO and UPOs - a higher $f_{S'up}$ will result in a higher UPO and a lower BPO concentration. The BPO and UPOs are split into settleable and non-settleable particulates. The ratio between settleable and non-settleable particulates is kept constant for all profiles. For the UPO, this ratio is 4.65 mgCOD/L of settleable UPO to 1 mgCOD/L of non-settleable UPO (4.65:1), i.e. ~ 75-85% settleable, for the BPO, this ratio is

0.63:1, i.e. 35-45% settleable (Wentzel *et al*., 2006). It is assumed that the PST removes all settleable particulates; with this assumption, these ratios equate to 35% to 40% COD removal in the PST depending on the raw WW influent COD concentration.

The ADWF and the diurnal flow pattern determine the raw WW flow rate at each time step (6AM to 4AM). The PS flow rate is calculated using the entered PST underflow % of the raw ADWF. The difference between the raw WW and PS flow rate is then the settled WW flow rate. The flow rate at each time step then determines the organic fluxes at each time step. It is important to note that the flow rates do not determine the FWA concentrations; it only determines the organic load because the FWA concentrations are fixed for each profile.




Profile 1:Sti 1150 - Raw Wastewater

| Parameter \ Time | 06H00 | 08H00 | 10H00 | 12H00 | 14H00 | 16H00 | 18H00 | 20H00 | 22H00 | 00H00 | 02H00 | 04H00 | 06H00 | FWA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % Ave ADWF | 65.3 | 77.3 | 145.6 | 181.9 | 184.9 | 116.6 | 85.3 | 102.3 | 110.6 | 81.9 | 34.9 | 26.6 | 65.3 | 100.0 |
| % Ave COD | 70.6 | 70.6 | 135.9 | 172.2 | 175.3 | 107.0 | 75.6 | 92.6 | 106.9 | 93.2 | 64.3 | 50.0 | 70.6 | 100.0 |
| % Ave FSA | 60.9 | 64.9 | 133.2 | 163.5 | 163.5 | 101.2 | 99.9 | 111.9 | 118.2 | 98.5 | 65.5 | 39.2 | 60.9 | 100.0 |
| % Ave OP | 64.1 | 73.1 | 141.4 | 177.7 | 180.7 | 112.4 | 82.1 | 101.1 | 114.4 | 89.7 | 46.7 | 31.4 | 64.1 | 100.0 |
| % Ave ISS | 74.3 | 83.2 | 147.5 | 179.9 | 180.9 | 112.6 | 81.3 | 93.2 | 98.5 | 73.9 | 50.9 | 40.6 | 74.3 | 100.0 |
| % Flux COD | 43.0 | 45.8 | 181.1 | 281.7 | 286.6 | 108.3 | 75.6 | 103.7 | 126.4 | 91.9 | 42.1 | 19.6 | 43.0 | 114.3 |
| % Flux FSA | 37.1 | 42.1 | 177.4 | 267.4 | 267.5 | 102.5 | 99.8 | 125.2 | 139.7 | 97.1 | 43.0 | 15.4 | 37.1 | 114.7 |
| % Flux OP | 39.0 | 47.4 | 188.3 | 290.6 | 295.5 | 113.8 | 82.0 | 113.1 | 135.2 | 88.4 | 30.6 | 12.3 | 39.0 | 116.8 |
| % Flux ISS | 45.2 | 54.0 | 196.5 | 294.1 | 295.8 | 114.0 | 81.2 | 104.3 | 116.5 | 72.8 | 33.3 | 15.9 | 45.2 | 115.5 |

**Figure 5.35: Preloaded Profile – Diurnal Flow Pattern for selected profile**

## 5.5.3 Comments and Conclusion

The Preloaded Profile should only be used if no data is available. This method allows for a generic set of wastewater characteristics to be used. The designer is left with only three decisions: 1) what type of WWTP is required; 2) what ADWF or PDWF is required; and 3) $f_{S'up}$. The first decision is the selection of which preloaded profile to be used, a large WWTP with low diurnal flow variation, or maybe a small one with high variation. The second decision determines the overall organic load on the WWTP; a high ADWF equals a high organic load. The third decision determines the UPO fluxes, the higher the UPO flux the larger the AS system. These three decisions allow for the creation of generic wastewater profile; and although it might not necessarily be accurate, it is still better than selecting random wastewater characteristics and flow rates to create a wastewater profile.

## 5.6 WWChar Summary

When the WWChar method is complete, the WWChar Summary window is shown to the designer. On this window, the characterisation results are presented and organised in the following categories: COD, N, P, C, Particulates, TOD, Other and Flow (**A**). These categories are further organised according to raw WW, settled WW, and PS (**B**). In addition to this, the mass ratios for all seven organic components are displayed (**C**). The data in this window is contained in a spreadsheet (WWChar_Sum). The primary purpose of this spreadsheet is to collect and organise the WWChar results from the different methods so that they can be displayed to the user, be transferred to a different spreadsheets for exporting, or be transferred to the WWChar_Inputs spreadsheet where it used in the steady-state models. Figure 5.36 shows the WWChar Summary window with enlargements of certain parts.

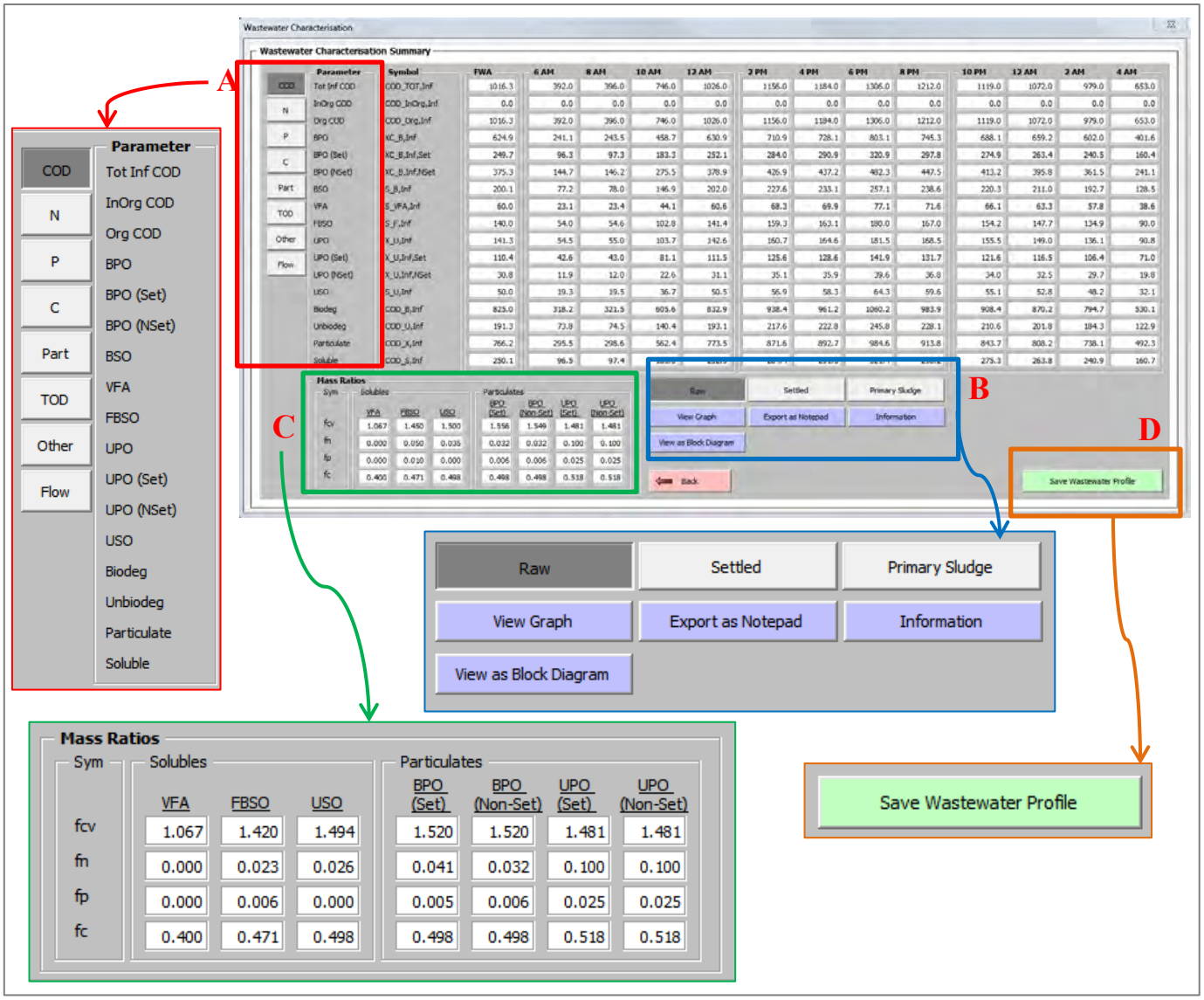



**Figure 5.36: WWChar Summary**

If this is a new wastewater profile, the designer can save this profile (**D**) and link it to any plant-wide design or capacity estimation project. This save function is an internal feature and no external files are generated, this is discussed further in Section 5.7.4 WWChar Save Data. The designer can also perform the following tasks (**B**):

- View the FWAs as a block diagram – *View as Block Diagram* button (Figure 5.37)
- View a graphical summary of the characteristics – *View Graph* button (Figure 5.38)
- Export the entire profile to a Notepad for external use – *Export as Notepad* button

With the *View as Block Diagram* button, the designer can view a summary of the FWAs presented in wastewater characteristic block diagrams. The designer can use the tab buttons to navigate the block diagrams for the COD, N, P, C and particulates (Part: ISS, VSS) for the raw WW, settled WW, and PS. With the *View Graph* button, the designer can view a graph of the DFP for all the wastewater characteristics groups (flow rate COD, TKN, FSA, TP, OP, etc.) for the raw WW, settled WW, and PS. The *Export as Notepad* buttons will export the data as presented in the WWChar Summary window as a Notepad file (i.e. delineated text file). Additional export functions will be added depending on what is required by users of the program, examples include Excel spreadsheets, PDF, CSV etc. If possible, file types relevant for dynamic simulation software can also be created.

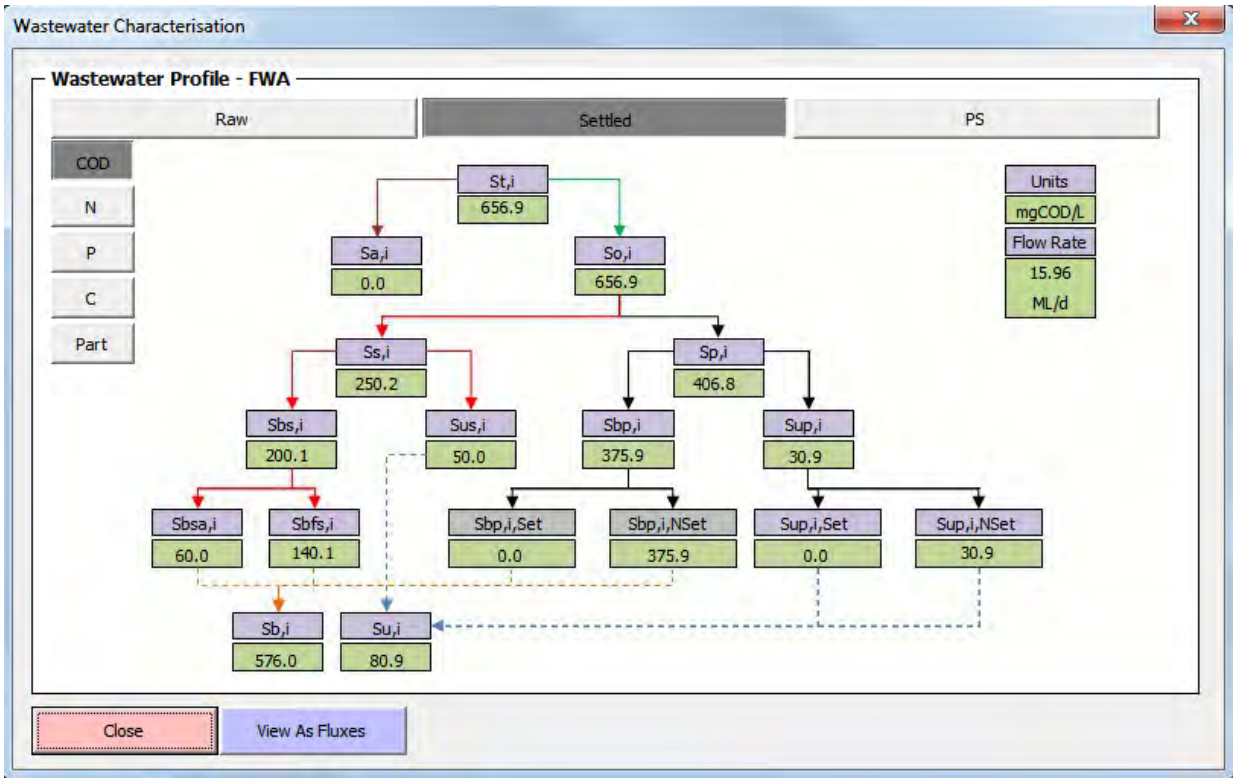
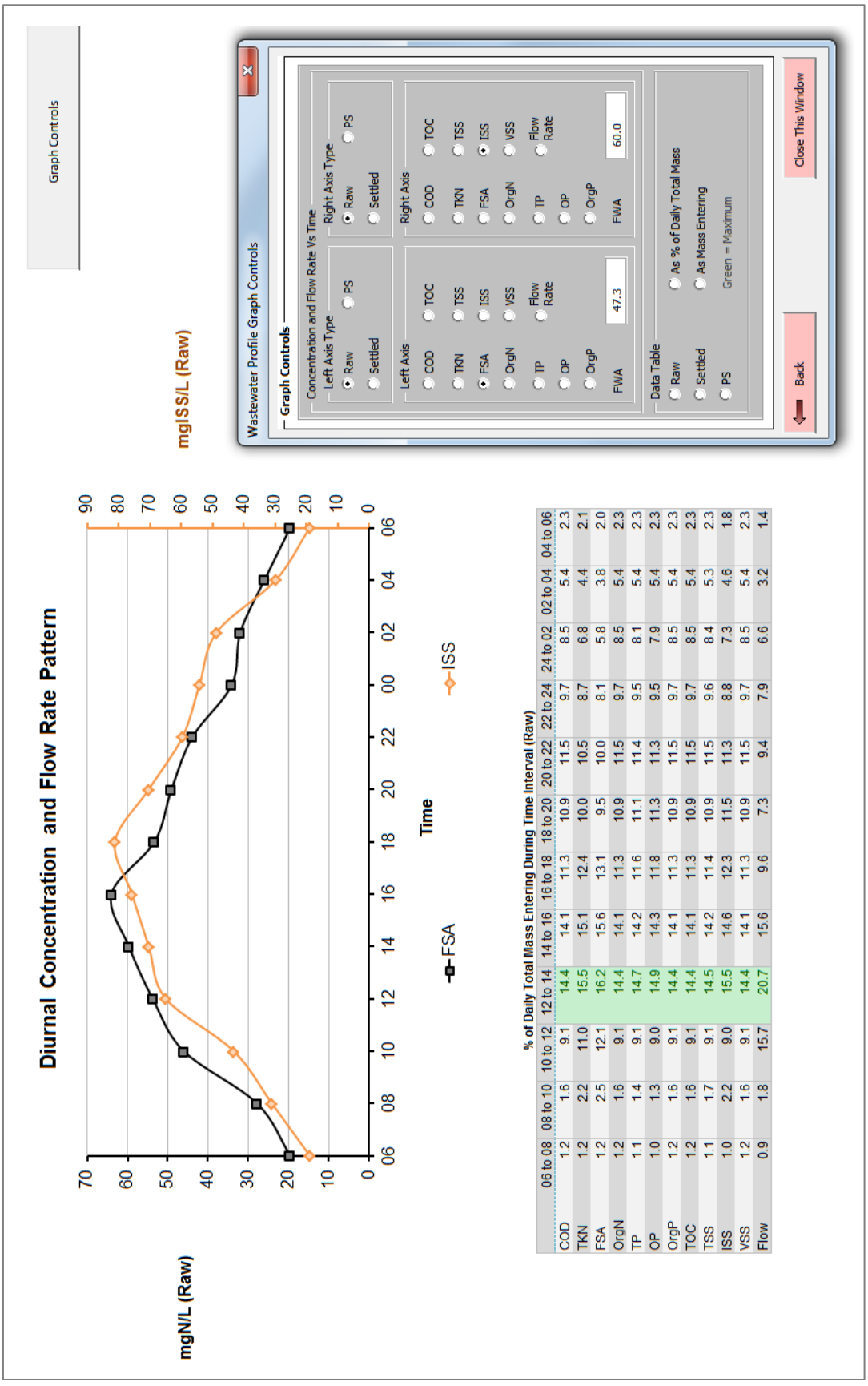



**Figure 5.37: WWChar Block Diagram window**




| | 06 to 08 | 08 to 10 | 10 to 12 | 12 to 14 | 14 to 16 | 16 to 18 | 18 to 20 | 20 to 22 | 22 to 24 | 24 to 02 | 02 to 04 | 04 to 06 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COD | 1.2 | 1.6 | 9.1 | 14.4 | 14.1 | 11.3 | 10.9 | 11.5 | 9.7 | 8.5 | 5.4 | 2.3 |
| TKN | 1.2 | 2.2 | 11.0 | 15.5 | 15.1 | 12.4 | 10.0 | 10.5 | 8.7 | 6.8 | 4.4 | 2.1 |
| FSA | 1.2 | 2.5 | 12.1 | 16.2 | 15.6 | 13.1 | 9.5 | 10.0 | 8.1 | 5.8 | 3.8 | 2.0 |
| OrgN | 1.2 | 1.6 | 9.1 | 14.4 | 14.1 | 11.3 | 10.9 | 11.5 | 9.7 | 8.5 | 5.4 | 2.3 |
| TP | 1.1 | 1.4 | 9.1 | 14.7 | 14.2 | 11.6 | 11.1 | 11.4 | 9.5 | 8.1 | 5.4 | 2.3 |
| OP | 1.0 | 1.3 | 9.0 | 14.9 | 14.3 | 11.8 | 11.3 | 11.3 | 9.5 | 7.9 | 5.4 | 2.3 |
| OrgP | 1.2 | 1.6 | 9.1 | 14.4 | 14.1 | 11.3 | 10.9 | 11.5 | 9.7 | 8.5 | 5.4 | 2.3 |
| TOC | 1.2 | 1.6 | 9.1 | 14.4 | 14.1 | 11.3 | 10.9 | 11.5 | 9.7 | 8.5 | 5.4 | 2.3 |
| TSS | 1.1 | 1.7 | 9.1 | 14.5 | 14.2 | 11.4 | 10.9 | 11.5 | 9.6 | 8.4 | 5.3 | 2.3 |
| ISS | 1.0 | 2.2 | 9.0 | 15.5 | 14.6 | 12.3 | 11.5 | 11.3 | 8.8 | 7.3 | 4.6 | 1.8 |
| VSS | 1.2 | 1.6 | 9.1 | 14.4 | 14.1 | 11.3 | 10.9 | 11.5 | 9.7 | 8.5 | 5.4 | 2.3 |
| Flow | 0.9 | 1.8 | 15.7 | 20.7 | 15.6 | 9.6 | 7.3 | 9.4 | 7.9 | 6.6 | 3.2 | 1.4 |

**Figure 5.38: WWChar Diurnal Pattern Graph window**

## 5.7 WWChar Navigation

The WWChar component contains linking windows that allow for navigation in the PWSSD program. These linking windows are presented in this section.

### 5.7.1 WWChar Landing

When the WWChar component is started, the WWChar Landing (Figure 5.39) is the first window that is displayed. This window provides an overview of the importance of WWChar. A short description of each WWChar Method is also given. WWChar Landing contains two buttons: *Load Saved Profile,* and *Create New Profile*; these buttons can be used to load a previously completed and saved wastewater profile or to create a new wastewater profile. The loaded or new profile can be used in the current plant-wide design or capacity estimation. The WWChar component can be used separately from the plant-wide steady-state design and capacity estimation components, if so then the *Load Saved Profile* button is not available, i.e. the wastewater profile cannot be loaded into any project because a project does not exist.

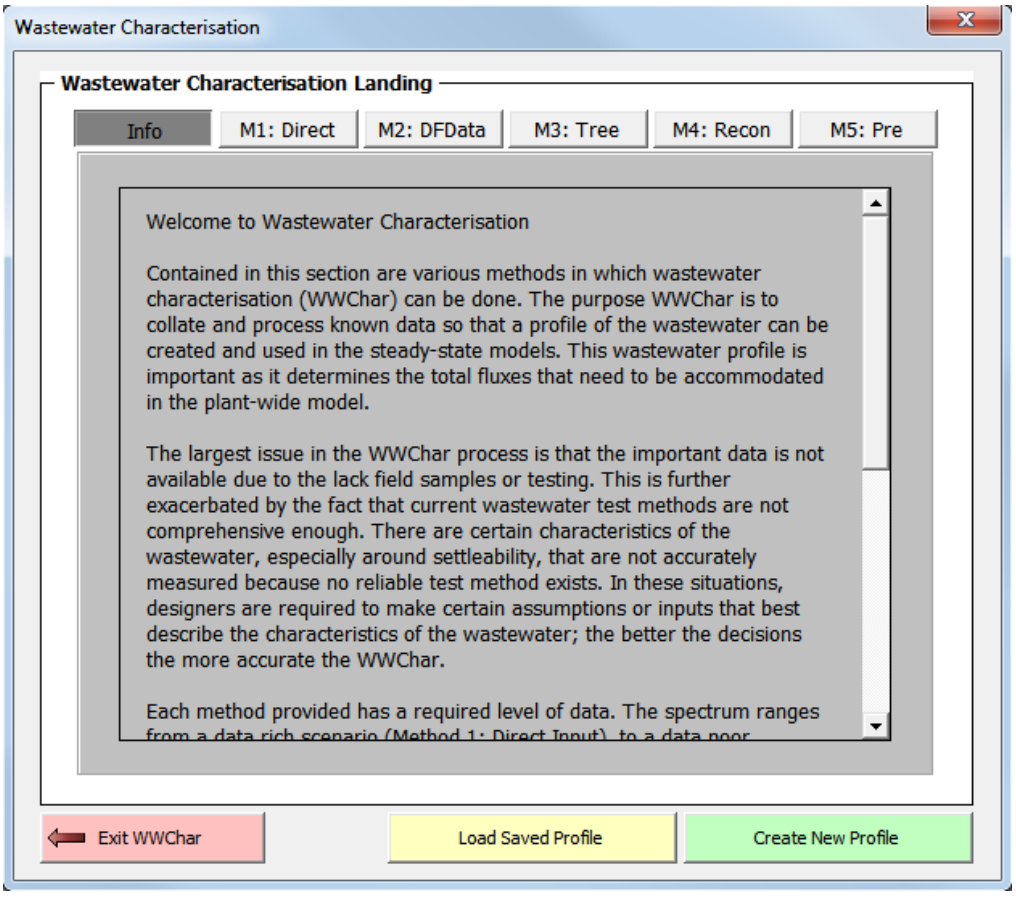



**Figure 5.39: WWChar Landing**

### 5.7.2 WWChar New

On the WWChar Landing window, if *Create New Profile* is clicked (Figure 5.39) then the WWChar New window is opened (Figure 5.40). This window allows for the selection of the WWChar method to be used for characterisation. Five buttons are shown, each one opens up its respective WWChar method. These methods were discussed in Sections 5.1 to 5.5.

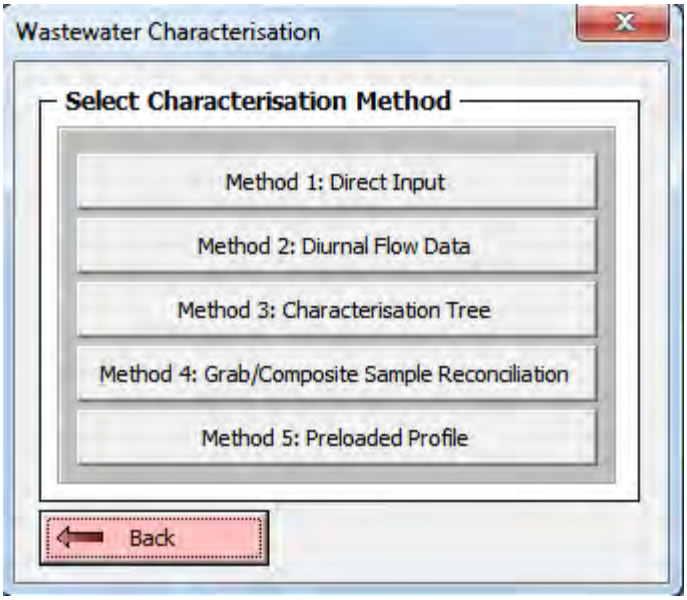



**Figure 5.40: WWChar New**

### 5.7.3 WWChar Load

If *Load Saved Profile* is clicked on the WWChar Landing window (Figure 5.39) then the WWChar Load window is opened (Figure 5.41). This window allows a previously completed and saved wastewater profile to be loaded into the current plant-wide design or capacity estimation.

There are three main buttons on the WWChar Load window: *Load Profile*, *Delete Profile*, and *Duplicate Profile*. The *Load Profile* button loads the selected profile into the current project, the *Delete Profile* button deletes the saved wastewater profile from the saved data spreadsheet (Section 5.7.4 WWChar Save Data discusses this spreadsheet), and the *Duplicate Profile* makes a copy of the selected wastewater profile.

A summary of the selected profile wastewater characteristics is also shown, this summary consists of the flow rates, total influent COD, $f_{S'up}$, $f_{S'us}$, $f_{Sb's}$, TKN, FSA, TP, OP, TSS, ISS, and UPO settleable and non-settleable mass ratios; all for raw WW, settled WW, and PS.

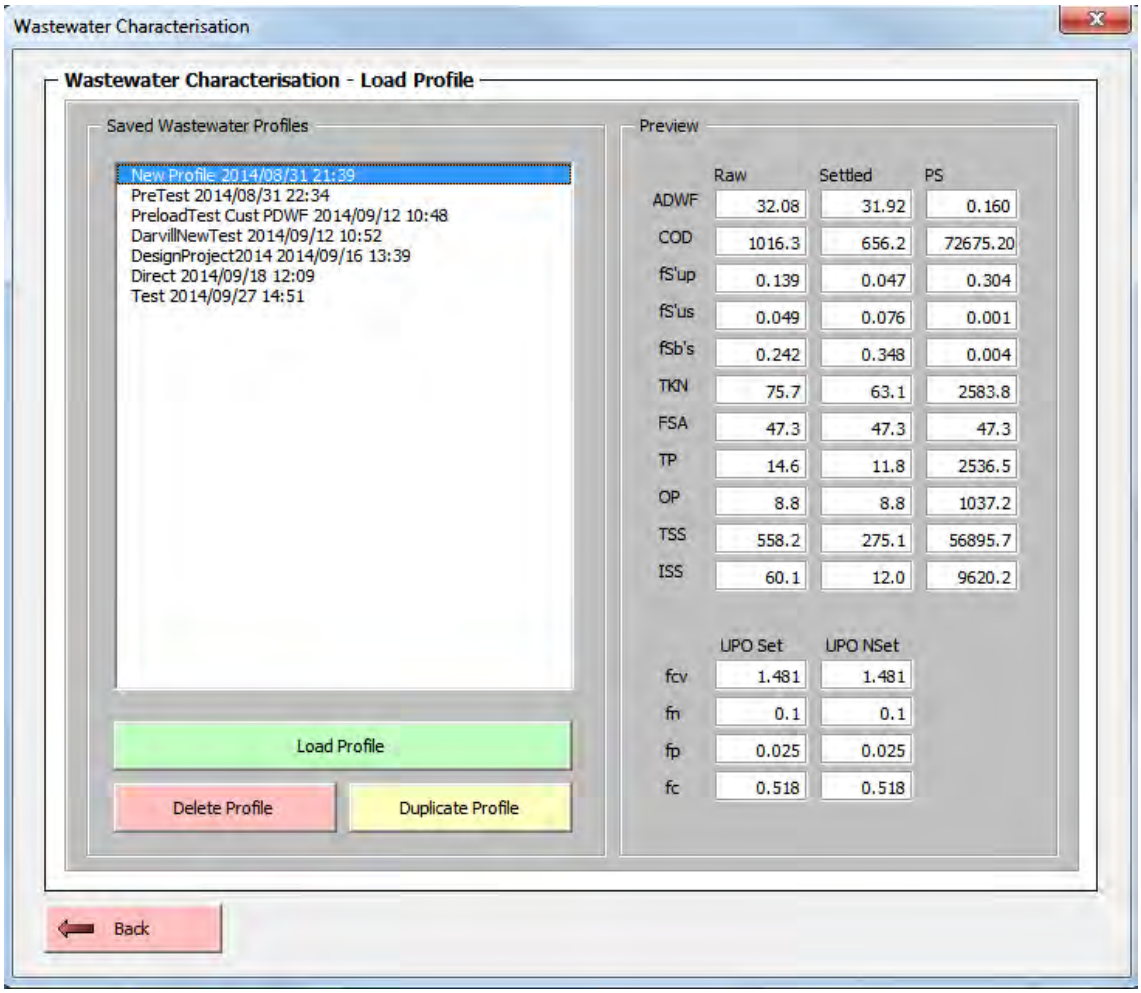



**Figure 5.41: WWChar Load**

## 5.7.4 WWChar Save Data

The WWChar Save Data is an internal feature of this program. The created wastewater profiles are internally saved; and when called upon, these profiles can then be loaded into any plant-wide design or capacity estimation project. The spreadsheet WWChar_SaveData serves as the host of all the save data.

## 5.7.5 WWChar Inputs

The results from each WWChar method are directly linked to the WWChar_Sum spreadsheet, and the WWChar_Sum spreadsheet is linked to the WWChar Summary window. If the plant-wide design or capacity estimation component is used, the FWA concentrations, i.e. the wastewater characteristics, stored on WWChar_Sum spreadsheet are transferred to the WWChar_Inputs spreadsheet. The WWChar_Inputs spreadsheet is directly linked to the steady-state models.

The FWA concentrations on the WWChar_Sum spreadsheet are transferred as static data to the WWChar_Inputs spreadsheet. Static data allows for independence between the WWChar and steady-state models. If this was not the case, then if there are any changes to the inputs during the characterisation process, the WWChar_Inputs spreadsheet will continuously update and hence the steady-state models will be continuously updated as well. The WWChar_Inputs spreadsheet is therefore crucial for the integrity of the program. Figure 5.42 shows the links between the different navigation windows and spreadsheets.

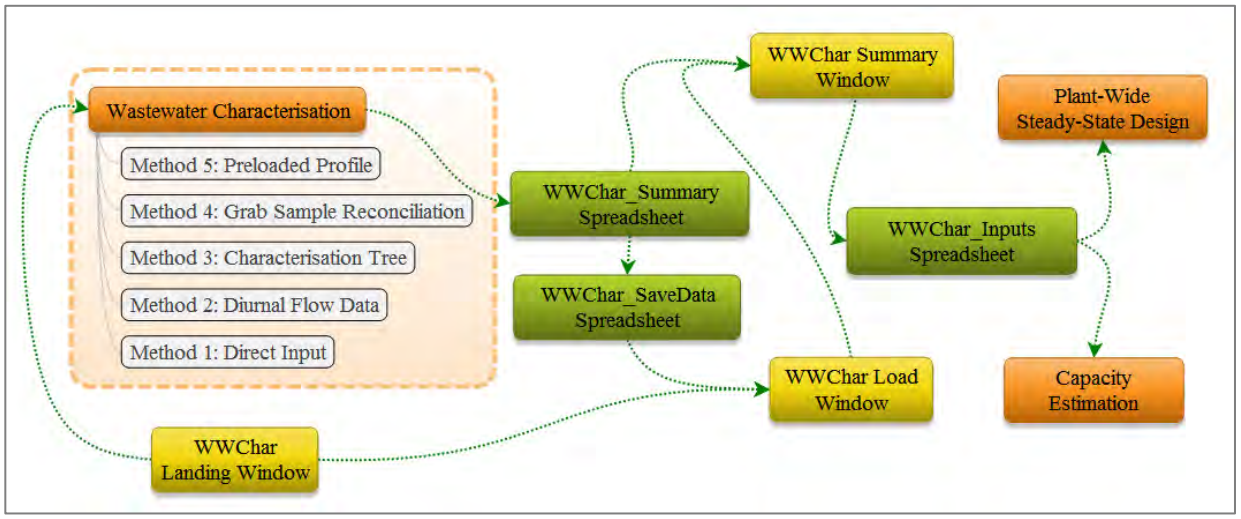



**Figure 5.42: Flow chart for navigation in WWChar and linking spreadsheets**

## 5.7.6 WWChar Flow Chart

A flow chart of the entire WWChar process is shown in the Figure 5.43 on the next page. This flow chart illustrates the different routes that the designer can take in the WWChar component. In the WWChar component, there are two primary routes that the designer can take, creating a new profile, or loading a saved profile. From there, the WWChar Summary window is shown where an overview of the profile is presented. If the WWChar component is used outside of the PWSSD or Capacity Estimation component then the profile displayed in the WWChar Summary window is a newly created profile and is not attached to any plant-wide design or capacity estimation. The designer will only have one option and that is to save the newly created profile and return to the main program window. Alternatively, if the WWChar component was used inside the PWSSD or Capacity Estimation component, the profile displayed on the WWChar window can be loaded into the current PWSSD or Capacity Estimation project. The profile that is displayed here would be either a newly created profile or an existing profile created previously with the WWChar component. This structure allows any created profile to be loaded into any PWSSD project or Capacity Estimation.

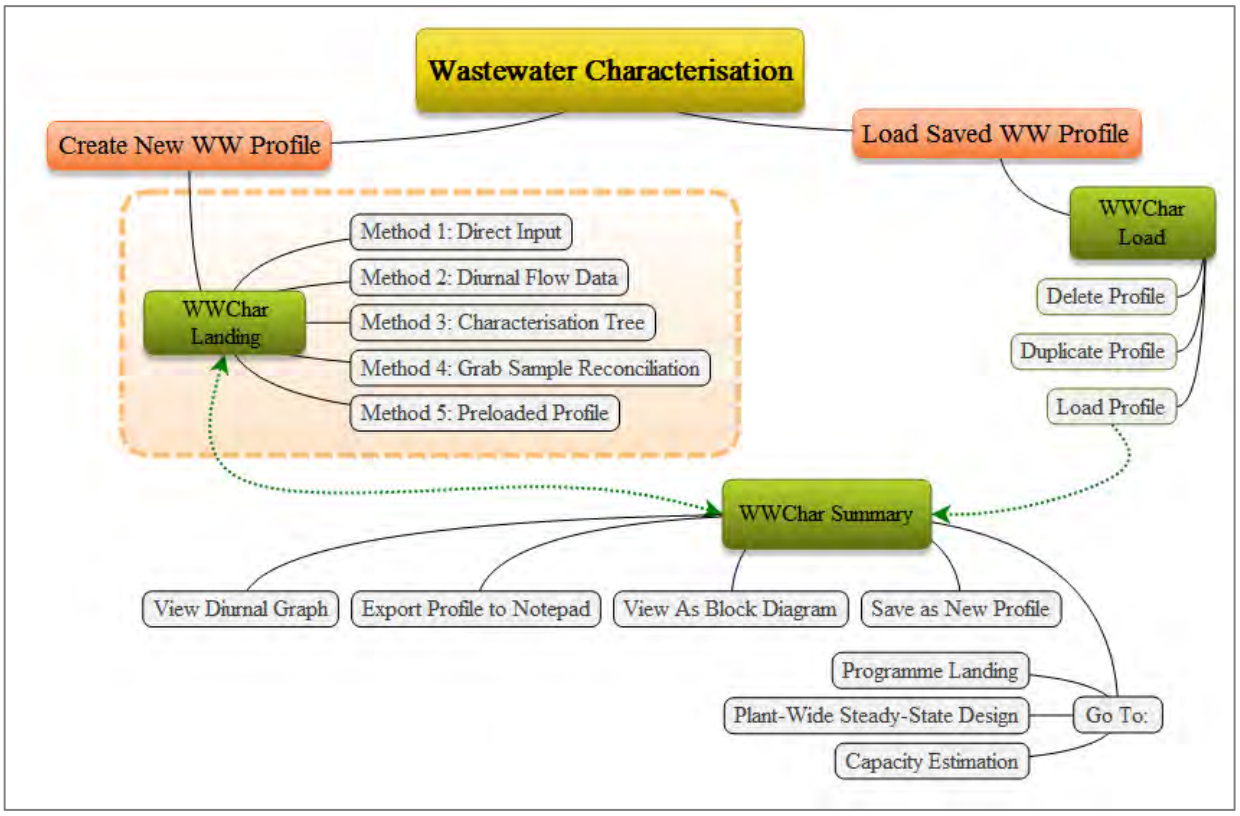



**Figure 5.43: Flow chart for WWChar**

## 5.8 WWChar Conclusion

The wastewater characteristics have an immense impact on the design of the WWTP, and thus the wastewater should be characterised as accurately as possible. The greatest issue in WWChar is the quantity and quality of the data available. Therefore, the application of a generic WWChar method might be difficult because of the different data level scenarios. To address this, the WWChar procedure must be suitable for the available input data. For data poor scenarios, the inputs in should focus on the characteristics that determine the global scheme of the wastewater, such as flow rate, COD strength, DFP intensity, and the UPO fractions. For richer data scenarios, the more detailed characteristics can be given more attention because the available data allows for it. With this philosophy in WWChar, different WWChar methods were developed. Each method deals with a different data level scenarios and thus have different input requirements.

The WWChar component is an important component that serves a pre-processor for the all the steady-state models without it, these models cannot be processed. The WWChar component is a collection of WWChar methods that are tailored for specific data scenarios. For all the WWChar methods, assumptions were made in order to simplify the WWChar procedures. By far the most impactful assumption is that the relative proportions of the seven organic groups do not change throughout the day, and thus their $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios are

also fixed. It is important to note that this does not reflect reality; however, this is necessary, otherwise too much data will be required for the characterisation – the improvements to the characterisations results might only be small in comparison to the additional effort in data collection.

Seven organic groups were used in the WWChar component (and as well as the rest of the program). The BPO and UPO groups were each split into two physical groups, settleable and non-settleable, with the assumption that all settleable particulates are removed in the PST. The settleable and non-settleable groups can have different mass ratios. However, currently, there is not enough data to define the different mass ratios; but hopefully, with further research into the behaviour of the particulates in the PST and their stoichiometric compositions, their mass ratios can be better defined. This information will be extremely helpful and will improve the characterisation of the wastewater.

The WWChar component is an important component that serves a pre-processor for the all the steady-state models without it, these models cannot be processed. With the WWChar component concluded, the PWSSD and Capacity Estimation components can be discussed.

# 6. Program Design Part D: Plant-Wide Steady-State Design

Plant-wide wastewater treatment plant (WWTP) design is a design philosophy that focuses on holistic and integrated WWTP design. It begins with the specification of the influent organic and inorganic loads, i.e. wastewater characterisation (WWChar). At the end of the characterisation procedure, a wastewater profile is generated. This profile contains a 24h diurnal flow pattern, the total and the flow-weighted concentrations of the seven* individual organic groups, viz. COD, TKN, TP, TOC and particulates (VSS), and the three inorganic groups (FSA, OP and ISS) for the raw WW, settled WW and PS, and as well as the influent alkalinity and pH. An integral part of this profile is that the $f_{cv}$, $f_n$, $f_p$, and $f_c$ mass ratios for the seven organic groups are also known or calculated from the characterisation procedure. These mass ratios allow the stoichiometric compositions ($C_xH_yO_zN_aP_b$) of the seven organic groups to be calculated. The flow rate and influent characteristics determine the organic load to the WWTP, and thus, have a direct impact on the outputs of the WWTP models. In a plant-wide design, these outputs are utilised in an integrated manner where the outputs from upstream unit processes are the inputs to downstream unit processes. In doing so, the unit processes are linked together and the WWTP is evaluated as a whole treatment system.

By combining the plant-wide design philosophy with the steady-state models, useful information is generated. The steady-state models require few inputs but they have the ability to generate important information. This includes the optimum or minimum sludge age (SRT), reactor volumes (anaerobic, anoxic, and aerobic) and SST surface area for minimum cost, required mass fractions and recycle ratios to achieve certain N and P removals, waste flow rates for defined SRT, and oxygen demand (Wentzel *et al*., 2006). These size defining outputs provide high-level information that is vital for decision making, for example, can the current 16ML/d raw WW system, be upgraded to a 32 ML/d settled WW system, and what is the best system configuration in terms of capital costs and effluent quality. Thus, the steady-state models are useful as they provide a platform to evaluate the overall integrity, design, and capacity of the treatment system.

The steady-state model outputs are the inputs to the dynamic simulation models. As Ekama (2009) explains, the dynamic models require as inputs the WWTP layout, reactor sizes, inter-connecting flows and starting reactor concentrations. The optimal values for these inputs are conveniently generated with steady state models. Generation of this information is the primary purpose of this plant-wide steady-state program. Dynamic models cannot generate this high-level input information, and therefore, the simulation process becomes more efficient and reliable because one does not have to guess, or obtain by trial and error, the high-level size-defining inputs to initiate the dynamic simulation models. Even more importantly, the steady-state model outputs provide a basis for crosschecking the dynamic simulation (Wentzel *et al*.,

* BPO (settleable), BPO (non-settleable), UPO (settleable), UPO (non-settleable), FBSO, VFA, and USO

2006). If the averages of dynamic results are substantially different to the steady-state results, it is highly probable that incorrect inputs were entered into the dynamic models. The power of the plant-wide steady-state design philosophy is that an entire WWTP plant can be designed or analysed with remarkable accuracy in a much shorter time than using trial and error simulations with dynamic models. If required, the outputs from the steady-state models can be fed to the dynamic models to allow for fine-tuning and detailed optimisation of the system.

Recent developments by the UCT WRG has supplemented the steady-state models with a bioprocess stoichiometric model (Ekama, 2009). This extends the traditional COD based steady-state models, and provides additional information such as $CO_2$, $N_2$ and $CH_4$ gas production. With this information, complete CHONP and COD elemental mass balancing across the entire WWTP can be achieve and the CHONP and COD fluxes exiting the WWTP via the solid, liquid and gas phases can be tracked and evaluated.

This section covers the Plant-Wide Steady-State Design (PWSSD) part of the program and discusses the various available steady-state models – *inter alia* the activated sludge model, the anoxic-aerobic and anaerobic digestions models and physical separation models. The focus of this section is the development of the program, the user-interfaces for the steady-state models and, in general, how they are used and linked together. The calculation procedures and the details of the equations of the steady-state models are not the focus of this section; the reader is directed to the respective literature for this information, e.g. Henze *et al*. (2008), Ekama *et al*. (1997), Sötemann *et al*. (2005a), see Table 2.1 in Chapter 2: Literature Review. This chapter concludes with a few sections discussing the navigation within the PWSSD component.

A case study (design and upgrade of an MLE system) is provided in Appendix D. This case study is an example of the information that can be generated with the steady-state models in the PWSSD component. Where relevant, parts of this case study are utilised in this section to show the workings of the design windows and user-interfaces for the different unit processes available in the PWSSD component.

## 6.1 Steady-State Activated Sludge Models

The steady-state Activate Sludge (AS) model is the core of the plant-wide steady-state design (PWSSD) part of the program. The AS model provides various useful outputs, such as the required recycle and waste flow rates, reactor volumes, overall performance of the COD, N and P removal processes and the effluent concentrations. The outputs from the AS model are linked to various other unit operation models to form a plant-wide design.

Various AS systems have been developed; the main difference between all these systems is their configuration of anaerobic, anoxic, and aerobic reactors, and the recycle flows to and from each reactor. Conceptually only one steady-state AS model exists, but this steady-state AS model is tailored for each AS plant type depending on its configuration, and so in the program

there is a steady-state AS model for each system configuration. There are currently three AS systems in the program: the Modified Ludzack-Ettinger (MLE) system, the University of Cape Town (UCT) system, and the Johannesburg (JHB) system (Table 6.1). There are plans to expand the available systems to include the 4-stage and 5-stage Bardenpho systems as well as AS systems operating with membrane solid liquid separation.

**Table 6.1: Activated sludge system configuration list**

| System | Abbreviation | AS Type | Figure |
|---|---|---|---|
| Modified Ludzack-Ettinger | MLE | AS Nitrification Denitrification (ND) | Figure 6.1 |
| University of Cape Town (VIP) | UCT | AS ND Biologically Enhanced Phosphorus Removal (BEPR) | Figure 6.2 |
| Johannesburg | JHB | AS ND BEPR | Figure 6.3 |
| 4-Stage Bardenpho (possible addition in future versions) | 4BPHO | AS ND BEPR | |
| 5-Stage Bardenpho (possible addition in future versions) | 5BPHO | AS ND BEPR | |

Each system configuration is contained in its own spreadsheet and has its own user-interface that allows the designer to enter the required input data for the AS model. On each user-interface, the outputs from the models are also displayed. Before the outputs are displayed they are analysed, and any relevant information (for example alkalinity problems or nitrification failure) is presented to the designer. The input data for each configuration is collected and organised on a separate spreadsheet and is fed to the spreadsheet that contains the model. The WAS output from each of the configurations is sent to a WAS summary spreadsheet where the data is filtered, organised, and formatted for the sludge treatment models. This WAS summary spreadsheet links the AS model to the WAS digestion models.

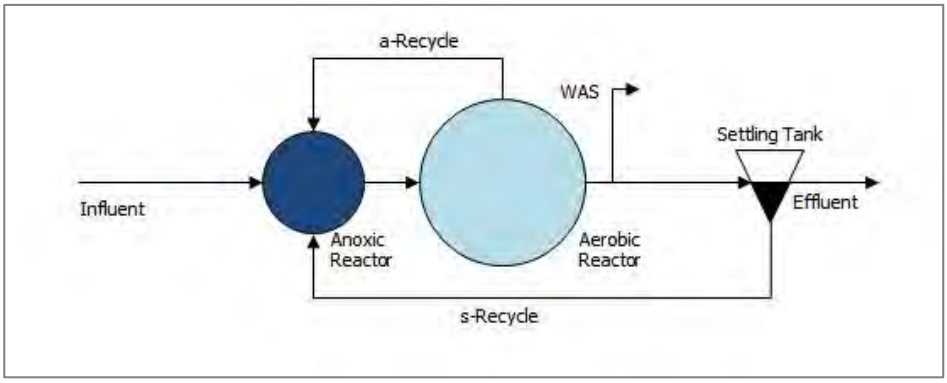



**Figure 6.1: MLE AS system**

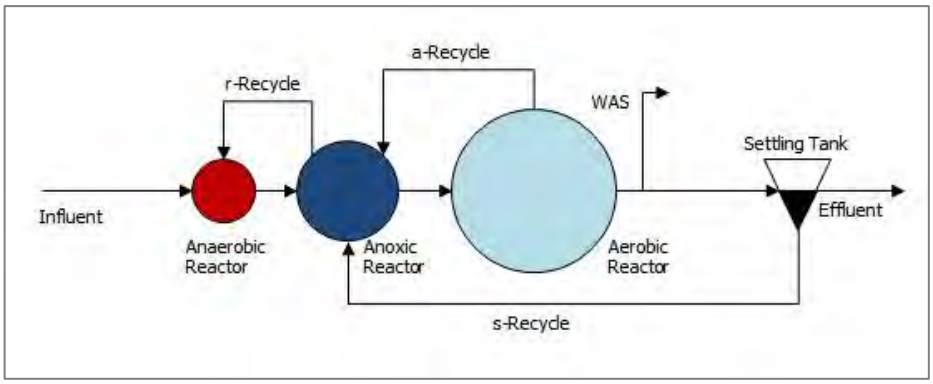



**Figure 6.2: UCT AS system**

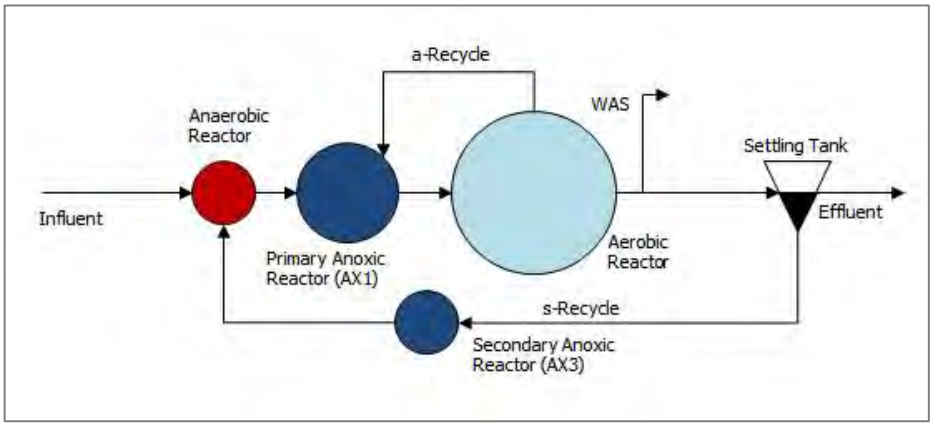



**Figure 6.3: JHB AS system**

Each configuration has advantages and disadvantages relating to operational ease, treatment quality and system capacity. For example in the MLE and UCT systems, there is no anoxic reactor following the aerobic reactor thus complete denitrification is not possible because a fraction of the nitrate generated in the aerobic reactor escapes with the effluent. However, denitrification rates are very high due to the large primary anoxic reactor; therefore, a high influent TKN concentration can be accommodated. This type of conceptual information is provided to the designer when the configuration is selected and when the steady-state design is processed. The quantitative outputs from the models further aid in reinforcing this conceptual knowledge. The steady-state component was developed in a way that allows the designer to switch seamlessly between the different configuration options and for quick computation of the models. Along with the conceptual information and quantitative outputs, this allows the designer to evaluate effortlessly the performance of different WWTP configurations.

The provision of the conceptual information during the design process is termed *Design Guidance*. The purpose of the *Design Guidance* is to provide an expert-guided user interface to aid the designer in making the correct decisions. The *Design Guidance* focuses on the fundamentals of the models and brings to forefront the relationships between the decisions

made by the designer, the input parameters required, and the outputs of the models. The choice of AS system configuration and sludge age is a prime example of *Design Guidance* because these relate so fundamentally to the overall design of the WWTP. *Design Guidance* relating to the smaller, often overlooked, elements is also provided. For example, what safety factor for nitrification ($S_f$) should the designer choose? Additionally, and on what basis should the value be chosen? Another example would be the maximum growth rate of nitrifiers; does the designer choose the default of 0.45? Or should the designer choose a higher value, and what is the impact of this higher value on the design of the WWTP? Aspects such as these are covered in a concise manner without hindering the designer's use of the program; but if the designer requires it, detailed explanations are available. The *Design Guidance* is not limited to the AS system design, it is also incorporated throughout the program in the design windows for the other unit processes, and as well as the WWChar and capacity estimation components.

The user-interface for the AS configurations, as well as some important aspects for each configuration, are discussed in the sections that follow. The user-interfaces for the different AS systems are largely the same in terms of its conceptual design and overall functionalities, and so the first AS system (MLE) that is discussed in this section is discussed in more detail than the other systems.

### 6.1.1 MLE System

The MLE configuration is an ND only system that consists of an anoxic reactor followed by an aerobic reactor with recycle flows from the aerobic reactor and the SST to the anoxic reactor (a- and s- recycles). This system configuration has a high %N removal capacity (~85%) because of the primary anoxic reactor's high denitrification rate, which is attributed to the availability of the influent RBCOD (BSO) and SBCOD (BPO) in the anoxic reactor.

A disadvantage of this configuration is the lack of a post-aerobic anoxic reactor, thus complete denitrification is impossible. However, complete denitrification with a post-aerobic anoxic reactor, such as in a 4-stage Bardenpho system, is difficult to achieve in practice, especially once the influent TKN/COD ratio is above 0.10 mgN/mgCOD (WRC, 1984; Henze *et al*., 2008). This of course depends on other wastewater characteristics, such as the different COD fractions w.r.t the total influent COD. Considering the issues in achieving complete denitrification, the MLE system is popular and is suitable for influent TKN/COD ratios above 0.10 mgN/mgCOD. In addition to this, its layout is simple but at the same time it provides flexible expansion options – with the addition of a single reactor, it can be converted to a 3-stage modified Bardenpho, 4-stage modified Bardenpho, or a UCT system.

The design window for the MLE system is shown in Figure 6.4. The MLE design window is the same for raw WW and settled WW and it consists of three frames (or sections), from left to right: 1) *Model Inputs*, 2) *Design Summary*, and 3) *Design Guidance*. Each frame provides certain functionalities, which are discussed below.

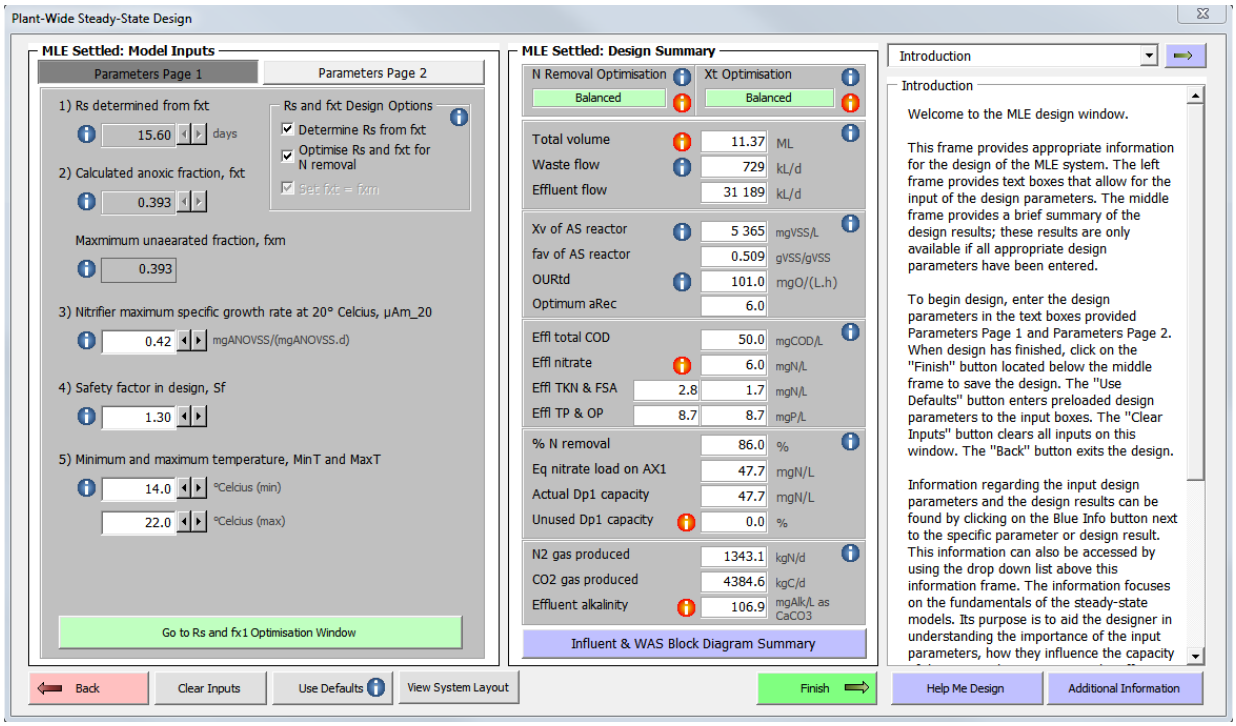



**Figure 6.4: AS Design – MLE system**

The *Model Inputs* (1) frame contains all the input boxes and checkboxes. These allow the designer to enter input parameters and select the design options for the AS model. The *Design Summary* (2) frame provides a summary of the important outputs from the AS model. Outputs displayed include %N removal, denitrification potential of the primary anoxic reactor ($D_{p1}$), active fraction of the VSS ($f_{av}$), the VSS concentration ($X_v$), and oxygen utilisation rate including nitrification and denitrification (ND) ($OUR_{td}$), and as well as the $CO_2$ and $N_2$ gas production calculated from the stoichiometry model. The design outputs are automatically loaded, provided all inputs have been supplied. This quick and seamless feedback provides the designer with a powerful tool to evaluate quickly the sensitivity of the different input parameters. The *Design Guidance* (3) frame provides important information to the designer. Information such the importance of certain design parameters or the effect they have on the outputs are displayed in the *Design Guidance*. The *Design Guidance* focuses on the fundamentals of the design process and the models. Its purpose is to further the designer's understanding of the models concepts and to function as a tool to aid the design procedure.

The *Model Inputs* frame is divided into two pages: *Model Parameters Page 1* and *Model Parameters Page 2*. The first page focuses on the crucial AS model parameters, whereas the second deals with lesser parameters. The crucial parameters govern largely the performance of the AS system and directly determine the failure or success of the system. For the MLE system, failure is related to the inhibition of nitrification. This occurs primarily because the sludge age (SRT) is too low, or the anoxic fraction ($f_{xt}$) is too high. The crucial parameters are the parameters that determine the $f_{xt}$ and SRT for safe operation. The lesser parameters are required

for the design of the system; in fact, the model cannot be processed if any are missing. However, their impact on the size and performance of the system is indirect and less sensitive.

The *Model Parameters Page 1*, Figure 6.5, contains the inputs for:

1. Sludge age (SRT or $R_s$)
2. Anoxic fraction ($f_{xt}$)
3. Maximum nitrifier growth rate ($\mu_{Am20}$)* at 20°C
4. Nitrifier safety factor ($S_f$)
5. Temperature (MinT/MaxT)

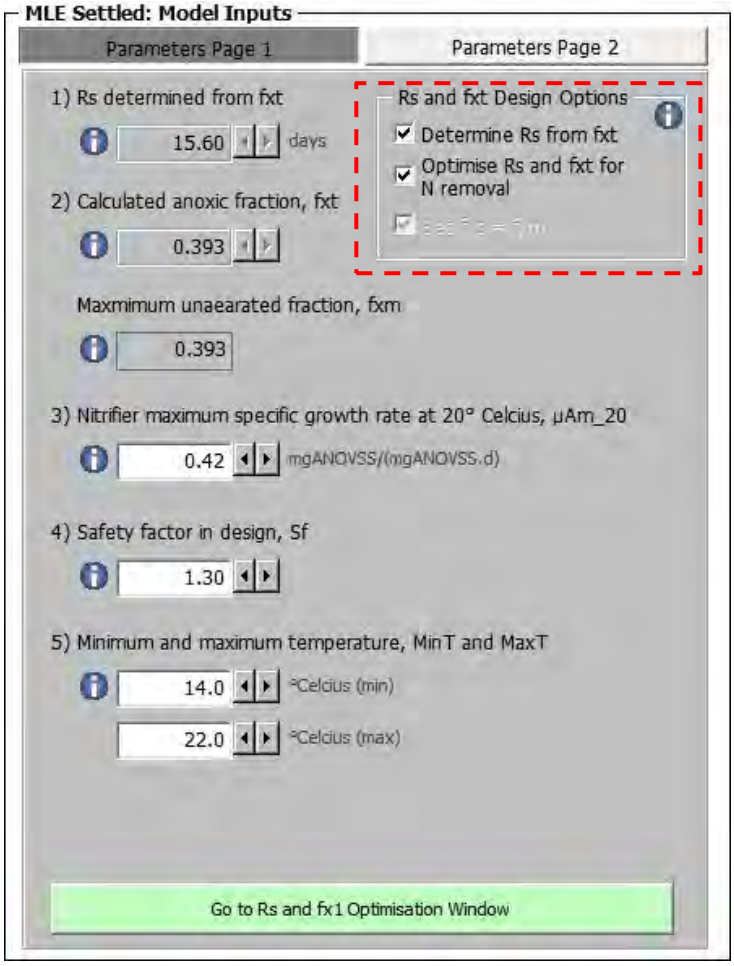



**Figure 6.5: AS Design – MLE Model Inputs, Parameters Page 1**

The maximum unaerated fraction ($f_{xm}$), which is calculated from SRT, $\mu_{Am20}$, MinT and $S_f$, is also shown on this page. All of the parameters can be entered using the textboxes or the spin buttons adjacent to the textbox. When all parameters have been entered, the AS model is computed and the *Design Summary* presents the model outputs automatically. Provided all the inputs are valid, the *Design Summary* will automatically update whenever there are changes to the input parameters. If the parameters are not valid then the *Design Summary* will not be displayed. This seamless model computation and output display allows the designer to evaluate quickly the impact of selecting certain values for each parameter.

For the SRT and $f_{xt}$ parameters, there are three available options for their selection. Firstly, they can be entered directly by the designer, in order to do this, the checkboxes in the *SRT ($R_s$) and $f_{xt}$ Design Options* frame (red rectangle), must all be unchecked. This allows SRT and $f_{xt}$ to be free floating and any value can be entered by the designer. Alternatively, if any of these checkboxes are ticked then the SRT and $f_{xt}$ will be determined for the conditions specified. If *Determine SRT ($R_s$) from $f_{xt}$* is ticked then SRT is calculated from the $f_{xt}$, $\mu_{Am20}$, MinT and $S_f$ parameters. All of these have to be entered by the designer. Note that the

* $\mu_{Am20}$ is technically a wastewater characteristic; however, it was considered as an AS model input. This is discussed in Section 6.1.6.

maximum $f_{xt}$ value allowed ($f_{xm}$) is 0.60. Ticking *Determine SRT ($R_s$) from $f_{xt}$* will enable the *Optimise SRT ($R_s$) and $f_{xt}$ for N removal* and *Set $f_{xt}$ = $f_{xm}$* checkboxes. If *Set $f_{xt}$ = $f_{xm}$* is then checked, $f_{xt}$ is made equal to the $f_{xm}$ (up to 0.60), and SRT will be calculated with $f_{xt}$ = $f_{xm}$. If *Optimise SRT ($R_s$) and $f_{xt}$ for N removal* is checked then both SRT and $f_{xt}$ will be calculated automatically for a balanced MLE system. A balanced MLE system is one in which a set a-recycle ratio of (say) 6:1 loads with nitrate the primary anoxic reactor exactly to its denitrification potential, where the SRT fixes the size and denitrification potential of the anoxic reactor and the influent TKN the nitrate load on it. If the balanced MLE system is selected, then because in the balanced system the $f_{xt}$ is set equal to the $f_{xm}$, the *Set $f_{xt}$ = $f_{xm}$* checkbox is automatically ticked. A detailed SRT and $f_{xt}$ optimisation window can be viewed by clicking on the *Go to SRT ($R_s$) and $f_{xt}$ Optimisation* button; on this window the designer can a view a breakdown of how each parameter affects the optimisation. This is discussed in further in Section 6.1.5 Nitrogen Removal (ND) Optimisation

The option of having both SRT and $f_{xt}$ calculated for a balanced MLE system is the option illustrated in Figure 6.5. For this system, the balanced SRT and $f_{xt}$ are 15.60 days and 0.393. This is calculated with the WW characteristics specified in the DFData example (Section 5.2, summarised in Appendix C), the model inputs as shown in Figure 6.5, and where relevant, the inputs shown in Figure 6.6. The latter figure (6.6) s the *Model Parameters Page 2*, and it contains the inputs for:

6. Recycle ratios (aRec and sRec)
7. Dissolved oxygen in the recycles ($DO_a$ and $DO_s$)
8. Reactor total particulates concentration ($X_t$)
9. Maximum single reactor volume, after which reactor is divided into equal volume modules.

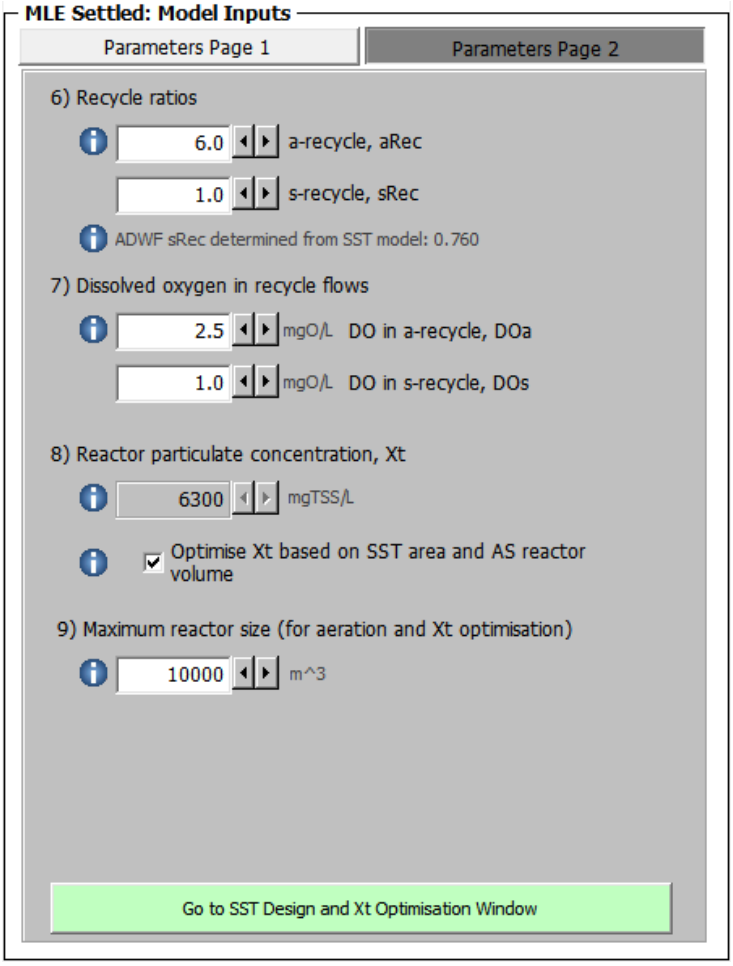



**Figure 6.6: AS Design – MLE Model Inputs, Parameters Page 2**

The parameters on *Page 2* are also important for the design of the system; however, they do not have an impact on the SRT and $f_{xt}$ determination. The recycle ratios (a- and s-recycle) and the dissolved oxygen concentrations ($DO_a$ and $DO_s$) have an effect on the

denitrification potential of the MLE system and the overall N removal. The $X_t$ and maximum reactor size are directly linked to the capital costs of the MLE system. $X_t$ affects the design outputs from the SST model; in general, the higher the $X_t$, the higher the applied flux to the SST and hence a greater SST area is required. The maximum reactor size determines how many modules are required for the MLE system, this does not affect the outputs of the steady-state AS model but it will affect the cost of the system and the aeration requirements. Like the *Model Inputs Page 1*, the *Design Summary* is automatically updated when any changes are made to the input parameters.

The value of $X_t$ can either be entered by the designer or it can be calculated with an AS reactor volume and SST area cost optimisation model. To calculate an optimised $X_t$, the checkbox *Optimise $X_t$ based on SST area and AS reactor volume* must be ticked. In order for $X_t$ to be calculated, the inputs for the SST and the cost model are required; therefore, when selecting this option the designer will be taken to the SST design window where SST design parameters and inputs for the cost function can be entered. The maximum reactor size is also a requirement for the $X_t$ optimisation model. When the SST design and optimisation process is finished, the designer is taken back to the MLE design window. The SST design window can be accessed afterwards by clicking on the *Go to SST Design and $X_t$ Optimisation Window* button. $X_t$ optimisation is discussed in more detail in Section 6.2.3 Xt Optimisation. In the example shown in Figure 6.6, $X_t$ has been optimised to 6300 mgTSS/L.

A function to use default parameters is provided; by clicking on the *Use Default* button default parameters for all the inputs can be loaded into the design window. These defaults are commonly found in the literature or in practice; they might not necessarily be suitable for the designer's project and hence should not be blindly used. Next to the *Use Defaults* button is also a *Clear Inputs* and *View System Layout* button. *Clear Inputs* will reset and clear the design window; *View System Layout* displays an image of the AS system.

The outputs from the steady-state model are shown in the *Design Summary*, (Figure 6.7). The goal of this interface is to provide the designer with quick and seamless feedback from the steady-state models. In the *Design Summary* important outputs such as the reactor volumes, waste flow rate, effluent concentrations, active fractions, and gas production are shown. For the nitrogen removal, the *%N Removal* is the percentage of the influent TKN that has been removed, i.e. $(N_{ti} - N_{te} - N_{ne}) / Nti$. The *Eq Nitrate Load on AX1* is the equivalent nitrate load on the anoxic reactor from the a- and s-recycles including the nitrate equivalent of the dissolved oxygen in those recycles. The *Actual $D_{p1}$ Capacity* is the denitrification potential ($D_{p1}$) of the anoxic reactor and the *Unused $D_{p1}$ Capacity* is the percentage difference between the $D_{p1}$ and the equivalent nitrate load; a percentage >0 means that the system has an excess N removal capacity, i.e. it can remove more N. For a balanced MLE system, this percentage is 0%. At the top of the *Design Summary* are two textboxes that display the optimisation state of the N removal system and the $X_t$. For the example displayed, the N removal and $X_t$ are optimised, hence the *N Removal Optimisation* and *$X_t$ Optimisation* textbox displays *Balanced.* If N removal was not optimised, it will display either "Underloaded" or "Overloaded", or

alternately "ND Fail" if no nitrification occurs. If $X_t$ is not optimised, "Underloaded" will be displayed.

The outputs in the *Design Summary* are linked to various analysis functions that run in the background. These functions check the model outputs and flag any possible design errors. If any of these errors occur, an *Orange Info* button is displayed next to the location of the error. Note that for illustrative purposes, all *Orange Info* buttons have been displayed even though there are no design errors. The *Orange Info* buttons form part of the *Design Guidance* and is a useful tool that provides feedback on the design. This feedback can be automatically displayed in pop-up message boxes, or can be accessed by clicking on the *Orange Info* buttons – which display the information in message boxes or in the *Design Guidance* frame. For example if the MLE system is overloaded (too much nitrate to the anoxic reactor), then an *Orange Info* button will be displayed in the *N Removal Optimisation* frame (top left of Figure 6.7). Clicking on this *Orange Info* button, the message box shown Figure 6.8 will be displayed. This message box informs the designer that the anoxic reactor is overloaded (for the selected a-recycle ratio, aRec), and in order to fix the problem, the aRec must be decreased (which will decrease the N removal), or the SRT or $f_{xt}$ must be increased (which will increase the reactor volume). If these changes cannot fix the problem (overloaded anoxic reactor), then the influent TKN concentration is too high for the system. Figure 6.9 shows another example; in this case if the influent alkalinity ($mgCaCO_3/L$) is too low and therefore a depressed pH can potentially occur. This will negatively affect nitrification, as it will decrease the maximum specific growth rate of the nitrifiers ($u_{Am20}$). A recommendation to dose alkalinity is given.

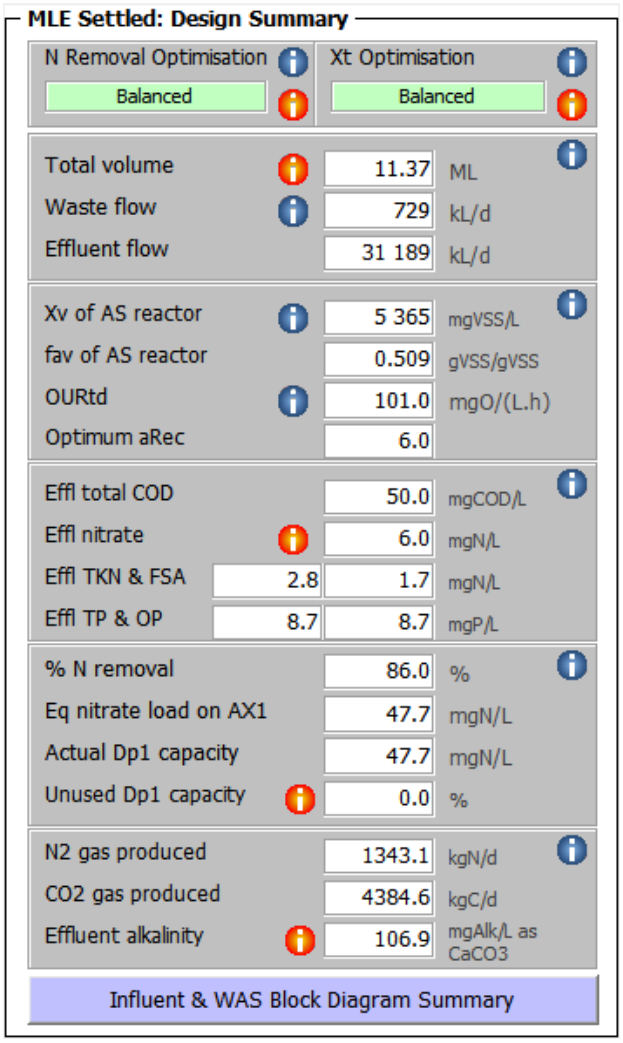



**Figure 6.7: AS Design – MLE Design Summary**

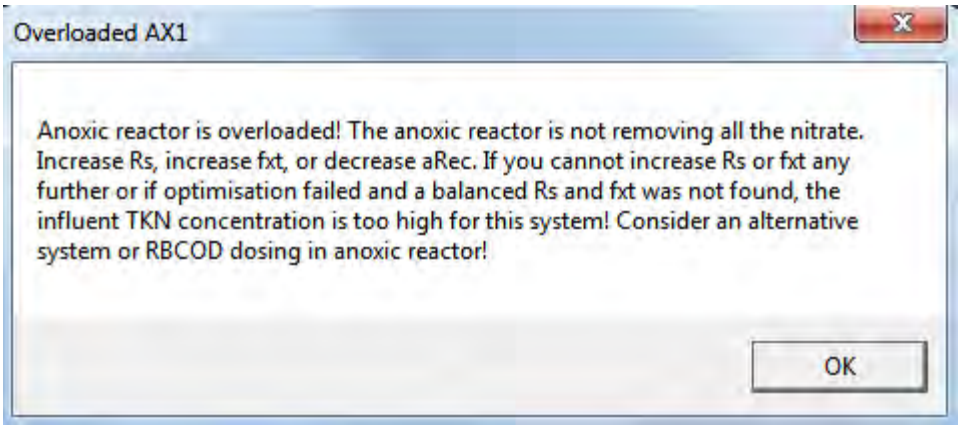



**Figure 6.8: AS Design – Overloaded anoxic reactor warning**

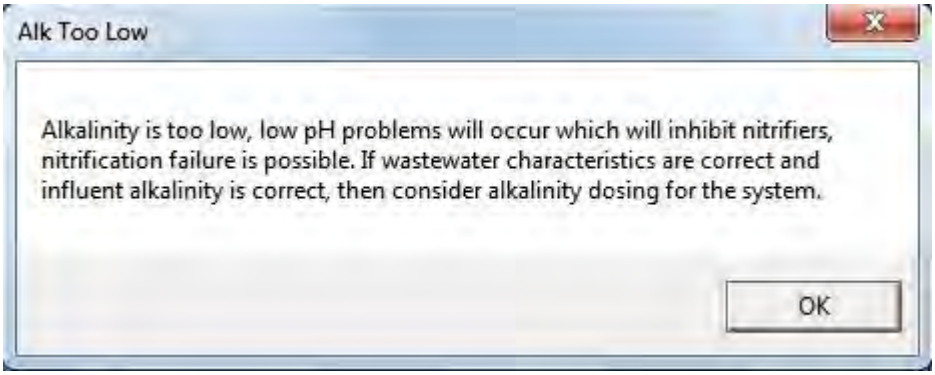



**Figure 6.9: AS Design – Low influent alkalinity warning**

At the bottom of the *Design Summary*, the *Influent & WAS Block Diagram Summary* button opens a window displaying the block diagrams for the influent wastewater and the WAS for the designed system (Figure 6.10). The block diagrams available are: COD, N, P, C and particulates (VSS, TSS, and ISS). Tab buttons on the left and top of the block diagram allow navigation between the different types. The full name of the each of the characteristic can be displayed by hovering over the symbol, e.g. by hovering over $S_{us,w}$ then a caption will popup displaying "unbiodegradable soluble COD". The fluxes can be viewed by clicking on the *View AS Fluxes* button. The WAS characteristics shown here are the characteristics that will be used in the WAS aerobic digestion or anaerobic digestion model.

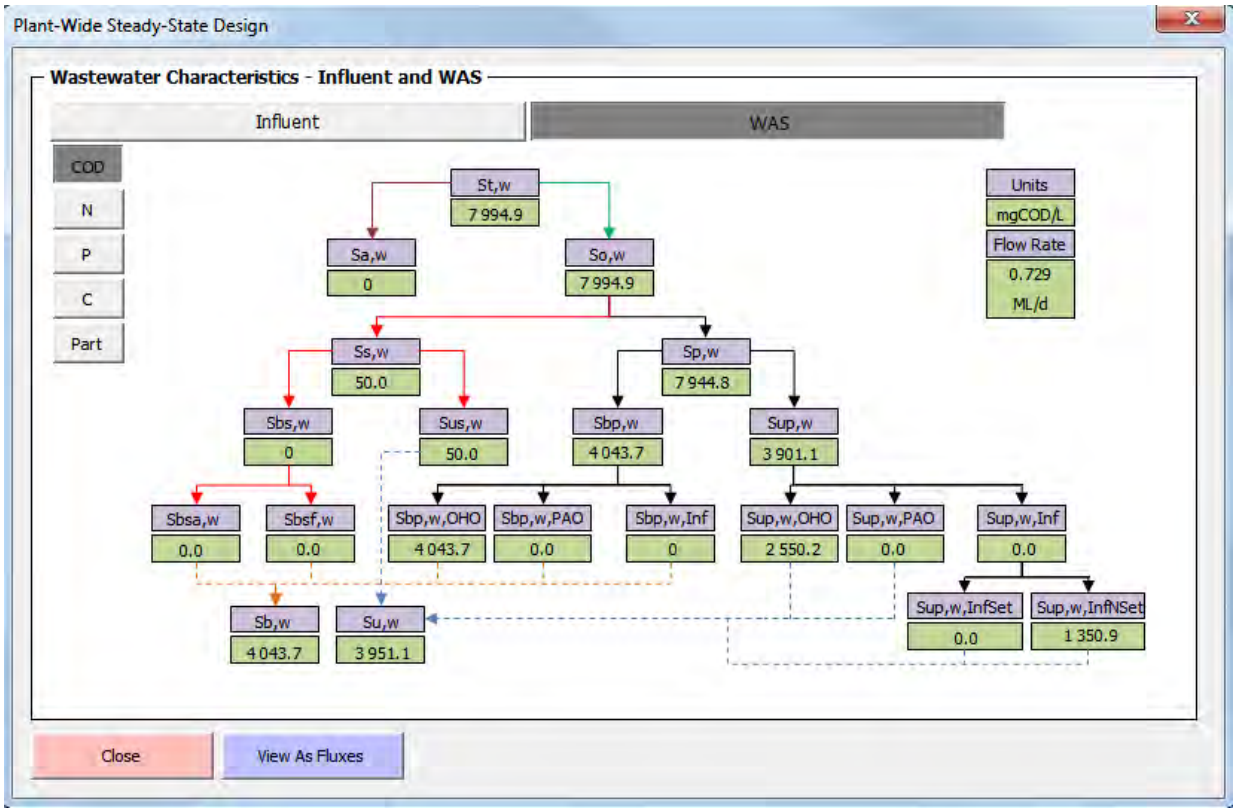



**Figure 6.10: AS Design – Influent and WAS Block Diagram**

The *Design Guidance*, located on the right side of the MLE design window, contains all the information relevant to the design of the system. At the top of the *Design Guidance* section, a drop down list that contains an index of the information is available. This index is shown in Figure 6.11. Appendix G: Overview of Design Guidance Content presents an overview of the information contained in this list. This information is separated into three parts. The first part focuses on the background information of the AS model and as well any important unit processes linked to the AS model (e.g. sludge treatment, primary settling etc.); the second part of the information delves exclusively on the model inputs that are required for the selected configuration (in this case the MLE). The second part of the information can also be accessed by clicking on the *Blue Info* buttons next to the respective input parameters (SRT, $f_{xt}$, $\mu_{Am20}$ etc.). The third part of the information focuses on the outputs of the AS model, the design options selected for the system, and as well as any uncovered, but important, topics related to the AS model that do not fall under the first and second category (e.g. wasting from the SST underflow or AS reactor).

The *Design Guidance* information is qualitative rather than quantitative; it focuses on the fundamentals and highlights the impact that the respective topic has on the overall design of the system. For example, for the SRT parameter, the information focuses on how it should be selected rather than the numerical value that it should be, i.e. if an economical design is required, then the designer should use an optimised N removal (balanced) system with SRT optimised. Alternatively, a longer SRT should be used for a lower WAS activate fraction, or to ensure excess N removal capacity to accommodate future increases in N loads. For the quantitative impacts of SRT (and the design in general), the designer can see this from the quantitative outputs of the model shown in the *Design Summary*.

Once the designer has finalised the design of the MLE system the *Finish* button must be clicked. The designer is taken to the previous window and the other models can be accessed. If the designer wishes to change the AS system, say from an MLE to a UCT system, this can be done in the System Configuration window, however all AS model inputs will have to be re-entered because a new AS configuration has been selected. The System Configuration window is discussed in Section 6.6.2 towards the end of this chapter.

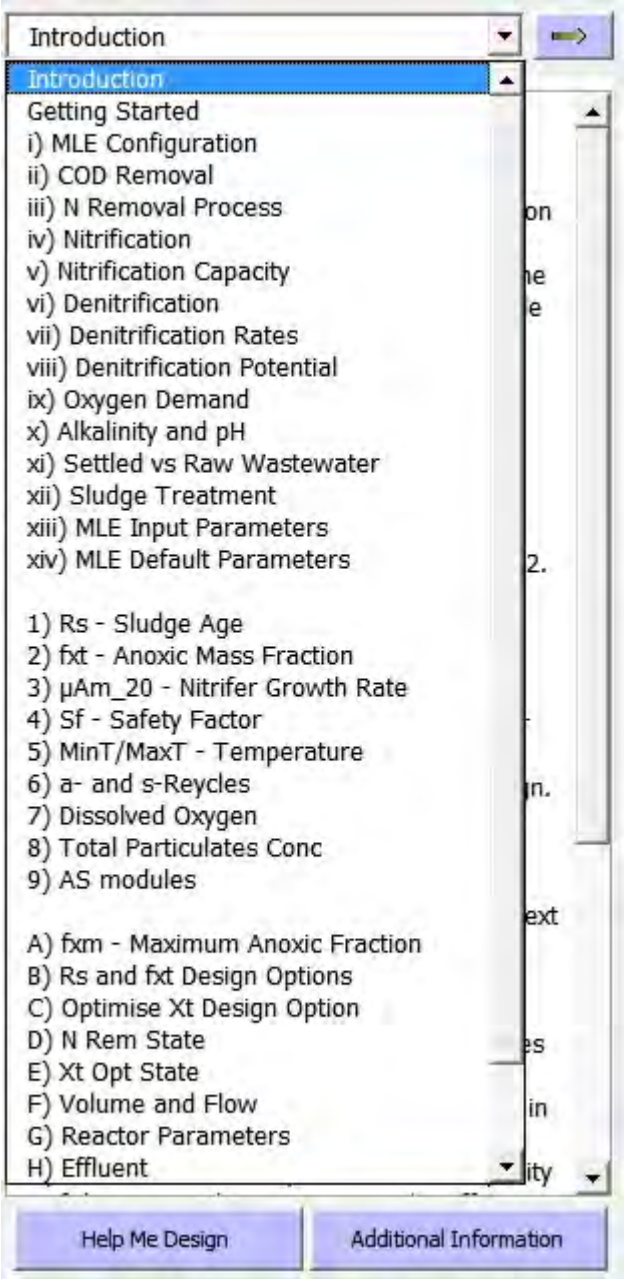



**Figure 6.11: AS Design – MLE Design Guidance drop down list**

### 6.1.2 UCT System

The UCT system is a nitrification/denitrification biologically enhanced phosphorous removal (NDBEPR) AS system. The UCT NDBEPR system consists of three reactors: an anaerobic reactor followed by an anoxic reactor and then an aerobic reactor. Recycle flows are from the anoxic reactor to the anaerobic reactor (r-recycle), the SST to anoxic reactor (s-recycle), and the aerobic reactor to the anoxic reactor (a-recycle).

The UCT system is similar to the MLE system in that complete denitrification is not possible because it lacks a post-aerobic anoxic reactor. Furthermore, as with the MLE system, the primary anoxic reactor (AX1) has a high denitrification rate and hence can provide a high %N removal (~80%). However, if the unaerated mass fraction is the same in an MLE and UCT system, the UCT system has a lower %N removal compared to the MLE system. This is due to the anaerobic mass fraction requirement (~10%), i.e. a portion of the unaerated sludge mass is anaerobic which does not allow for denitrification. Thus, to provide for a balanced N removal system or the same %N removal as the MLE system, the UCT system will require a longer sludge age (SRT, $R_s$) than the MLE system because the unaerated mass fraction ($f_{xt}$) is larger. In terms of the process volume, due to the low total suspended solids concentration of the influent flow, the anaerobic reactor's total particulates concentration is diluted by (r+1)/r. Therefore to maintain the desired sludge mass fraction in the anaerobic reactor, the anaerobic reactor volume has to be increased by (r+1)/r relative to the aerobic reactor volume. This makes the UCT system reactor larger (~10%) than an equivalent 3-stage Bardenpho system, in which the TSS concentration is the same in the anaerobic, anoxic and aerobic zones. However, unlike the Bardenpho configurations, the UCT system protects the P release (and concurrent VFA uptake) in the anaerobic reactor from nitrate ingress. Although, sufficient denitrification potential ($Dp_1$) must be provided in the anoxic reactor to ensure this protection. Satisfying this will result in an r-Recycle that is devoid of nitrate and oxygen and thus the OHOs, which are always present in the anaerobic reactor, will not be able to utilise the influent RBCOD. The PAOs' uptake of the VFA, fermented from the influent RBCOD by the OHOs, is then maximised, which allows for higher and more efficient P removal.

Due to its similarity to the MLE system, the design window for the UCT system is similar to the design window of the MLE system; however due to the inputs required for the P removal part, a few adjustments are made to accommodate those inputs. The information contained in the *Design Guidance* is also expanded to include the P removal part. Figure 6.12 is a screen capture of the UCT design window. As before, it consists of three frames: 1) *Model Inputs*; 2) *Design Summary*; 3) *Design Guidance*, and is identical for the raw WW and settled WW systems.

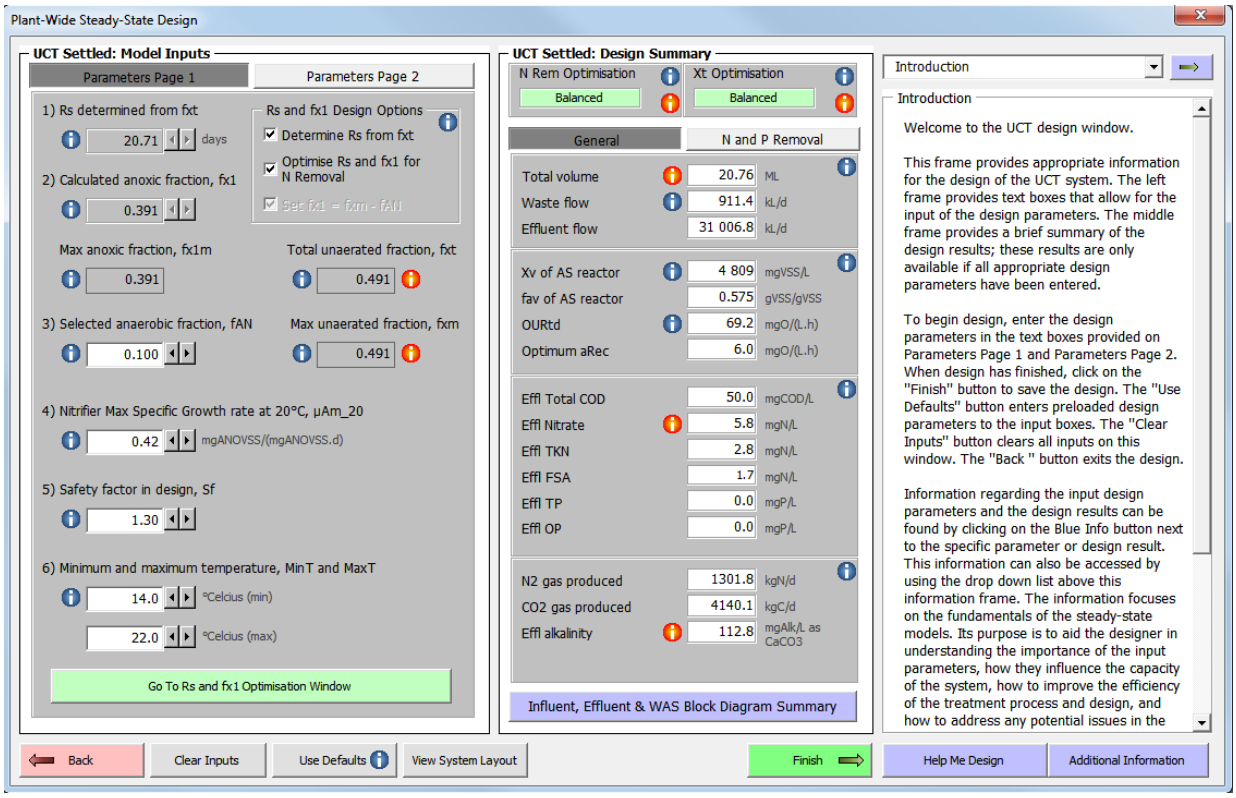
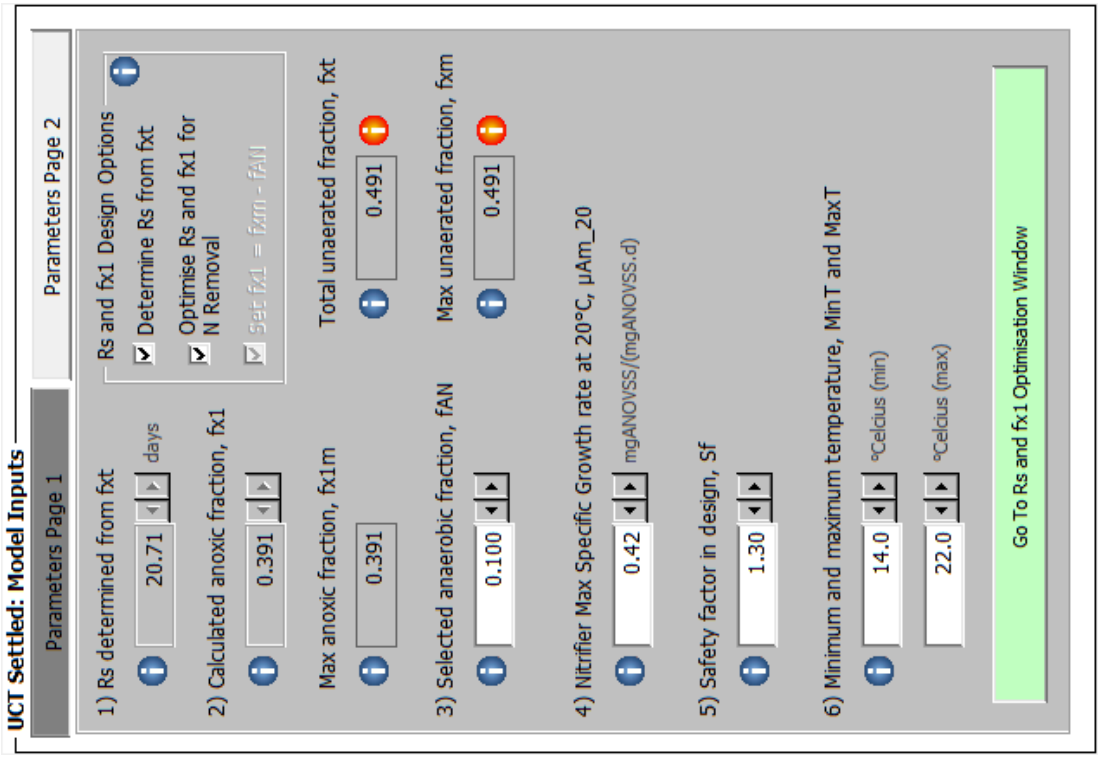



**Figure 6.12: AS Design – UCT system**

The *Model Inputs* contains two pages for inputs. The inputs for the COD and N removal part are the same as for the MLE system – SRT, $f_{x1}$, $f_{xm}$, $\mu_{Am20}$, MinT, MaxT, aRec, sRec, $DO_a$, $DO_s$, $X_t$, maximum reactor volume. The only difference is the additional inputs that pertain to the P removal part of the UCT system: the anaerobic mass fraction ($f_{AN}$), number of anaerobic compartments (ANn), the r-recycle (rRec), and the dissolved oxygen in the r-recycle ($DO_r$). In the MLE system only the maximum unaerated fraction ($f_{xm}$) is displayed because there is only one unaerated mass fraction type (anoxic); however in the UCT system there are two unaerated types (anaerobic and anoxic), therefore two new textboxes have been included which display the maximum anoxic fraction ($f_{x1m}$) and the total unaerated fraction ($f_{xt}$). The $f_{xt}$ is the sum of $f_{AN}$ (anaerobic) and the primary anoxic mass fraction ($f_{x1}$) and the $f_{x1m}$ is $f_{xm}$ minus $f_{AN}$. The $f_{xm}$ is calculated from the SRT, $\mu_{Am20}$, MinT and $S_f$ inputs as for the MLE (or any BNR) system. Screenshots of *Model Parameters Page 1* and *Page 2* are shown in Figure 6.13 on the next page. For the inputs that overlap with the MLE system, they are also used for the UCT system.



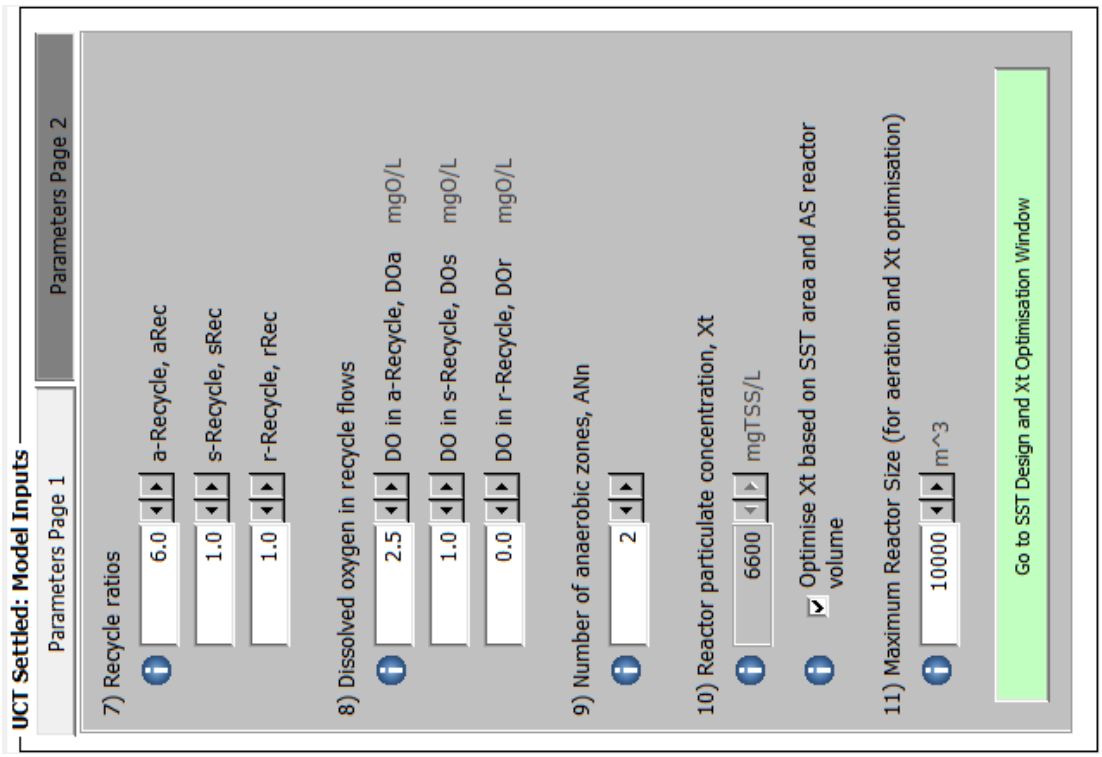




**Figure 6.13: AS Design – UCT Model Inputs, Parameters Page 1 and 2**

N removal (balanced UCT system) and $X_t$ optimisation (for minimum cost of AS reactor and SSTs) are also provided for the UCT system, and like the MLE system, the *Go to SRT ($R_s$) and $f_{x1}$ Optimisation Window* and *Go to SST Design and $X_t$ Optimisation Window* buttons are available. A balanced UCT system can be selected by ticking the *Determine SRT ($R_s$) from $f_{xt}$* and the *Optimise SRT ($R_s$) and $f_{x1}$ for N Removal* checkboxes; an optimised $X_t$ can be obtained by ticking the *Optimise $X_t$ based on SST area and AS reactor volume* checkbox. The $X_t$ optimisation procedure is the same as for the MLE system, except that it uses the different volume requirements and sludge generation applicable to the UCT system (OHO, PAO and high ISS from polyphosphate).

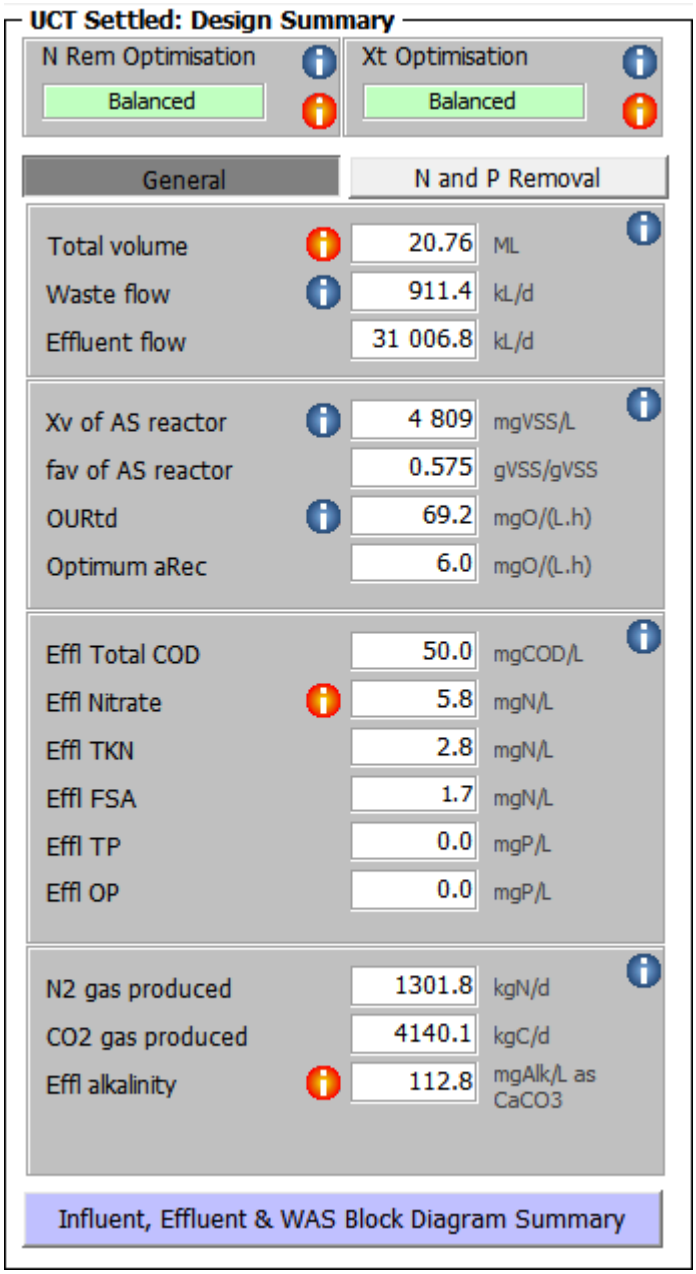



**Figure 6.14: AS Design – UCT General Design Summary**

The UCT's N removal optimisation procedure is similar in structure to the MLE system's procedure; however, it is different in that the anaerobic mass fraction ($f_{AN}$) must be included in the total unaerated mass fraction ($f_{xt}$), i.e. the anoxic mass fraction is equal to maximum anoxic mass fraction ($f_{xm}$) minus the $f_{AN}$. The denitrification kinetic rates are also different, but this does not affect the optimisation procedure. N removal and Xt optimisation are discussed in more detail in Section 6.1.5 Nitrogen Removal (ND) Optimisation and Section 6.2.3 Xt Optimisation.

The *Design Summary*, like the *Model Inputs*, has been expanded accommodate the P removal part of the AS model. The two pages are shown in Figure 6.14 and Figure 6.15 It is separated into two pages; the first for the general AS model outputs such as process volume, oxygen utilisation, effluent concentrations, gas production and alkalinity etc.; the second page is dedicated to N and P removal.

Due to the similar AS layout, the N removal process in the MLE and UCT system are almost identical, therefore the N removal part of the *Design Summary* is essentially the same (%N removal, equivalent nitrate load on the anoxic reactor, actual and excess denitrification potential). The P removal part of the *Design Summary* is new and it contains the following outputs: the %P removal, the potential P removal, the actual P removal, the unused P removal capacity, the polyphosphate (PP) mass in the system, the total P content of the PAOs ($f_{xbgp}$), and the influent cation (Mg, K, Ca) requirements for the system to provide the stated P removal. Above the *General* and *N and P Removal* pages are the textboxes that display the N and $X_t$ optimisation state of the system.

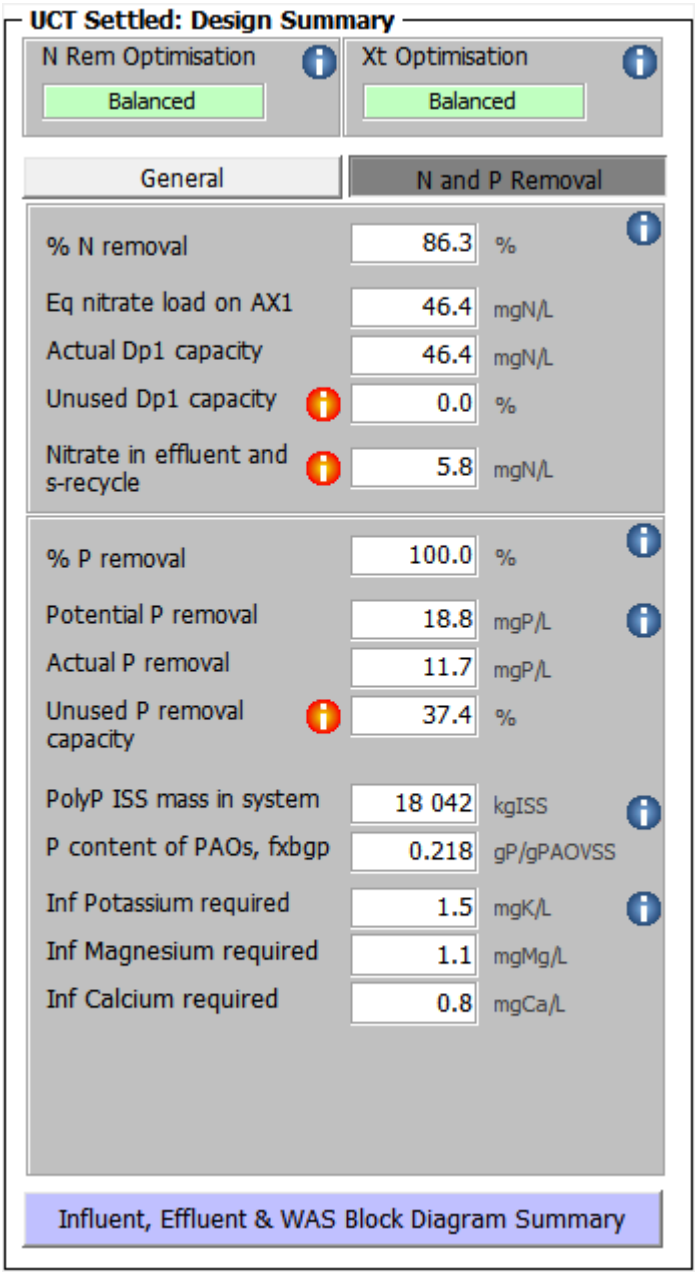



**Figure 6.15: AS Design – UCT N and P Removal Design Summary**

By evaluating the P removal results, the efficiency of the P removal can be assessed. The %P removal is the amount of P removed by the system expressed as a percentage of the influent P; the maximum %P removal possible for any system is 100%. When it is at 100%, all the influent P is utilised for sludge mass growth (OHOs and PAOs) and will exit the system in the waste activated sludge mass via the waste flow. The effluent orthophosphate (OP) concentration in this scenario will be zero. If the %P removal is less than 100% then the influent P is not fully utilised and effluent OP concentration will not be zero. The potential and actual P removals are expressed as mgP/L of influent. The potential P removal is the maximum amount of influent P that the system can remove based on the influent wastewater characteristics (mainly RBCOD concentration) and UCT system configuration; the actual P removal is the influent P that the system is actually removing. The actual P removal can never exceed the potential P removal, when the %P removal is 100% then the actual P removal is either equal to or less than the potential P removal. If the actual P removal is equal to the potential P removal then the influent

P matches the potential P that can be removed, i.e. the P removed is equal to the P entering the system and no additional P can be removed by the system. If the actual P removal is less than the potential P removal then the P removed is equal to the P entering the system but the system can remove additional P, i.e. it has excess capacity. Alternatively, if the %P removal is less than 100% then the potential P removal will be equal to the actual P removal, but the system is overloaded with P - the influent P exceeds the actual P removal and the excess P exits as effluent OP.

Numerical examples of the P removal scenarios are shown in Table 6.2. For this UCT design example (shown in Figure 6.15), the potential P removal is 18.8 mgP/L influent and the actual P removal is 11.8 mgP/L influent. This indicates that the system can remove more P than it is receiving and thus, the %P Removal is 100%. The unused P removal capacity is (18.8-11.8)/18.8 = 37.2%, and thus the influent TP concentration can be increased by 37.2%, An increase greater than 37.2% will result in the system being overloaded with P and excess P will escape via the effluent as OP.

**Table 6.2: P removal evaluation for NDBEPR systems**

| Parameter | Value | Value | Value | Units |
|---|---|---|---|---|
| %P removal | 100 | 100 | 73.3 | % |
| Potential P removal | 14.6 | 25.4 | 25.4 | mgP/L influent |
| Actual P removal | 14.6 | 14.6 | 25.4 | mgP/L influent |
| Unused P removal capacity | 0 | 42.5 | -36.2 | % |
| Influent TP | 14.6 | 14.6 | 34.6 | mgP/L |
| Effluent OP | 0 | 0 | 9.2 | mgP/L |
| Comment (P removal state) | P removal is at its maximum. All influent P is removed, system cannot handle any more influent P. Effluent OP is 0 mgP/L. | P removal is NOT at its maximum, but all influent P is still removed. System can handle 42.5% more influent P before being overloaded. Effluent OP is 0 mgP/L. | P removal is at its maximum, but NOT all of the influent P is removed. System is overloaded by 34.6%. Effluent OP is 9.2 mgP/L. | |

For the P removal system the polyphosphate (polyP) inorganic suspended solids (ISS) mass in the system, the P content of the PAOs ($f_{xbgp}$) and influent cation (potassium, magnesium and calcium) requirements are also displayed. The polyP ISS consists of calcium, magnesium, and potassium cations in the stoichiometric ratios of 0.12:0.27:0.22. For every gram of polyP, this equates to 3.286 grams of polyP ISS. The mass of the polyP ISS in the system is equal to the product of 3.286 gISS/gPP and the polyP content of the PAOs. The polyP content ($f_{xbgpp}$) is the

$f_{xbgp}$ less the "normal" P content of the PAOS (0.025gP/gVSS)*. Knowing the cation ratios for one mole of polyP, the influent cation requirements are calculated – as shown in Figure 6.15, this influent requirement is 1.5 mgK/L, 1.1 mgMg/L and 0.8 mgCa/L. The actual P removal assumes that the influent wastewater's cations concentration exceeds the required concentrations. If this is not the case then the PAO sludge mass production will be limited by the influent cations concentration, the actual PAO sludge mass in the system will be less than predicted and the %P removal, stated in the *Design Summary*, will not occur in the system.

As with the MLE design window, the UCT design window contains various *Blue Info* and *Orange Info* buttons that aid the design of the system and allow access to some of the topics in the *Design Guidance* drop list. The *Blue Info* buttons provide background information on the design or parameter/s. The information is qualitative instead of quantitative; it is conceptual and focuses on the fundamentals of the models and how the selected topic affects the design of the system. The *Orange Info* buttons provide feedback on the outputs of the model and they focus on potential errors in the design. In Figure 6.13 to Figure 6.15, for illustrative purposes, all the *Orange Info* buttons are made visible; however during design only the applicable ones are made visible. The info buttons for the UCT are more extensive than the MLE system simply because the UCT system is more complex because of the P removal part. For this UCT design example, the system has excess P removal capacity therefore an *Orange Info* button will be displayed next to the *Unused P removal capacity* text box. Clicking on this button will display a message box (Figure 6.16) informing the designer that this is the case and that measures, such as decreasing the $f_{AN}$, can be used to decrease the excess capacity.

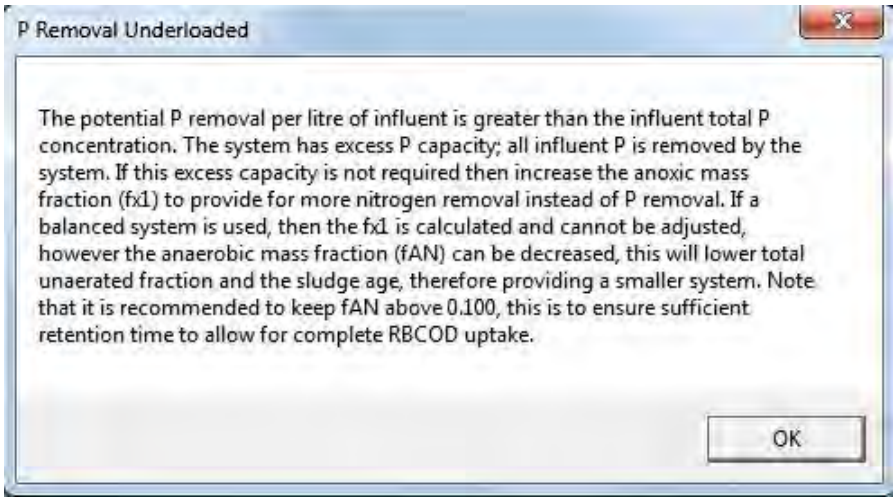



**Figure 6.16: AS Design – Underloaded P removal system message box**

*The $f_p$ mass ratio is a default and can be changed if required

The *Design Guidance* is also expanded, and includes all the relevant topics and parameters for the UCT system such as the polyphosphate mass in the system, the non-denitrification behaviour of the PAOs, the additional model parameters ($f_{AN}$, ANn, rRec, $DO_r$), P removal and influent cation requirements etc. The drop down list containing the index of the *Design Guidance* for the UCT system is shown in Figure 6.17. Appendix G: Overview of Design Guidance Content presents an overview of the information contained in this list.

The UCT design also contains the *Clear Inputs*, *Defaults*, and *View System Layout* buttons. These buttons reset and clear the design window, load the default parameters in to the design window, and display an image of the selected AS system. Also, at the bottom of the *Design Summary*, the *Influent & WAS Block Diagram Summary* button displays the COD, N, P, C and particulate block diagrams for the influent wastewater and the WAS of the system (see Figure 6.10 in Section 6.1.1 MLE).

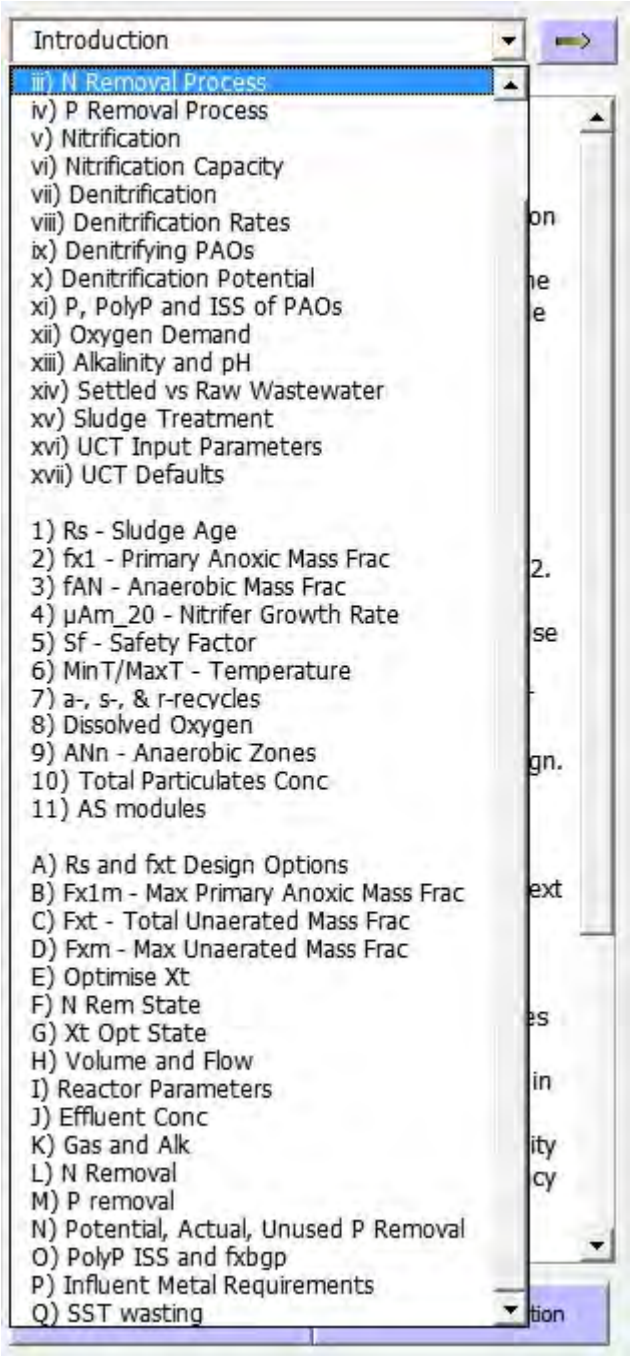



**Figure 6.17: AS Design – UCT Design Guidance drop down list**

## 6.1.3 JHB System

The JHB system is an NDBEPR configuration consisting of an anaerobic reactor (AN) followed by a primary anoxic reactor (AX1) and then an aerobic reactor (AE). A secondary anoxic reactor (AX3) is situated in the sRec. Recycle flows are from the AE to the AX1 (aRec) and the SST to AX3 to the AN (sRec).

The JHB system is a modification of the 5-stage Modified Bardenpho system. In the 5-stage system, the secondary anoxic reactor (AX2) is a mainstream reactor that is located immediately after the AE. The purpose of the AX2 is to denitrify the nitrate exiting the AE, but for influent TKN/COD > ~0.10 mgN/mgCOD, this is not possible, resulting in elevated nitrate concentrations in the effluent and underflow (sRec). The latter negatively affects P removal.

The JHB system addresses the nitrate recycling problem by repositioning the AX2 from the mainstream flow to the underflow, thus creating an underflow secondary anoxic reactor (AX3). Doing so utilizes the anoxic mass fraction ($f_{x3}$) to denitrify only the nitrate in the underflow and allows the underflow nitrate to be fully denitrified by the AX3, thereby mitigating the adverse effects of recycling nitrate to the AN. However, the repositioning the AX2 sacrifices the ability for complete denitrification and a zero effluent nitrate concentration is no longer possible (although in practice complete denitrification is often not achieved with an AX2). It is important to note that the AX3 has a low denitrification potential because of the lack of RBCOD (like AX2); therefore, sufficient denitrification capacity in the AX3 should be provided. The AX3 can be overloaded with nitrate if the AX1's denitrification potential is too low, if the AX3 mass fraction is too small, or if the influent TKN/COD ratio is too high. If an overloaded AX3 scenario occurs, then having an AX3 is impractical as the it is not serving its purpose of protecting the AN reactor is from an influx of nitrate. It would be better to remove the AX3 and increase the AX1 mass fraction, i.e. creating a UCT system. In consideration of these ND details, the JHB system should only be used if complete denitrification in the AX3 can be achieved. This is used as one of the criteria in the design of the JHB system.

In terms of the system volume, due to the concentrating effect of the SST on sRec sludge (TSS) concentration ($X_s$) compared with the mainstream reactor's TSS concentration ($X_t$), the concentration in the AX3 ($X_s$) is a factor of (s+1)/s higher than $X_t$. For a sRec of 1:1, the AX3's $X_t$ is double that of the AN, AX1, and AE. As a result of the increased $X_t$ in the AX3, the volume required for the AX3 is reduced resulting in an overall smaller total reactor volume to contain the TSS mass. A capital cost saving is therefore realised relative to the UCT system in which, due to the lower $X_t$ in the AN, a larger volume is required to contain the same TSS sludge mass. However, the cost saving for the JHB system can be lost because of the lower denitrification potential in the AX3 of the JHB system, which results in a longer SRT compared with the UCT system. A longer SRT can result in a total JHB system volume larger than the total UCT system volume; hence, cancelling the cost savings of the smaller AX3. This of course will depend on the influent wastewater characteristics and the selection of whether or not to optimise the SRT and anoxic mass fractions ($f_{x1}$ and $f_{x3}$).

The layout of the design window for the JHB system is the same as for the MLE and UCT systems. It contains three frames, from left to right: 1) *Model Inputs*, 2) *Design Summary, and* 3) *Design Guidance*. A screen capture of the JHB design window is shown in Figure 6.18. The *Orange Info* buttons have already been discussed in the MLE and UCT sections (Section 6.1.1 and Section 6.1.2), they have not been made all visible for the screen captures in this section and the purpose and concept behind it will not be further repeated.

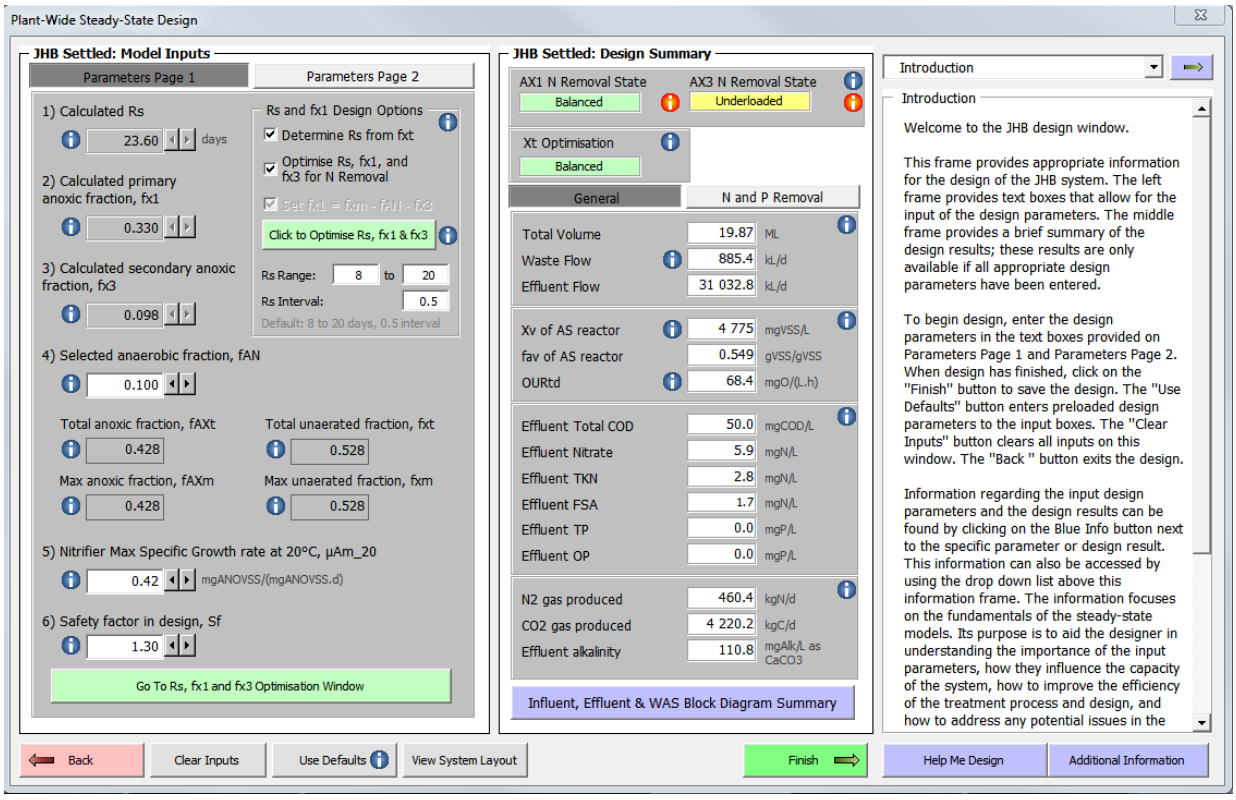
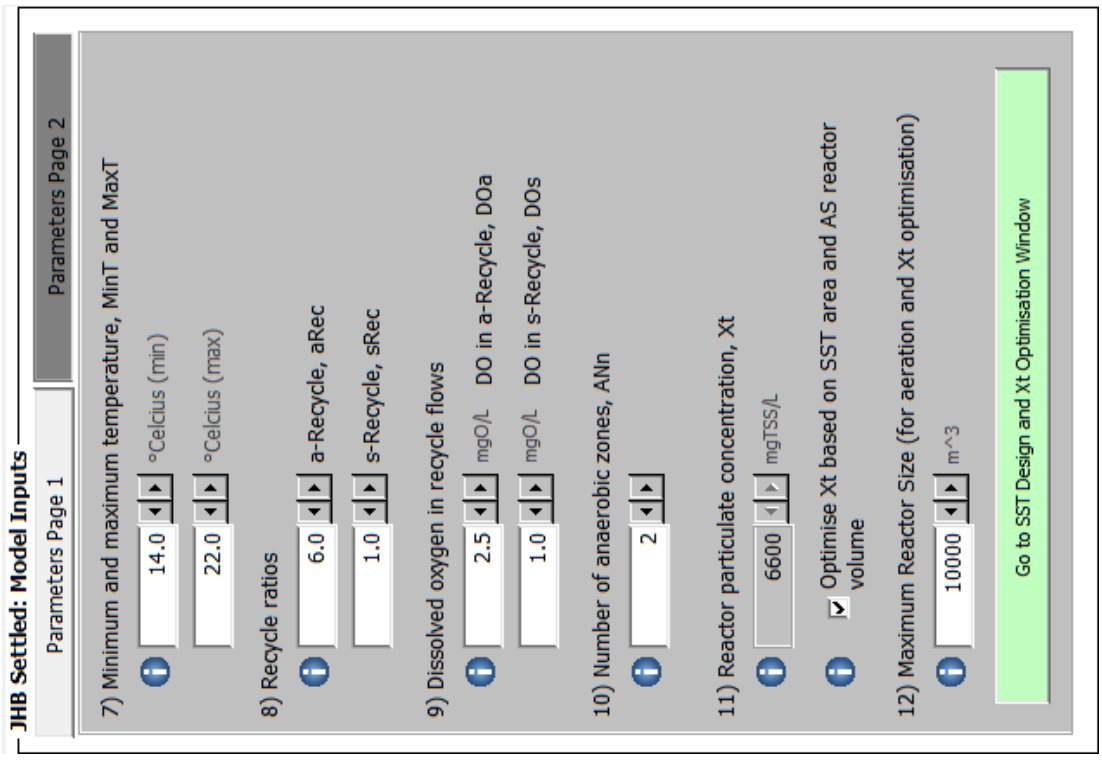



**Figure 6.18: AS Design – JHB system**

The *Model Inputs* contains two pages for the model inputs. The first page contains inputs for the sludge age (SRT), primary anoxic mass fraction ($f_{x1}$), secondary anoxic mass fraction ($f_{x3}$), anaerobic mass fraction ($f_{AN}$), nitrifier growth rate ($\mu_{Am20}$) and the nitrifier safety factor ($S_f$). The second page contains the remaining inputs for the model: minimum and maximum temperature (MinT and MaxT), a- and s-recycle (aRec and sRec), dissolved oxygen in the a- and s-recycle ($DO_a$ and $DO_s$), number of anaerobic zones (ANn) total particulates concentration ($X_t$), $X_t$ optimisation, and maximum AS reactor volume. Screen captures of the two input pages are shown in Figure 6.19.

The *Model Parameters Page 1* is more extensive than that of the UCT system, particularly the *SRT ($R_s$), $f_{x1}$ and $f_{x3}$ Design Options* frame. Three checkboxes for the SRT and mass fractions are provided. These are inherently similar to the ones provided for the UCT and MLE systems. This first checkbox (*Determine SRT ($R_s$) from $f_{xt}$*) allows SRT to be calculated from $f_{xt}$, the second (*Optimise SRT ($R_s$), $f_{x1}$, and $f_{x3}$ for N removal*) allows for optimisation of SRT and the anoxic mass fractions, and the third (*Set $f_{x1} = f_{xm} - f_{AN} - f_{x3}$*) sets the $f_{x1}$ to the maximum $f_{x1}$ allowed. Below these checkboxes are additional input controls that relate to the N removal optimisation option; however, in order to understand their function, the JHB N removal optimisation procedure needs to be discussed first.



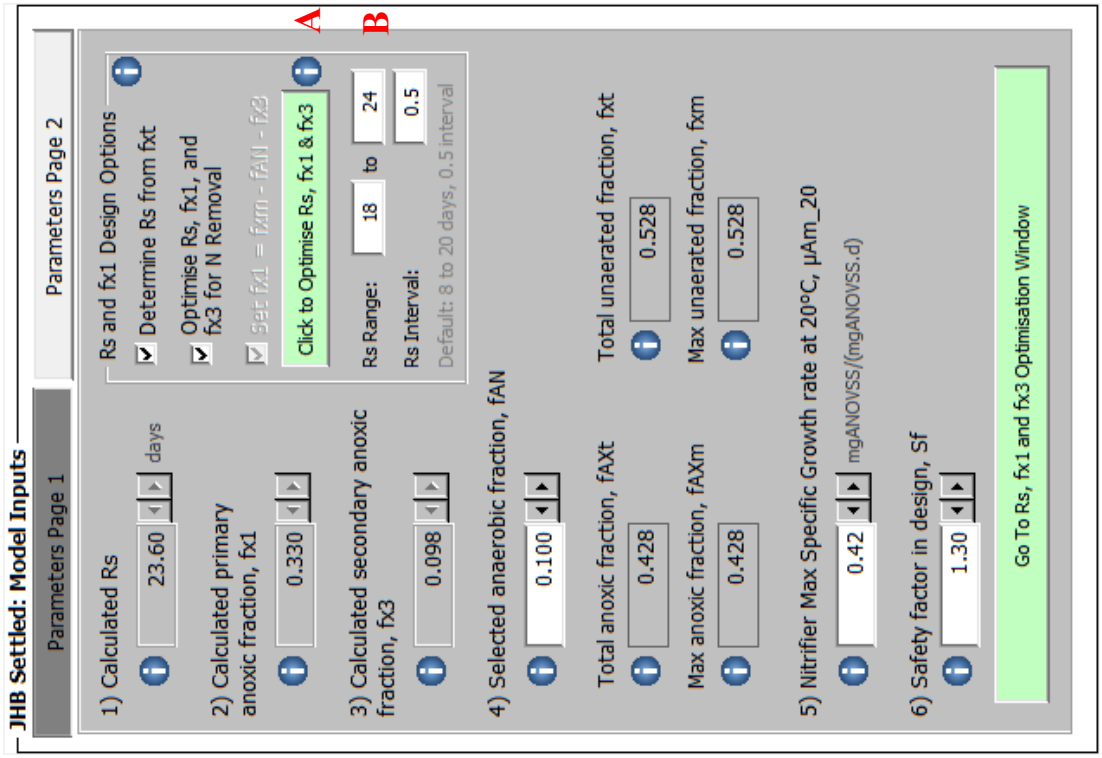




**Figure 6.19: AS Design – JHB Model Inputs, Parameters Page 1 and 2**

The N removal optimisation process for the JHB system is more complicated than for the MLE and UCT system. This is primarily because of the inclusion of a secondary anoxic reactor ($f_{x3}$) and hence a split of anoxic mass fraction between $f_{x1}$ and $f_{x3}$ is required and thus both fractions need to be optimized. The optimisation procedure to find a balanced JHB system is not an elegant procedure. The $f_{x3}$ creates problems in that there is no direct way of optimising the split between the $f_{x1}$ and $f_{x3}$. The only known facts are that (1) the nitrate concentration exiting $f_{x3}$ must be zero and (2) the sum of $f_{x1}$ and $f_{x3}$ must not exceed the maximum anoxic mass fraction allowed ($f_{x1m}$), which is the maximum unaerated mass fraction ($f_{xm}$) less the anaerobic mass fraction ($f_{AN}$), i.e. $f_{x1} + f_{x3} \leq f_{x1m}$, where $f_{x1m} = f_{xm} - f_{AN}$. A two-step trial and error optimisation procedure was developed for the JHB system. A short overview of the procedure is presented below; the complete procedure is Section 6.1.5 Nitrogen Removal (ND) Optimisation.

1. Start by selecting an SRT
2. Calculate $f_{xm}$ from SRT (as for the MLE and UCT systems)
3. $f_{AN}$ is specified (at say 0.12) therefore let $f_{x1} = f_{xm} - f_{AN} - f_{x3}$, where $f_{x3}$ is varied
4. Via trial and error, find $f_{x3}$ that provides an $f_{x1}$ that balances the AX1 at the selected maximum practical a recycle ratio (aRec = a-prac say 6:1), i.e. the equivalent nitrate load on AX1 ($EqN_{nl}$) equals AX1's denitrification potential ($D_{p1}$) at an a-recycle ratio of a-prac, viz. $D_{p1} = EqN_{nl} = a[N_c/(a+s+1)+DO_s/2.86)]$
5. When AX1 is balanced, the nitrate load on AX3, $N_{nl3} = s[N_c/(a+s+1)+DO_s/2.86)]$*
6. If the denitrification potential of AX3 ($D_{p3}$) is greater than nitrate load on AX3 ($EqN_{nl3}$), then AX3 is underloaded and the selected sludge age (SRT) is too long.
7. If $D_{p3}$ is less than nitrate load on AX3 then AX3 is overloaded and SRT is too short
8. If $D_{p3}$ equals the nitrate load on AX3 then AX3 is balanced and SRT is correct. At this SRT, both AX1 and AX3 are loaded to their denitrification potential and so gives the lowest effluent nitrate and shortest SRT while protecting the AN from nitrate input.
9. Hence a solution is found when AX1 and AX3 are balanced or slightly underloaded (8 above)
10. If no solution found (6 or 7 above), then increase or decrease SRT by a specified interval and repeat from step 2.

Note that the equations presented above can be used without the optimisation procedure. In developing the optimisation procedure, the nitrification/denitrification (ND) equations for the JHB system had to be developed first. The JHB optimisation procedure is simply a

* An assumption in the JHB model is that all the underflow nitrate is denitrified either in the AX3 or subsequent AN, thus the nitrate entering the AE from AX1 is zero and the nitrate concentration in AE is nitrification capacity divided by the total flow entering AE, i.e. Nc/(a+s+1)

manipulation of the ND equations to find achieve a specific set of conditions. The ND equations for the JHB system are described in detail in the Appendix F Steady-State JHB ND Equations.

The optimisation procedure described above is tedious to do by hand; it could tak a long time, and a solution might not necessarily be available. However, using a spreadsheet for the calculations and a loop function written in VBA code, the procedure is easy and quick (run time averages around 20 seconds). The procedure can be started by simply clicking the *Click to Optimise SRT ($R_s$), $f_{x1}$ and $f_{x3}$* **(A)** button. The SRT range and interval, apart from the normal AS model input parameters, is only preliminary requirement (**B**). The SRT range specify the start and end conditions of the trial and error procedure, e.g. start at 18 days SRT and end at 24 days SRT. The SRT interval specifies the increments from the start to the end SRT, e.g. if the SRT interval is 0.2 days, then the trial and error procedure will evaluate the system at 18, 18.2, 18.4 days etc.

From a conceptual coding point of view, the SRT range and interval is technically not required for the trial and error loop function. The loop function can be written in such a way that SRT starts at 0 days, increase by very small intervals, and only exit the loop when a solution is found. However this is unwise, because if there is no solution, i.e. AX1 will always be overloaded because of a high TKN/COD ratio, the loop procedure will continue to infinity or until the program eventually crashes due to a build of memory errors. Therefore, it is better to limit the trial and error procedure by providing an upper and lower SRT boundary. This boundary must be entered before optimisation can begin.

The default SRT range and interval is 8 to 20 days, and 0.5 days interval. This might not suite all wastewater characteristics - shown in Figure 6.19, the balanced SRT is at 23.60 days, giving $f_{x1}$ and $f_{x3}$ equal to 0.330 and 0.098 respectively. The optimisation procedure is not limited to a single attempt; if no solution was found with the entered range and interval or if a solution was found but a greater SRT accuracy is required then the optimisation procedure can be attempted again but with a higher, lower, or narrower SRT range and a smaller SRT interval. If the optimisation process was a successful, then a results window (*Optimisation Results*) will be displayed. This window shows the optimum SRT, mass fractions, and the N removal states of the AX1 and AX3. If are multiple solutions for the system, then the designer will be required to select the desired SRT, $f_{x1}$, and $f_{x3}$. If optimisation fails, the *Optimisation Results* will also be displayed. Figure 6.20 is a screen shot of the *Optimisation Results* window for an optimisation attempt with the default SRT range (8 to 20 days) and interval (0.5 days) for this JHB design example – the balanced SRT for this system is 22.20 days, therefore no optimum solution could have been found. The results for each SRT in the SRT range will be shown; from these results, by evaluating the N removal state of the AX3, whether to increase or decrease the SRT range and interval can be easily identified. This is discussed further.

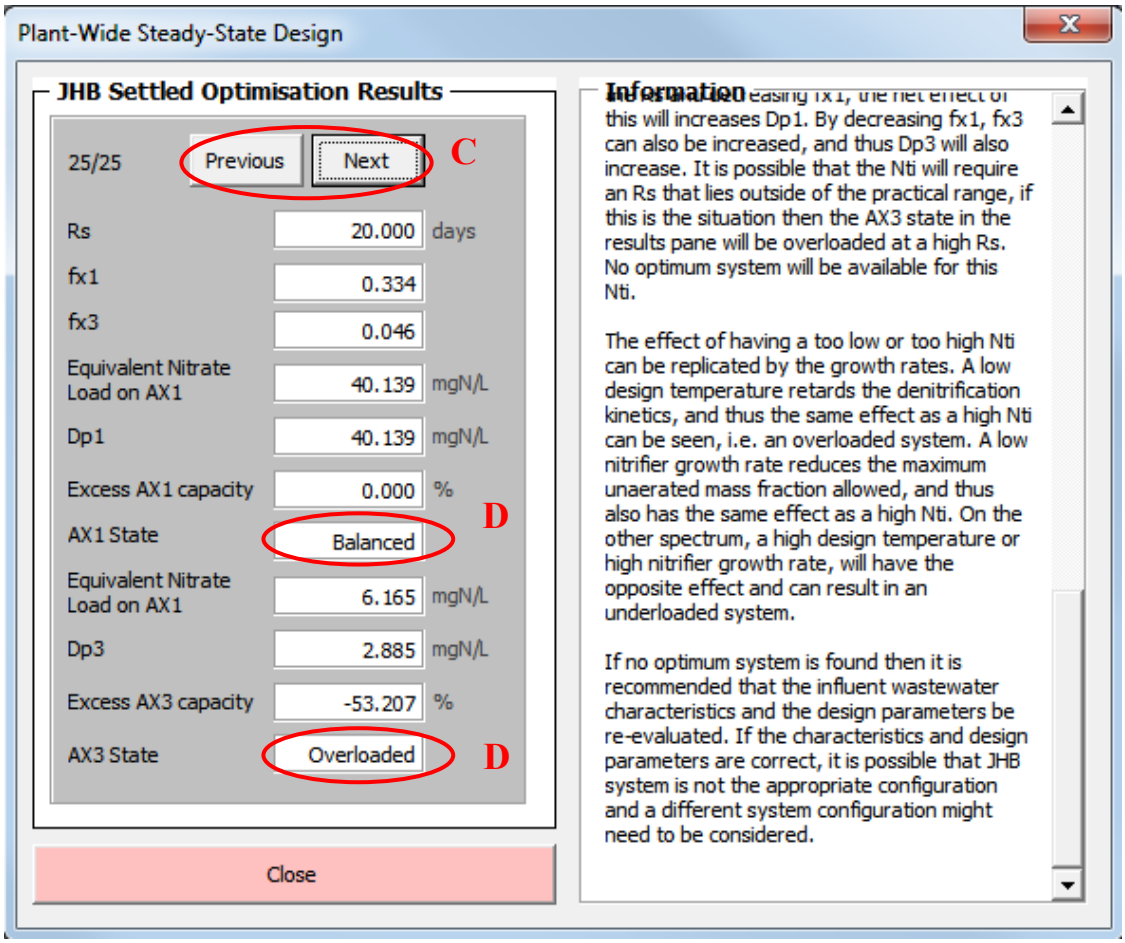



**Figure 6.20: AS Design – JHB N removal Optimisation Results**

On the *Optimisation Results* window each SRT in the SRT range can be cycled through by using the *Previous* and *Next* controls at the top of the window (**C**). For the AX1, the AX1 state will always be balanced (**D**); this is because the trial and error balances the AX1 before it evaluates the AX3 state. The AX3 results will indicate if the SRT range needs to be increased or decreased. In this example, for the SRT range from 8 to 20 days, every SRT will give an overloaded AX3 (**D**). From the AS model, we know that if an anoxic reactor is overloaded then its anoxic mass fraction is too low and thus need to be increased in order to increase the AX3's denitrification potential ($D_{p3}$). In order to increase the $D_{p3}$, the SRT needs to be increased so that a greater anoxic mass fraction is available for the AX1 and AX3, thus the entered SRT range (8 to 20 days) is too low and the optimum SRT is greater than 20 days. Alternatively if each SRT gave an underloaded AX3, then too much anoxic mass fraction is available, and thus the SRT range is too high. The SRT range needs to be decreased so that less anoxic mass fraction is available. If there are overloaded and underloaded results (e.g. 8 to 15 days is overloaded, but 15.5 days to 20 days is underloaded), then the optimum SRT is within the specified SRT range, but the SRT interval is too high. The sensitivity of the optimisation needs to be increased, which will affect the final step of each iteration.

The final step of each iteration in the optimisation procedure is the analysis of the AX3 state. If the AX3 is excessively underloaded then that SRT, $f_{x1}$, and $f_{x3}$ is not a solution. The difference between the $D_{p3}$ and the equivalent nitrate load must be less than 2 mgN/L* for it to be deemed acceptable. If the SRT interval is too high then results are not sensitive enough to provide the 2 mgN/L difference. A percentage was not used to evaluate the AX3 because it would be difficult to obtain a solution for an AX3 with a low $D_{p3}$; for example if the $D_{p3}$ is 4 mgN/L, for a 10% allowance, the difference between the $D_{p3}$ and equivalent nitrate load has to be between 0 and 0.4 mgN/L. To get this type of result will require an extremely small SRT interval and thus an unnecessary high amount of optimisation attempts. If the overloaded/underloaded results occur, then optimisation should be attempted again but with a narrower SRT range and a smaller interval (e.g. 15 to 15.5 days because it is known from the previous iteration that 15 days is overloaded but 15.5 days is underloaded therefore balanced SRT is between those two).

For the *Design Preview*, the N removal part has been expanded to include AX3. The N removal state of the AX3 is displayed at the top of the *Design Preview*, and the equivalent nitrate load, the actual $D_{p3}$, and the unused $D_{p3}$ of the AX3 is shown in the N removal part of the *N and P Removal* results section. The nitrate in the AX3 effluent is also displayed, this is will be 0 mgN/L if the AX3 is balanced or underloaded, if it is not 0 mgN/L then an *Orange Info* button is displayed providing warning and information on how to fix this. In the general section the optimum aRec is not presented, this is due to the manner in which N removal is optimised – an optimum aRec cannot be explicitly found. The two pages of the *Design Preview* are shown in Figure 6.21 and Figure 6.22 on the next page.

In closure, the JHB system allows for the protection of P removal, however it is important to stress that this is possible only if sufficient denitrification potential can be provided for in the AX3. Thus for influent wastewater with low TKN/COD ratios the JHB is a viable alternative to the UCT system, particularly for raw WW systems because the raw WW has a lower TKN/COD ratio than the settled WW (PST's remove a higher percentage of COD than TKN).

* This can be edited in the defaults spreadsheet

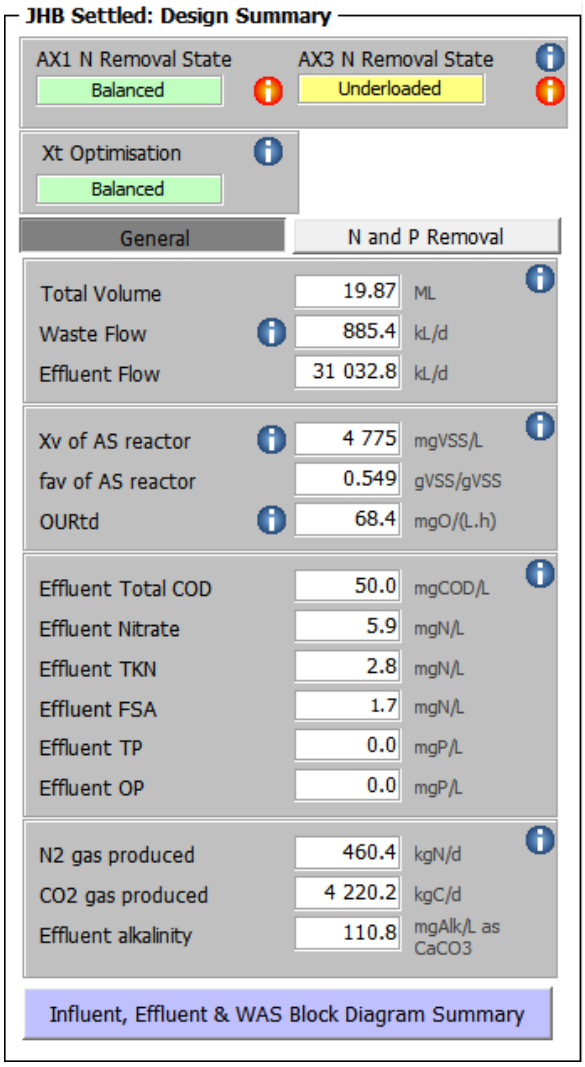



**Figure 6.21: AS Design – JHB General Design Summary**

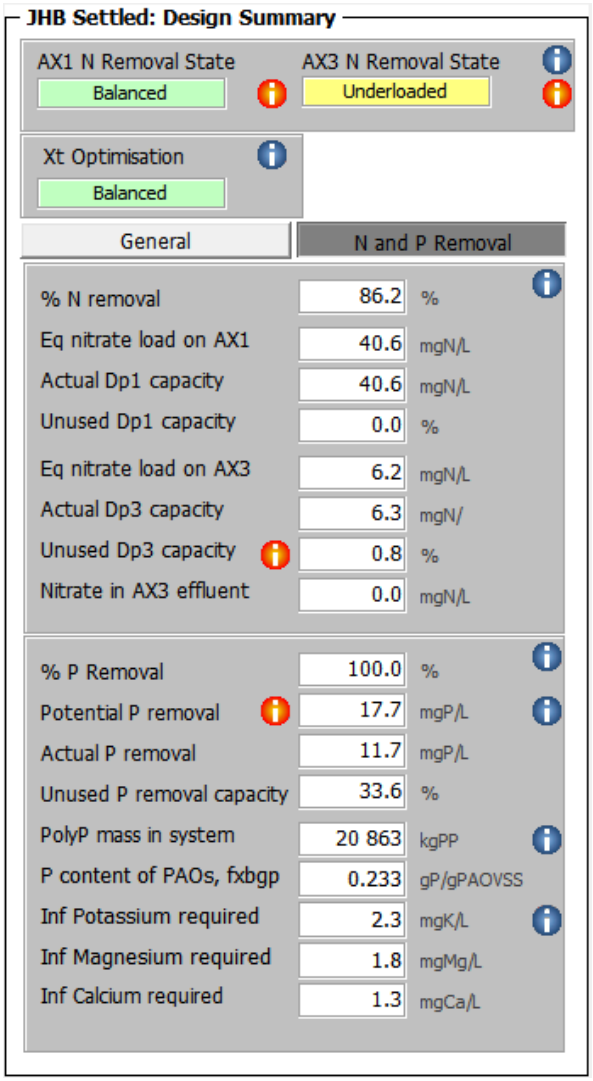



**Figure 6.22: AS Design – JHB N and P Removal Summary**

### 6.1.4 4-Stage and 5-Stage Bardenpho

The 4-Stage Bardenpho configuration is an ND only system that consists of a primary anoxic reactor (AX1) followed by an aerobic reactor (AE), then a secondary anoxic reactor (AX2) and another aerobic reactor (re-aeration reactor). The recycle flows are from the AE to the AX1 (aRec) and the SST to the AX1 (sRec). The purpose of the re-aeration reactor is to strip to the nitrogen gas and to nitrify the ammonia released during the denitrification process in AX2. This configuration addresses the deficiency of incomplete nitrate removal in the MLE system. For very low influent TKN/COD ratios (e.g. 0.09:1), this is theoretically possible; however, in practice, most wastewater influent TKN/COD ratios are not as low, particularly for settled WW. In fact, even at low TKN/COD ratios, the small amount of ammonia released during denitrification in the AX2 and its subsequent nitrification in the re-aeration reactor will result in a low concentration of nitrate in the effluent. The slow denitrification rate in the secondary

anoxic reactor ($K'_2$) usually results in an inefficient use of anoxic sludge mass fraction (does not minimize effluent nitrate); in most scenarios, it is better to exclude the secondary anoxic reactor and increase the primary anoxic reactor and a-Recycle ratio. At low TKN/COD ratios, the primary reactor is small even at a higher a-recycle ratio (> a-prac = 6:1) and for such situations a primary anoxic reactor can be considered. However, usually a secondary anoxic reactor is added to a system, not to rely on its own (low) denitrification potential, but to dose methanol to meet low effluent nitrate standards.

The 5-stage Modified Bardenpho is a NDBEPR system consisting of 5 reactors in the following order: anaerobic, primary anoxic, aerobic, secondary anoxic, aerobic (re-aeration). Recycle flows are from the aerobic to the anoxic reactor. Like the 4-stage Bardenpho system, the 5-stage has the ability for complete denitrification. However, this does not always happen in practice, nitrate is therefore recycled to the anaerobic reactor via the underflow. When higher N removal is required, the secondary anoxic mass fraction should be combined with the primary anoxic mass fraction, giving a 3-stage Modified Bardenpho configuration. The JHB system is in fact an improvement on the 3-stage Bardenpho because it provides for denitrification of nitrate in the underflow recycle. Hence, the 3-stage Bardenpho is not considered in this software.

While ND optimization procedures have been develop for the 4 and 5 Stage Bardenpho systems (see WRC, 1984, Ekama PG course material), these configurations are not currently available in the program; however, there are plans to add this in the future. Adding a new AS system is not difficult but it does require time, the following procedure is required:

1. Create the raw WW model in a spreadsheet; for the settled WW system, duplicate the raw WW model and change the wastewater inputs to the settled WW inputs
2. Create an inputs table for the new AS system in the inputs spreadsheet
3. Create the design window that transfer the users inputs to the input table
4. Link the new raw and settled AS model to the inputs table
5. Link the WAS fluxes from the model to the WAS characterisation spreadsheet – this links the system to the WAS AD model
6. Link the WAS fluxes from the raw and settled WW models to the NDBEPR WAS aerobic digestion model
7. Link the model outputs to all other relevant spreadsheets and tools: $X_t$ to the SST model, $OUR_{td}$ to the aeration model, volumes to the cost-model, design specifications and the WAS/effluent fluxes to the summary spreadsheets etc.
8. Edit all relevant design windows to include the new AS system

The program is not limited to only the 4-stage and 5-stage models, any steady-state model can be added to the program - if it can be set-up in a spreadsheet or in VBA code.

### 6.1.5 Nitrogen Removal (ND) Optimisation

The AS models have an optimisation function for nitrogen removal and for the reactor TSS concentration ($X_t$). These optimisation models are an additional tool available to the designer. Optimisation is not required, but it is recommended as it improves the efficiency of the designed WWTP without the loss of effluent quality. The nitrogen removal optimisation involves the balancing of the nitrification/denitrification (ND) design so that excess (unused) nitrogen removal capacity is minimised. ND optimisation is discussed further in this section.

The goal of the ND optimisation function is to calculate the optimum (lowest) sludge age (SRT) and anoxic mass fractions ($f_{x1}$, $f_{x2}$, $f_{x3}$) for the selected AS configuration. The optimum values are the values that match the systems' nitrification capacity ($N_c$) and denitrification potential ($D_p$). When the equivalent nitrate load on anoxic reactor, generated by the nitrification capacity, is equal to anoxic reactor's denitrification potential at the maximum practical a-recycle ratio (e.g. 6:1), then this occurs, the system is termed a balanced system and yields a system with the shortest sludge age (SRT) and lowest effluent nitrate concentration. For AS configurations with a secondary anoxic reactor (AX2 or AX3), the secondary reactor also fully denitrifies its nitrate load, or at least almost fully so that there is limited excess denitrification capacity. The balanced system provides the most economical ND scenario as the system operates at the minimum SRT, and hence, the lowest reactor volume (for a selected $X_t$), and concurrently allowing for the highest N removal and lowest effluent nitrate ($N_{ne}$). Typical performance of a balanced system is 80-85% N removal and $N_{ne}$ < 6-7 mg$NO_3$-N/L.

The optimisation procedure varies for each type of configuration; this is due to the configuration and number of the anoxic reactors. Configurations with more than one anoxic reactor (JHB, 4BPHO and 5BPHO) are more difficult to optimise than for configurations with only one anoxic reactor (MLE and UCT). There are no explicit solutions for the minimum SRT and anoxic mass fractions. Optimisation involves a trial and error procedure; thus, when there is more than one anoxic reactor, the optimisation procedure increases in complexity. The optimisation procedure is independent of the WAS treatment option and the presence or absence of the primary settling tank (PST). However, the PST does have a significant impact on the calculated minimum SRT and anoxic mass fractions. In general, the PST removes a greater proportion of COD (40%) than TKN (16%), therefore the TKN:COD ratio of settled WW is higher than for the raw WW. This higher ratio results in a longer balanced SRT and larger anoxic mass fractions – but not necessarily a larger reactor volume because the PST removes a large portion of the influent COD, ISS and UPO.

For the MLE design, to optimise the AS system, the designer simply checks the *Determine SRT ($R_s$) from $f_{xt}$* check box and the *Optimise SRT ($R_s$) and $f_{xt}$ for N removal* checkboxes on the AS design window (see Figure 6.5). If all AS inputs have been entered and are valid, then the optimisation procedure will be executed and the optimised SRT and $f_{xt}$ will be returned to the designer. This is also valid for the UCT system (Figure 6.13) and JHB system (Figure 6.19); for the UCT system, the $f_{xt}$ in the second checkbox is changed to $f_{x1}$, for

the JHB system it is $f_{x1}$ *and* $f_{x3}$. Also for the JHB system, because the optimisation procedure is more complicated (see the JHB ND optimisation topic in Section 6.1.3), the designer needs to specify the upper and lower sludge age boundary for the optimisation.

If ND optimisation is selected, the designer has access to the ND Optimisation window. An analysis of the ND optimisation can be performed on this window. To access this window, click on the *Go to SRT ($R_s$) and $f_{xt}$ Optimisation Window* button. Figure 6.23 shows the UCT ND Optimisation window. The ND Optimisation window for the MLE and JHB systems are identical to structure and functionality. The only difference being the AS model inputs (e.g. no rRec for JHB). On the ND Optimisation window (Figure 6.23), the *Optimisation Input Parameters* frame allows the entering/changing of the AS model inputs. Once all parameters are entered, the *Click to Optimise* buttons will optimise the SRT and anoxic mass fraction ($f_{x1}$ for the UCT system). When the optimisation window is opened, the AS model parameters that were entered in the AS design window are transferred to the *Optimisation Input Parameters* page, and the system is then optimised for these parameters; i.e. on start-up, the values displayed in the *Before* column are the optimised values for the AS system. In this example, with the original AS parameters from the UCT settled WW system presented in Section 6.1.2, the balanced system requires an SRT of 20.71 days and $f_{x1}$ of 0.391, giving 86.3% N removal.

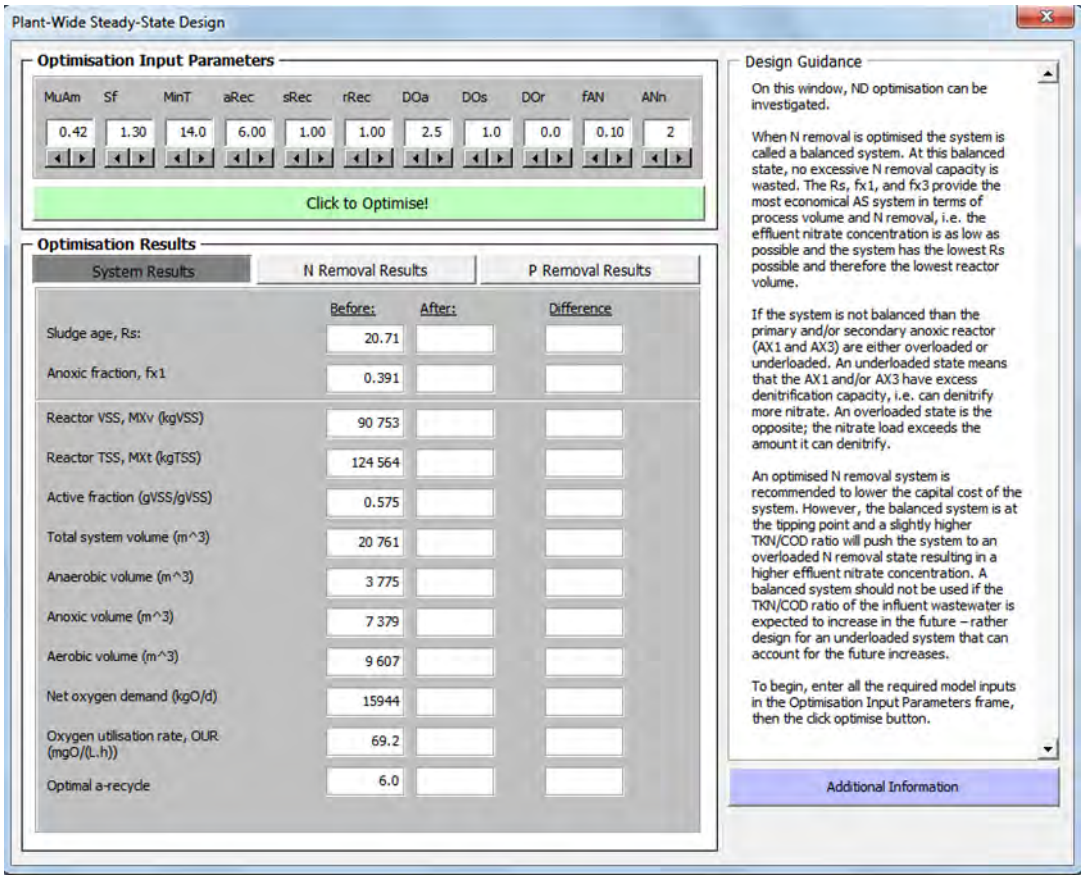



**Figure 6.23: ND Optimisation – UCT**

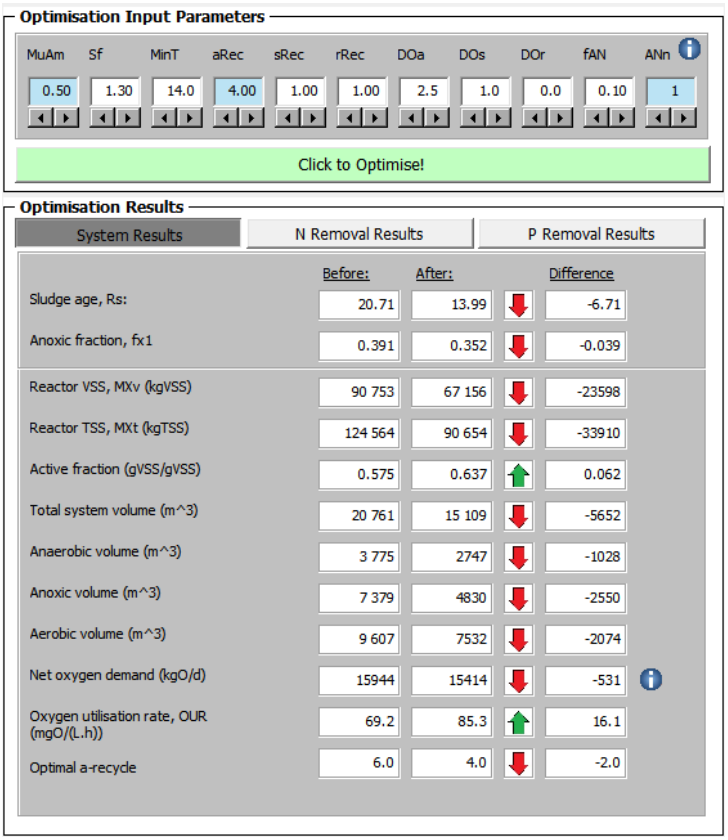



**Figure 6.24: ND Optimisation – UCT System Results**

If any of the *Optimisation Input Parameters* are changed, they are highlighted in blue, as shown in Figure 6.24. If the designer clicks on the *Click to Optimise* button, the AS system is optimised with the new input parameters. In this example, the original $\mu_{Am20}$ (0.42), aRec (6:1), and ANn (2), were changed to 0.50, 4.0, and 1 respectively. The new optimised AS results are displayed in the *After* column, and the difference between the *Before* column and the *After* column is shown in the *Difference* column. Positive, negative, and no change differences are indicated with the green up, red down, and grey "equal sign" icons. In this example, the changes to the three parameters resulted in a 6.71 days decrease in the optimum SRT. A decrease (0.039) in the optimum $f_{x1}$ mass fraction is also seen. In terms of reactor volume, the lower optimum SRT requires total system volume of 15 109 $m^3$ which is 5652 $m^3$ less than the original balanced system. However, the decrease in SRT has increased the $OUR_{td}$ in the aerobic reactor from 69.2 mgO/(L.h) to 85.3 mgO/(L.h), and the effluent active fraction of the WAS from 0.575 to 0.637. In terms of percentage N removal, it has decreased from 86.3% to 83.6% N removal. For P removal, the decrease in SRT resulted in an increase in sludge production per influent flow, and thus an increase in the P removal capacity from 18.75 mgP/L influent to 20.00 mgP/L influent. P removal is still at 100% because the influent TP is only 11.74 mgP/L. The N and P removal results can be viewed on the *N Removal Results* and *P Removal Results* pages. These pages are shown in Figure 6.25

Note that the $X_t$ input is unavailable on the ND Optimisation window. The $X_t$ selected on the AS design window is the $X_t$ used in the ND Optimisation window. The $X_t$ input is unavailable because it has an effect on the reactor volumes and $OUR_{td}$. The ND Optimisation window focuses on the AS model parameters that affect the efficiency and capacity of the ND design. Therefore, if $X_t$ is included as an input parameter on the ND optimisation window, the impact of the *Optimisation Input Parameters* on the *Before*, *After* and *Difference* of the reactor volume and $OUR_{td}$ items cannot be compared because the reactor concentration would have changed.

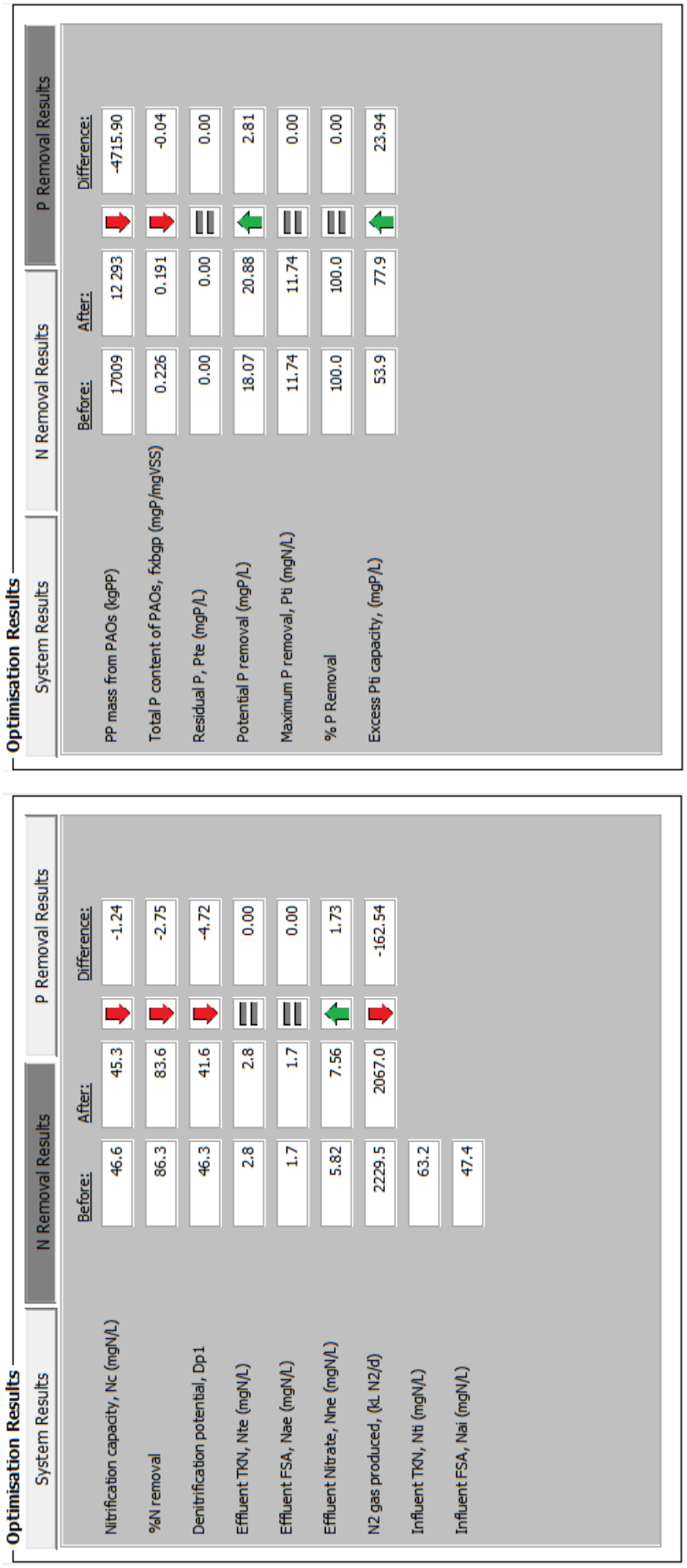



**Figure 6.25: ND Optimisation – UCT N Removal Results and P Removal Results**

The ND Optimisation window is useful for the evaluation of how the AS model parameters have an effect on the AS system design. It is highly recommended that a balanced AS system is used. However, in some cases it might be beneficial to have excess N removal capacity so that any future increases in the influent TKN concentration can be accommodated.

In the three sections below, the ND optimisation procedures for the MLE, UCT and JHB AS systems that run in the background of the ND Optimisation and the AS design windows are presented in detail. A short overview of the JHB ND optimisation procedure was provided in Section 6.1.3, the complete procedure is provided here. In the sections below, a few of the crucial equations used in the optimisation procedures is also presented.

#### 6.1.5.1 MLE

| MLE ND optimisation procedure to find minimum SRT: | Important Equations: |
|---|---|
| 1. Select SRT ($R_s$)<br>2. Calculate $MX_v$<br>3. Calculate $N_s$<br>4. Calculate $f_{xm}$<br>5. Calculate $f_{xt,min}$<br>6. Increase SRT if $f_{xm} < f_{xt,min}$<br>7. If $f_{xm} > f_{xt}$, set $f_{xt} = f_{xm}$<br>8. Calculate $N_{ae}$<br>9. Calculate $N_{ouse}$<br>10. $N_{te} = N_{ae} + N_{ouse}$<br>11. Calculate Actual $D_{p1}$<br>**Equation 6.1**<br>12. Select a-recycle. Let $N_c^* = EqN_{n1}$<br>$EqN_{n1}$ is the equivalent nitrate load on AX1<br>$N_c^*$ is the Nc required to give $EqN_{n1}$ that matches the Actual $D_{p1}$<br>13. Calculate $N_c^*$<br>**Equation 6.2**<br>14. $N_{ti}^* = N_s + N_{te} + N_c^*$<br>15. Change SRT until $N_{ti}^*$ = actual $N_{ti}$ | **Equation 6.1: ND Optimisation MLE – Actual $D_{p1}$**<br>$$D_{p1} = S_{bi} \times \left[ f_{Sb's} \frac{(1 - f_{cv,OHO})}{2.86} + f_{X1} \frac{k'_{2T} R_s Y_{OHO}}{1 + R_s b_{OHO,T}} \right]$$<br>**Equation 6.2: ND Optimisation MLE – $N_c$ required ($N_c^*$) to give EqNn1 that matches the Actual $D_{p1}$**<br>$$N_c^* = \frac{\left( D_{p1} - \frac{a \times DO_a}{2.86} - \frac{s \times DO_s}{2.86} \right)}{\left( \frac{a+s}{a+s+1} \right)}$$ |

### 6.1.5.2 UCT

UCT ND optimisation procedure to find minimum SRT:

1. Select SRT ($R_s$)
2. Calculate $MX_v$ including PAOs
3. Calculate $N_s$
4. Calculate $f_{xm}$
5. Calculate $f_{x1,min}$
6. Increase SRT if $f_{xm} < f_{xt,min}$
7. If $f_{xm} > f_{xt}$, Set $f_{x1} = f_{xm} - f_{AN}$
8. Calculate $N_{ae}$
9. Calculate $N_{ouse}$
10. $N_{te} = N_{ae} + N_{ouse}$
11. Calculate Actual $D_{p1}$ **Equation 6.3**
12. Select a-recycle. Let $N_c^* = EqN_{n1}$

    $EqN_{n1}$ is the equivalent nitrate load on AX1

    $N_c^*$ is the $N_c$ required to give $EqN_{n1}$ that matches the Actual $D_{p1}$
13. Calculate $N_c^*$ **Equation 6.4**
14. $N_{ti}^* = N_s + N_{te} + N_c^*$

    $N_{ti}^*$ is the Nti required to balance AX1 for the selected SRT
15. Change SRT until $N_{ti}^*$ = Actual $N_{ti}$

Important Equations:

**Equation 6.3: ND Optimisation UCT – Actual $D_{p1}$ (from α and β)**

$$D_{p1} = \alpha + f_{X1} k'_{2T} \beta$$

Where:

$$\alpha = \frac{S_{F,ANn}(1+r)(1-f_{cv,OHO})}{2.86}$$

$$\beta = \frac{(COD_{bi} - S_{S,PAO}) Y_{OHO} R_s}{1 + R_s b_{OHO,T}}$$

**Equation 6.4: ND Optimisation UCT – Nitrification capacity required ($N_c^*$) to give equivalent nitrate load on AX1 ($EqN_{n1}$) that matches the Actual $D_{p1}$**

$$N_c^* = \frac{\left(D_{p1} - \frac{a \times DO_a}{2.86} - \frac{s \times DO_s}{2.86}\right)}{\left(\frac{a+s}{a+s+1}\right)}$$

### 6.1.5.3 JHB

JHB ND optimisation procedure to find minimum SRT:

1. Select SRT ($R_s$)
2. Calculate $MX_v$ including PAOs
3. Calculate $N_s$
4. Calculate $f_{xm}$
5. Calculate $f_{x1}$,min
6. Increase SRT if $f_{xm} < f_{xt,min}$
7. If $f_{xm} > f_{xt}$, Select $f_{x3}$
8. Let $f_{x1} = f_{xm} - f_{AN} - f_{x3}$
9. Calculate $N_{ae}$ and $N_{ouse}$
10. $N_{te} = N_{ae} + N_{ouse}$
11. Calculate Actual $D_{p1}$
    **Equation 6.5**
12. Select a-recycle. Let $N_c^* = EqN_{n1}$

    $EqN_{n1}$ is the equivalent nitrate load on AX1

    $N_c^*$ is the $N_c$ required to give $EqN_{n1}$ that matches the Actual $D_{p1}$
13. Calculate $N_c^*$
    **Equation 6.6**
14. $N_{ti}^* = N_s + N_{te} + N_c^*$

    $N_{ti}^*$ is the $N_{ti}$ required to balance AX1 for the selected SRT
15. Change $f_{x3}$ until $N_{ti}^*$ = Actual $N_{ti}$

**Do not proceed until step 15 is satisfied.**

16. If $EqN_{n1}$ matches Actual $D_{p1}$ then AX1 is balanced, AX3 can be evaluated
17. EqNn1 = Actual $D_{p1}$ can be checked by calculating Actual $N_c$ with **Equation** 6.7; then with Actual $N_c$, $EqN_{n1}$ from **Equation 6.8** will equal $D_{p1}$ from **Equation 6.5**.

Important Equations:

**Equation 6.5: ND Optimisation JHB – Actual $D_{p1}$ (from α and β)**

$$D_{p1} = \alpha + f_{AX1} k'_{2T} \beta$$

Where:

$$\alpha = \frac{S_{F,ANn}(1+s)(1-f_{cv,OHO})}{2.86}$$

$$\beta = \frac{(COD_{bi} - S_{S,PAO}) Y_{OHO} R_s}{1 + R_s b_{OHO,T}}$$

**Equation 6.6: ND Optimisation JHB – Nitrification capacity required ($N_c^*$) to give equivalent nitrate load on AX1 ($EqN_{n1}$) that matches the Actual $D_{p1}$**

$$N_c^* = \frac{\left(D_{p1} - \frac{a \times DO_a}{2.86}\right)}{\left(\frac{a}{a+s+1}\right)}$$

**Equation 6.7: ND Optimisation JHB – Actual nitrification capacity ($N_c$)**

$$N_c = N_{ti} - N_{te} - N_s$$

**Equation 6.8: ND Optimisation JHB – Equivalent nitrate load on AX1 ($EqN_{n1}$)**

$$EqNn1 = a \times \left(\frac{N_C}{a+s+1} + \frac{DO_a}{2.86}\right)$$

18. Calculate equivalent nitrate load on AX3 ($EqN_{n3}$)
**Equation 6.9**
19. Calculate Actual $D_{p3}$
**Equation 6.10**
20. If Actual $D_{p3} > EqN_{n3}$
then AX3 underloaded, SRT too high

    If Actual $D_{p3} < EqN_{n3}$
    then AX3 overloaded, SRT too low

    If Actual $D_{p3} = EqN_{n3}$
    Then AX3 balanced, SRT optimum
21. Adjust SRT and repeat from beginning.

    System is balanced when AX3 balanced, or AX3 slightly underloaded, (Actual $D_{p3} - EqN_{n3} < 2$ mgN/L)

**Equation 6.9: ND Optimisation JHB – Equivalent nitrate load on AX3 ($EqN_{n3}$)**

$$EqNn3 = s \times \left(\frac{N_c^*}{a + s + 1} + \frac{DO_s}{2.86}\right)$$

**Equation 6.10: ND Optimisation JHB – Denitrification potential of AX3 ($D_{p3}$)**

$$D_{p3} = f_{x3} k'_{3T} \beta$$

### 6.1.5.4 Comments regarding the ND Optimisation

The equations and ND optimisation process for the MLE system is obtained, with some slight adjustments, from (Ekama & Wentzel, 2008b). The UCT and JHB ND optimisation procedure was developed specifically for this program and is based on the MLE ND optimisation procedure by Ekama & Wentzel (2008b).

For the UCT and JHB system, the second step involves the calculation of $MX_v$ which is the sum of the different organic particulate masses in the AS reactor. This mass comprises of settleable and non-settleable UPOs from the influent, active biomass and endogenous residue from the OHOs and PAOs. For the calculation of the active biomasses and endogenous residues, the split of the influent biodegradable soluble organics ($S_{bsi}$) between the OHOs and PAOs needs to be determined. This procedure can be found in Wentzel *et al*. (1990, 2008). To calculate the TSS mass in the reactor, the P removal needs to be determined first because the TSS mass depends on the PAO polyP content. Only once the TSS mass is known, can the reactor TSS concentration be determined from the reactor volume-SST area cost minimization procedure (described above for the MLE system).

For the JHB ND optimisation, it is assumed that the underflow (s-recycle) nitrate is fully denitrified, by either the underflow anoxic reactor (AX3) or the subsequent anaerobic reactor. Therefore, the equivalent nitrate load on the AX1 ($EqN_{n1}$) will always be given as Equation 6.8, provided the nitrate concentration exiting the primary anoxic reactor is zero. Hence the AE nitrate concentration is the nitrification capacity ($N_{c,}$ expressed as mg/L influent) diluted by the total flow entering the aerobic reactor (a+s+1) plus the dissolved oxygen equivalent in the a-recycle ($DO_a$), multiplied by the a-recycle ratio. For the AX3, if the AX1 is balanced or

underloaded, then the equivalent nitrate load on the AX1 ($EqN_{n3}$) will always be given as Equation 6.9. The ND equations for the JHB system, without the ND optimisation procedure, are described in detail in the Appendix F Steady-State JHB ND Equations.

All ND optimisation procedures are written in with a trial and error, goal seek, solver. This solver simply changes a variable until a predefined condition is satisfied. A simple solver such as this is possible because of the explicit equations in the steady-state models. The ND optimisation procedure can be also setup, in a spreadsheet, in a table-like format; it can even be done by hand. In both these alternative methods, solving for a balanced system is tedious and time-consuming. However, with a solver, the balanced system is solved for almost instantaneously, which is made possible by the explicit steady-state equations.

### 6.1.6 Comments and Conclusion

The usefulness steady-state AS model is clear when interacting with the design windows. The steady-state models are computed quickly because of their explicit equations, this makes them ideal for spreadsheets. The spreadsheets are containers that effectively store and process the models. They are advantageous in that they provide consistency in the outputs, which is made feasible by the explicit steady-state equations - if a particular set of inputs for a system is used then the outputs, such as volume, gas production, flow rates etc. will be the same every time the model is computed. The quickness in computation is extremely beneficial because it allows the model to be updated, almost immediately, when an input parameter has changed. The speed is made possible by the use of explicit equations in a spreadsheet, which allows for seamless evaluation of the model for different input parameters.

The design windows were created in a consistent manner. This can be seen by similar layouts for each AS system. The VBA code for each window is also very similar, it consists of four main parts: start-up, design option formatting, input transfer, and design summary display and analysis. The start-up part deals with the preliminary steps when the design window is first displayed, e.g. variable declarations, loading of saved values into the textboxes, the help information, etc. The design option formatting deals with the display of the controls, i.e. which ones are enabled or disabled based on the inputs. The input transfer part takes the entered inputs and transfers them to the inputs spreadsheet, which is linked to the model spreadsheets. On the inputs spreadsheet, the inputs are analysed for any invalid values; if any are invalid then the input check function is returned as *FALSE*. In the design summary display and analysis part, the result from the input check function is evaluated; model results are only displayed if the input check function's result is *TRUE*. The analysis part checks the model results and hides or displays the *Orange Info* buttons, or formats the textboxes depending on the model results.

The $\mu_{Am20}$ was included as an input in the *Model Input* pages. Strictly speaking, $\mu_{Am20}$ should actually be considered as a wastewater characteristic and not a kinetic input for the AS models. $\mu_{Am20}$ is significantly dependent on the influent wastewater and the designer has no

control over it, unlike the other AS model inputs such as aRec, SRT, $f_{xt}$ etc. If $\mu_{Am20}$ is considered a wastewater characteristic then it should be entered during the WWChar phase. However, because $\mu_{Am20}$ has a direct impact on the SRT and $f_{xt}$ selection and thus the entire design of the AS system, it is better to keep it as an AS model input. If it is assigned during the WWChar phase, then $\mu_{Am20}$ is fixed and the AS design windows will lose the functionality of being able to evaluate how $\mu_{Am20}$ value directly affects the SRT and $f_{xt}$ selection.

Each AS system has the option of raw WW or settled WW, which is determined by the presence of a primary settling tank (PST). The raw WW and settled WW design windows are identical in terms of layout and functions. In terms of the models, the raw WW and settled WW are kept separate – there are essentially two spreadsheet models for each AS system. There is no strong reason for keeping them separated, when the program was in its initial development phase it was kept separate to allow for comparison of the raw and settled WW system, this simply continued throughout the development of the program. In hindsight one AS model can be used for each AS system and the wastewater inputs toggled depending on the inclusion or exclusion of the PST; this however eliminates the benefit of being able to have the raw and settled WW models displayed next to each other in the model spreadsheet.

Each AS system also has the option of wasting sludge from the AS reactor (hydraulic control of SRT) or from the SST underflow. The waste flow location does not affect the biological process of the AS system, it primarily affects the operational conditions (Ekama, 2010). The AS systems needs to operate at a designed SRT; if the operating SRT falls below the designed SRT then the system can fail in terms of nitrification/denitrification or the required P removal. The selection of the wasting location is done before the AS system design and once selected the AS models update the waste flow rate calculations accordingly - the waste flow rate displayed in the *Design Summary* is the daily constant flow rate required for the system from the AS reactor or the SST underflow. It is always recommended to implement hydraulic control of sludge age by wasting sludge directly from the end of the activated sludge reactor. This fixes the sludge at a defined value, provides a much simpler sludge wasting system, ensures nitrification all year round under increasing organic load conditions and if overloaded conditions occur, will result in solids loss over the clarifier weirs rather than excess effluent ammonia due to poor nitrification (Ekama, 2010).

Care must be taken when selecting the waste location. When hydraulic control of SRT is applied, the SRT is established by wasting a fixed volume of the reactor per day because the reactor's particulates concentration does not fluctuate much during the day; SRT can be increased or decreased simply by adjusting the WAS flow rate. Hydraulic control provides very good control over the SRT; however it has a problem in that the WAS concentration will be the $X_t$ concentration of the AS reactor, therefore the WAS needs to be thickened (from around 5 gTSS/L to 40 gTSS/L) before it can be sent to the digesters. Wasting from the SST underflow partially mitigates this problem because the sludge in the SST underflow is thickened by a factor of (1+s)/1. However, this does not decrease the size of the thickening equipment because the thickening equipment (flotation or gravity thickening) is insensitive to feed concentration.

Problems arise when wasting from the SST underflow. Due to diurnal flow variations, the underflow concentration varies considerably during the day (4-15 gTSS/L). This is problematic because the underflow concentration must be tested frequently so that the correct mass of sludge can be wasted per day, which is extremely important to establish the correct sludge age. If the underflow concentration is not known, then the mass of sludge wasted is not known and hence the operating SRT is also not known. If the SRT falls below the design SRT, nitrification may stop at low WW temperature (winter). For large WWTP's with high technical capacity the frequent underflow testing can be manageable, but for small WWTP's with low technical capacity this is problematic. In terms of the AS models, when wasting from the underflow, two assumptions are made: 1) the flux of the average underflow WAS concentration is equal to the flux of the diurnal flow underflow WAS concentration, and 2) the underflow WAS flow rate is kept constant over the 24h day. If these two criteria are not viable for the system, for example, if the system is prone to shock loads thus the system regularly wastes more sludge than designed for (assumption one invalid), or if the underflow WAS flow rate changes during the day (assumption two invalid), then wasting from the underflow should not be selected.

In terms of the WAS treatment, the selection of the WAS digesters (or extended aeration) does not affect the design of the AS system. The AS system is an upstream process and the WAS flux from the AS system determines the process design of the WAS digesters. For ND only systems, AxAeD and AD of WAS are viable options for sludge treatment. For NDBEPR systems, because the P rich WAS will cause mineral precipitation in an AD, AxAeD of WAS is recommended with lime addition should be considered (Vogts & Ekama, 2015). The WAS fluxes from the models are linked directly to a WAS characterisation spreadsheet. This spreadsheet collects all the WAS fluxes from the different AS models. A function determines which type of system is used (MLE, UCT or JHB, raw or settled WW), and sends the appropriate WAS flux to the WAS digestion models. The WAS digestion and the PS digestion models are discussed further in the Section 6.3 WAS and PS Digestion Models.

## 6.2 Solid-Liquid Separation Models

Solid-liquid separation involves the complete or partial separation of particulates from the liquid. In WWTP's this is typically done with primary settling tanks (PSTs) and secondary settling tanks (SSTs) which utilise gravity to separate the solids (sludge) from the liquid.

PSTs are used to reduce the particulates concentration in the influent wastewater; the removal of the settleable particulates also reduces and changes the COD, TKN, TP, TOC, and VSS and TSS concentrations (but not the soluble concentrations). The change from raw WW to settled WW characteristics drastically changes the design of the WWTP. The PST produces primary sludge that typically ranges from 2-7 %TSS concentration, this PS is then commonly thickened by a gravity thickener to 5-10 %TSS (WEF, 1987). The gravity thickener consists of a circular, conically shaped tank. It is usually fitted with a collector or scraper at the bottom

that moves the thickened solids to a discharge point. This is a simple, cost-effective and easily operated unit process, and thus is widely used. The effluent thickened sludge from the thickener is directed to PS digesters for treatment, and in general, a thicker sludge results in lower transportation costs and a lower anaerobic digester volume for a fixed retention time.

SSTs are used for clarification of the mixed liquor from the AS system. SSTs have three objectives: to clarify (solid-liquid separation), to thicken, and to store AS solids during imbalances between the fluxes of solids entering and exiting the SST. The clarification objective is straightforward, the SST needs to discharge an effluent that is sufficiently low effluent suspended solids (ESS); a well-functioning SST will have an ESS of below 10 mgESS/L, which demands a solids removal efficiency in excess of 99.8%. The thickening objective, like the gravity thickener, relates to transportation of the sludge; the underflow sludge needs to be concentrated to remove it from the SST and to transport it back to the AS system in a significantly lower flow than it enters the SST. In terms of sludge storage, the SST's sludge blanket can increase, or decrease due to diurnal flow variations. This is due to imbalances between the fluxes of solids entering and exiting the SST during the day. If there is a sudden surge in influent flow, the SST can be temporarily overloaded with sludge mass; hence, it must be able to cope with the rising sludge blanket until the influent returns to normal (lower) operating conditions.

Unlike the PST, there is a large body of literature on the modelling of SSTs, this is most likely attributed to the fact that the design, operation, and efficiency of the SST has a direct impact on the effluent suspended solids (ESS) and the capacity of the WWTP. Due to the importance of the SST, much research attention has been given to the modelling of SSTs so that ESS and capacity criteria can be improved. However, despite its focus of attention, numerous uncertainties exist due to the complex hydrodynamic nature of the SST, which is exacerbated by the lack of effective sludge settleability testing during daily WWTP operation – the SVI is poor sludge settleability test but it is still widely used.

The inclusion of the solid-liquid separation process has a major impact on the design of the WWTP. The choice of including or excluding a PST affects the organic load to the AS system; raw WW and settled WW systems have different reactor volume, sludge treatment, and operational requirements. The SST is often the bottleneck of the WWTP, and hence the SST and AS settleability often determines the capacity of the system. MBR and aerobic granulation sludge (AGS) technology are becoming more popular and the selection of having the conventional SST or the newer MBR or AGS will have a major impact on the design of the system – particularly the volume requirements. Currently, MBRs are not available in the PWSSD program; however, they are planned to be included in future editions.

Sections 6.2.1 and 6.2.2 discuss the interfaces and as well as some important model concepts for the design of the PST and SST. Section 6.2.3 discusses the $X_t$ optimisation process, and Section 6.2.4 presents a short overview of MBRs and the design of MBR systems.

### 6.2.1 Primary Settling Tank and Gravity Thickener

An empirical PST and gravity thickening model has been included in the program. While there is a significant body of literature on flocculent and non-flocculent settling and empirical PST models, a detailed PST model, that describes the settling behaviour of unbiodegradable (UPO) and biodegradable (BPO) settleable particulates, does not exist. The current knowledge is that only (1) around 30-40% COD and 50-66% TSuspS removal takes place in a PST and (2) that UPO settle out in greater proportion than BPO (if this were not so, commonly measured raw and settled WW UPO fractions cannot be obtained (Ekama *et al*., 2006a; Ikumi *et al*., 2014a). The behaviour of these particulates in the PST has a pronounced impact on the wastewater characteristics (and WWChar process), thus there is a need to better understand and model it. So while the selection of raw WW and settled WW characteristics in WWChar routine reflects current knowledge regarding the removal of ISS, UPO and BPO in PSTs and conform to COD, TKN and TP mass balances, these are not in any way connected to the hydraulics of PSTs.

The PST and gravity thickener (GravThk) model uses empirical performance data to size the PST and GravThk. Currently, a more detailed model does not exist and thus the empirical model is the only option available. The PST and Gravity Thickener design window is split into three sections: 1) *Design Inputs*, 2) *Design Summary*, and 3) *Design Guidance*. A screen capture of the PST and GravThk design window is shown in Figure 6.26.

For the PST design, the following inputs are required: the maximum overflow rate at ADWF ($q_{A\_ADWF}$, m/h) and PWWF ($q_{A\_PWWF}$, m/h), and the maximum PST diameter (see Figure 6.27). The *Accept* button must be clicked to transfer the inputs to the PST model. The three PST inputs determine the PST area and number of PSTs required. The ADWF, PDWF, and PWWF are taken from the WWChar module (which must be completed before the sizing of the PSTs); $q_{A\_ADWF}$ and $q_{A\_PWWF}$ are used to determine the minimum area required at ADWF and PWWF. The total PST area is then equal to the maximum of the two minimum areas calculated, which is most often at PWWF. The maximum overflow rate typically ranges from 1.2 m/h for ADWF to 2.4 m/h[*] for PWWF, however these values are not fixed, and different design manuals recommend different values. If the entered overflow rate is outside of this range then the designer is notified of this (the input boxes change colour and an *Orange Info* button is displayed), but the designer can proceed with the out-of-range values if desired. Once the total area is determined, the number of PSTs required is calculated from the maximum PST diameter; the weir-loading rate is also calculated. The results are displayed in the PST part of the *Design Summary* frame, if there are changes to the PST inputs then the *Accept* button must be clicked again.

[*] 28.8$m^3/m^2$.d for ADWF and 57.6 $m^3/m^2$.d for PWWF

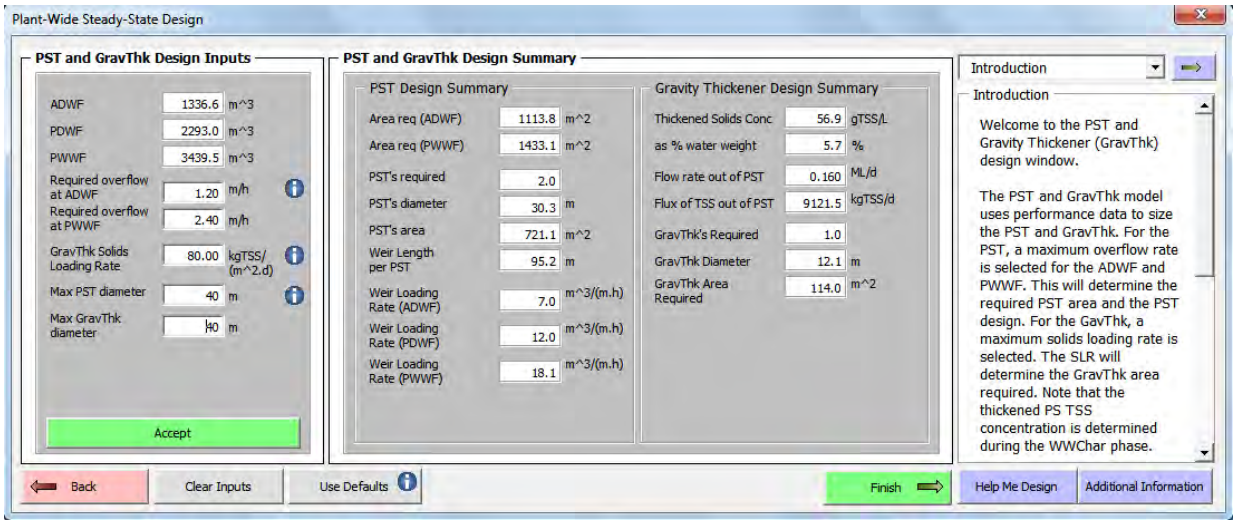



**Figure 6.26: PST and GravThk Design**

The GravThk design follows a similar empirical sizing approach to the PST. Two inputs are required, the solids loading rate (SLR) and the maximum GravThk diameter (which is usually the same as the maximum diameter for the PST). During the WWChar phase, the PS is characterised by selecting a PST underflow percentage (w.r.t to raw ADWF). The underflow percentage determines the PS flow rate and hence the TSS concentration of the PS. This TSS concentration is assumed as the thickened TSS concentration exiting the GravThk. The GravThk's SLR is selected from literature performance data, which typically relates the thickened TSS concentration with the SLR (though not very consistently, see Table 6.3). The product of the PS mass flow rate (kgSS/d) and the thickened TSS concentration is the solids flux that needs to be handled by the GravThk, therefore with the SLR, the GravThk's total area can be determined; the maximum diameter then determines the number of GravThk's required.

**Table 6.3: Common gravity thickener SLR vs thickened TSS concentration**

| Influent feed conc. (%TSS) | % Loading kgTSS/m2/d | Thickened conc. (%TSS) |
|---|---|---|
| 0,6 | 153 | 4,6 |
| 0,4 | 118 | 4,5 |
| 0,4 | 122 | 4,9 |
| 0,3 | 84 | 4,1 |
| 0,2 | 65 | 3,8 |
| 0,2 | 80 | 4,2 |

When *Accept* is clicked the PST and GravThk model is computed with the inputs (Figure 6.27); the results are then displayed in the *Design Summary*, a screen capture of this section is shown in Figure 6.28. The results contain the required area, diameter and number of PSTs and GravThks. The PST weir-loading rate is also shown. The weir loading rate, which should be in the range of 125 – 500 $m^3/(m.d)$, is primarily used for the design of the effluent launders and not a criteria for the size or quantity of PSTs. However, the selection of the maximum overflow rates is the critical inputs to the PST model. There are alternative methods for the design of the PST, such as ones that consider the retention time, side water depth, or solids loading rate. These alternative methods can be added to future editions. In the GravThk section, the *Thickened Solids Conc* is the PST TSS concentration determined in the WWChar procedure.

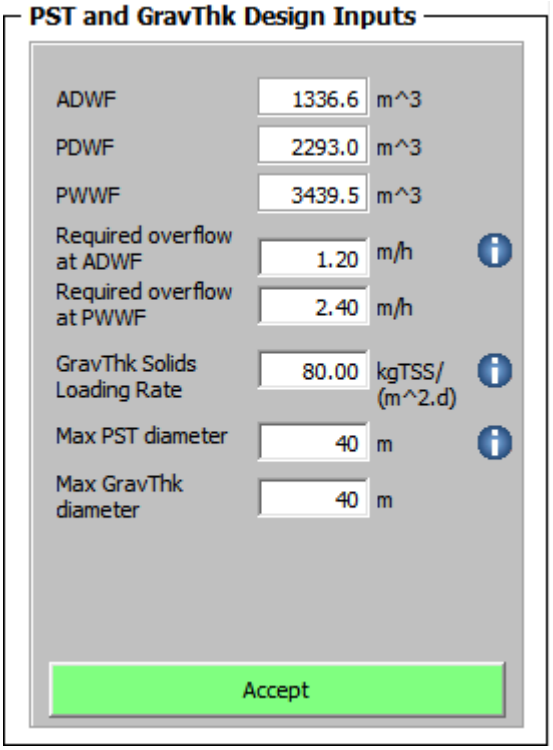



**Figure 6.27: PST and GravThk Design – Inputs frame**

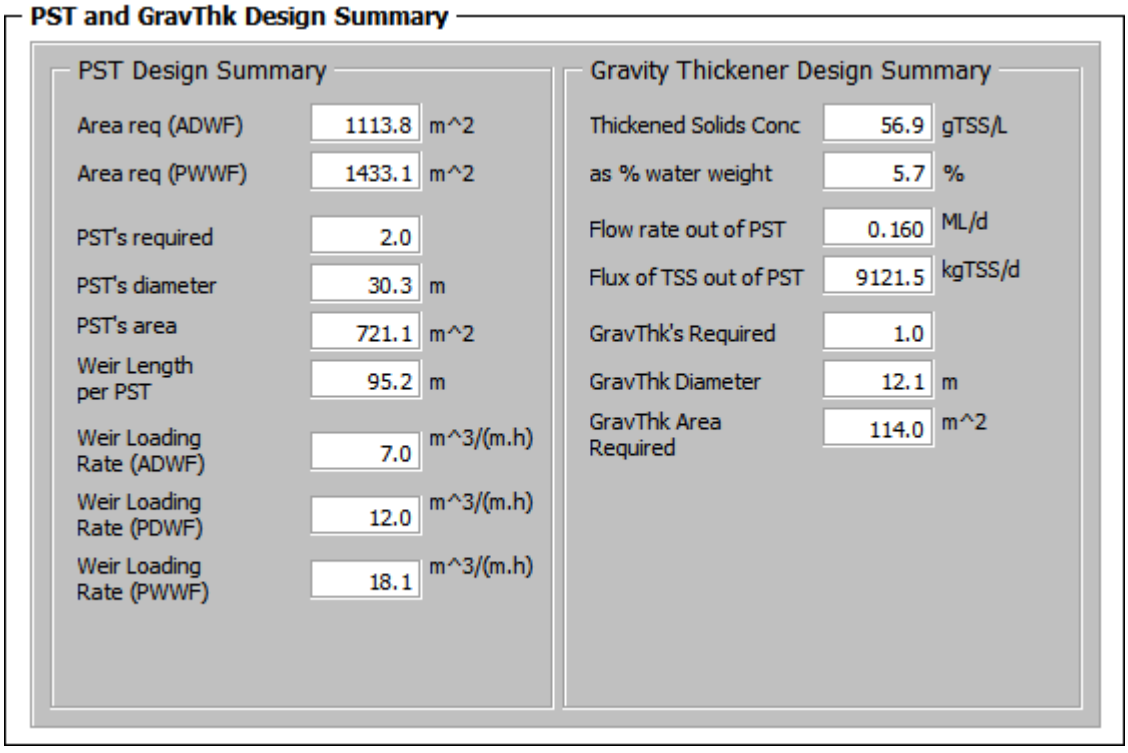



**Figure 6.28: PST and GravThk Design – Design Summary**

The *Blue Info* buttons shown in Figure 6.27 can be used to access information in the *Design Guidance* frame. This information can also be accessed using the drop down list above the *Design Guidance* section. All the content presented in this section is available, such as: GravThk performance data, design, and benefits; and PST design, inputs, PS characterisation, raw WW vs settled WW. A close up of the capture of the *Design Guidance* frame is shown in Figure 6.29.

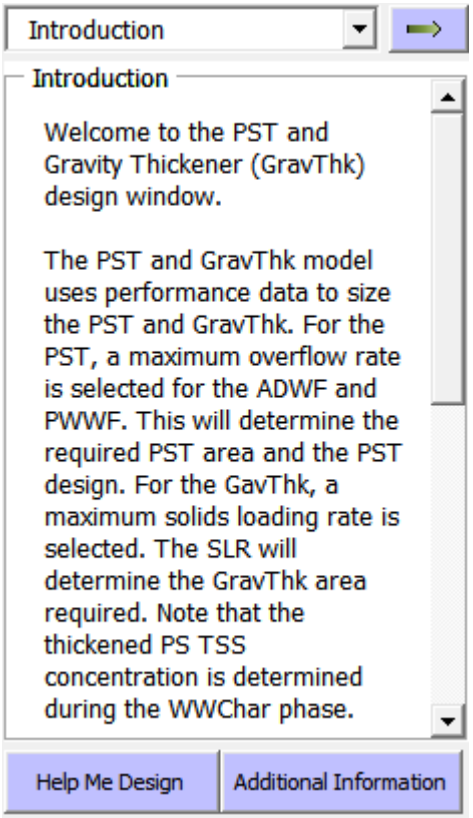



**Figure 6.29: PST and GravThk Design – Design Guidance**

The inclusion of the PST changes the WWTP from a raw WW system to a settled WW system. The choice between the two systems is up to the designer, the models can only provide the results of the decision. Both systems have advantages and disadvantages relative to each other. In the *Design Guidance* of PST and GravThk design window and the system configuration window, where the option of having a PST can be selected, the advantages and disadvantages of the raw and settled systems are presented.

Concerning the diurnal flow variations, a PST behaves similarly to a balancing tank, albeit not as effectively because it is always full; nevertheless when a PST is included in the treatment system, the diurnal flow and load variations are dampened and the amplitude of the settled WW peak TOD load wave is reduced by 25% (this can be adjusted in the defaults spreadsheet if required). There is no adjustment to the PWWF to ADWF flow factor. The effect of the PST and the balancing tank on the amplitude and flow factors a discussed in Section 6.4.1 Balancing Tank.

If a PST is included, PS treatment via anaerobic digestion needs to be included. Depending on the WAS treatment selected (anoxic-aerobic or anaerobic), a partially mixed or completely mixed WAS and PS digester can be used. Sludge treatment is discussed further in Section 6.3 WAS and PS Digestion Models.

### 6.2.2 Secondary Settling Tank

The SST is modelled using the 1-Dimensional Flux Theory (1DFT). This model determines the theoretical limit of the SST, which is then reduced by a flux rating to account for the non-idealities in real large scale SSTs relative to the idealized 1DFT model. The 1DFT is used to determine the minimum SST area required for safe operation during peak wet weather flow

(PWWF) conditions, and as well as the operating and critical recycle ratios for the PWWF and peak dry weather (PDWF) conditions.

In the 1DFT, a solids mass balance occurs at all times in the SST and the only route of exit for solids is via the underflow of the SST. Based on this assumption and the availability of sludge settling parameters that describe the settling behaviour and velocity of the sludge, the specification of the SST, such as overflow rates and minimum area required can be calculated for different flow conditions (average dry, peak dry, and peak wet weather flow). The following list shows some of the important outputs from the 1DFT.

- Minimum SST area required at PWWF
- Maximum overflow rate at PWWF
- Minimum s-recycle ratios at ADWF, PDWF, and PWWF
- Underflow and overflow rates at ADWF, PDWF, and PWWF
- Applied solids flux at ADWF, PDWF, and PWWF

The effluent suspended solids (ESS) cannot be predicted with the 1DFT. The main assumption in the idealized 1DFT is that the liquids and solids only move in the vertical direction (Marais *et al*., 2000; Marais & Ekama, 2004). A mass balance is applied and it is assumed that all solids exit via the underflow, and that the ESS is therefore essentially zero. Complex computational fluid dynamic (CFD) models can be used for ESS prediction. However, CFD models do not always guarantee accurate ESS prediction; this is because of the uncertainty in the settleability of solids at low (<200 mgSS/L) concentrations. Nevertheless CFD models are useful for optimising internal SST features, which in turn may improve the ESS prediction and allow for SST designs that can operate closer to the theoretical limit established by the 1DFT while maintaining a low ESS concentration (Ekama *et al*., 1997; Wahlberg *et al*., 1998). In terms of the PWSSD program, including a CFD model is impossible because the model requires enormous computational power; and as Plósz *et al*. (2011) explains, the use of CFD models in conjunction with AS models is currently still too computationally expensive. The 1DFT SST model, with a flux rating correction factor, is sufficient for steady-state design: sizing SST area and recycle ratios based in sludge settleability and feed concentration.

The SST design window, shown in Figure 6.30 on the next page, contains multiple pages for inputs and design results. Like PST and GravThk design window, there are three main parts: 1) *Design Inputs*; 2) *Design Summary*; and 3) *Design Guidance*. The $X_t$ optimisation model is also contained in this window; this is because there is a direct relationship between the $X_t$ optimisation procedure and the SST design; the three frames therefore also contain the inputs, results summary and design information for the $X_t$ optimisation model.


**Figure 6.30: SST Design and $X_t$ Optimisation**

The most important input in the SST design is the sludge settleability (DSVI, SSVI, SVI, or flux theory constants $V_0$ and n) around which there will be significant uncertainty. The 1DFT and SST models that are based on the 1DFT require the hindered settling (n) and the initial velocity ($V_0$) parameters. These two flux theory constants relate to the zone settling velocity of the sludge to the feed concentration ($X_t$); however, they are difficult to measure and as a result their measurement is often neglected in daily WWTP operation (Renko, 1998). To overcome this, studies have been conducted to relate commonly measured sludge indexes (DSVI, SSVI, and SVI) to the n and $V_0$ settling parameters, some examples include (Pitman, 1984; Daigger & Roper, 1985; Ekama & Marais, 1986; Catunda & van Haandel, 1992; Ozinsky & Ekama, 1995; Ekama *et al*., 1997).

With the uncertainty of the settling parameters in mind, the *SST Design Inputs* page was developed to accommodate a variety of inputs for data available and no data available scenarios. For example, if sludge index tests were done, the designer can enter a DSVI, SSVI, or SVI value. The empirical correlation equations of Ekama & Marais (1986) and Ekama *et al*. (1997) are used to calculate the $V_0$ and n from the DSVI, SSVI, and SVI values entered. The SVI is a poor measure of sludge settleability and should only be used if the 30 minute settled volume ($SV_{30}$) is less than 200 mL/L (Ekama *et al*., 1997). At this $SV_{30}$, it is equivalent to the DSVI. This is made explicitly clear by the red text next to the SVI option and a warning message if it is selected. It is recommended that the DSVI or SSVI be used. These two sludge indexes provide much more certainty in the settling behaviour of the sludge as they consider the effect of concentration on the sludge settleability – the SVI does not consider this. Alternatively, if no data is available, the designer can simply select a general sludge

settleability class, such as poor, medium, good, very good, for which then the $V_0$ and n values are selected to match the description of the settleability.

Figure 6.31 shows the first input option; the designer has answered Yes to the question *Sludge Settleability Index Available? (DSVI, SSVI, or SVI?)*. Alternatively, in Figure 6.32, *No* was selected, and the generalised settleability classes (*Very Good, Good, Medium, Poor,* and *Very* Poor) were made available. Table 6.4 shows the n and $V_0$ values for the four different settleability classes. The *Custom* option allows specific n and $V_0$ values to be entered. However, caution should be exercised when doing this because $V_0$ and n are correlated - as $V_0$ decreases, n increases, see Table 6.4 and Table 6.5 and Ekama *et al*. (1997).


**Figure 6.31: SST – Design Inputs for a selected sludge settleability index**

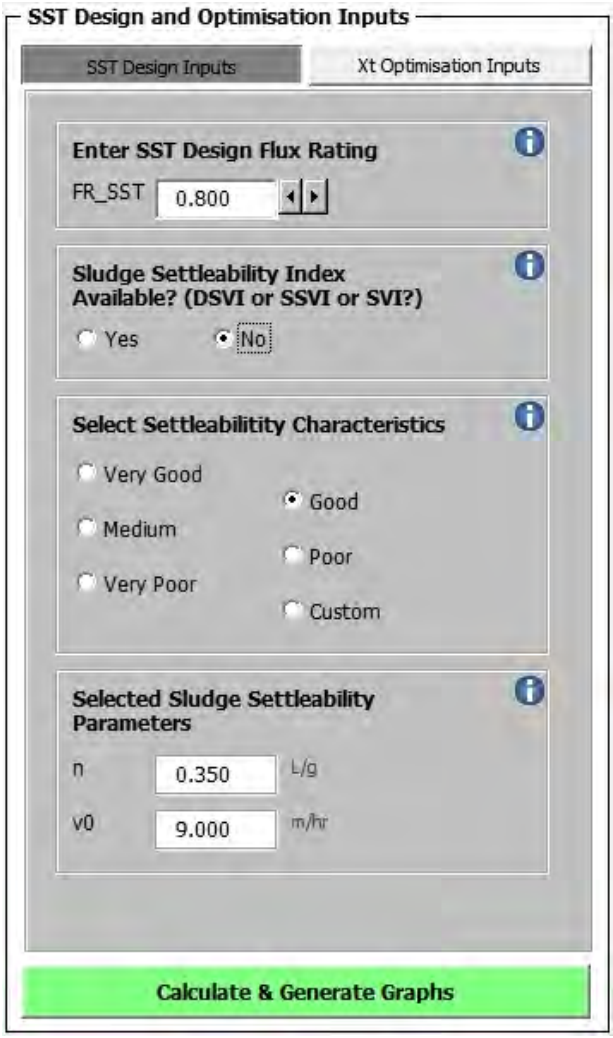



**Figure 6.32: SST – Design Inputs for a generalised sludge settleability class**

The generalised settleability classes and their respective n and $V_0$ values are in Table 6.4 below. This was obtained from von Sperling & Fróes (1999). Von Sperling & Fróes (1999) had unified the SVI, DSVI, and SSVI data for different classes of settling from different authors and then extracted the n* and $V_0$ values from the data pool. The average values for the n and $V_0$, as shown in Table 6.4, were then calculated for the different classes of settling (very poor, poor, medium, good, and very good).

Van Haandel & van der Lubbe (2007) also provide generalised n and $V_0$ values for different classes of settling, albeit only three classes were used (poor, medium, and good). Their generalised n and $V_0$ values are also shown in Table 6.4. A comparison of the two data sets was done by comparing the maximum overflow rates calculated using the n and $V_0$ values for each settling class, a default $X_t$ value of 4.5 gTSS/L was used. The comparison showed that van Haandel & van der Lubbe's (2007) generalised n and $V_0$ values for poor, medium, and good settling classes closely match the medium, good, and very good settling classes from von Sperling & Fróes (1999). Table 6.5 shows the maximum overflow rate comparison for the different settling classes. The similarity between the two independent data sets instils confidence that the generalised n and $V_0$ values for the different classes are not random values; hence, they can be incorporated into the settling tank design part of the PWSSD. Ultimately, the von Sperling & Fróes (1999) settling classes were used as it offered a greater variety.

**Table 6.4: Generalised n and $V_0$ values**

| von Sperling & Fróes (1999) | | | van Haandel & van der Lubbe (2007) | | |
|---|---|---|---|---|---|
| Settling Class | n (L/g) | $V_0$ (m/hr) | Settling Class | n (L/g) | $V_0$ (m/hr) |
| Very Good | 0.270 | 10.000 | Good | 0.310 | 12.000 |
| Good | 0.350 | 9.000 | Medium | 0.360 | 9.000 |
| Medium | 0.500 | 8.600 | Poor | 0.460 | 6.000 |
| Poor | 0.670 | 6.200 | | | |
| Very Poor | 0.730 | 5.600 | | | |

**Table 6.5: Comparison of maximum overflow rate generalised from n and $V_0$ values**

| von Sperling & Fróes (1999) | | van Haandel & van der Lubbe (2007) | |
|---|---|---|---|
| Settling Class | Maximum overflow rate (m/h) | Settling Class | Maximum overflow rate (m/h) |
| Very Good | 2.967 | Good | 2.974 |
| Good | 1.863 | Medium | 1.781 |
| Medium | 0.906 | Poor | 0.757 |
| Poor | 0.304 | | |
| Very Poor | 0.210 | | |

Max overflow calculated with an $X_t$ = 4.5 gTSS/L

*von Sperling & Fróes (1999) uses the symbol K instead of n for the hindered settling parameter

The flux rating also needs to be specified before the 1DFT SST model can be computed. The default flux rating used in the 1DFT SST design, as determined by Ekama and Marais (1986), is 0.8, i.e. the maximum SLR is reduced by 1/0.8 (25%). This 25% reduction in SLR is equivalent to an increase in the SST area by 25%. The flux rating is not a universal value, the internal features of the SST such as the SST depth, inlet configuration, effluent lauder placement, hydraulic flow patterns, flocculation chambers and sludge transport and collection systems affect the SST performance (Marais *et al*., 2000; Marais & Ekama, 2004). Nevertheless, the 25% reduction is applicable to most scenarios but can be decreased for deep SSTs (>4m side water depth).

When all inputs are entered, the *Calculate* button computes the 1DFT SST model and the results are displayed in the adjacent *Design Summary* frame. The *Design Summary* contains the results for the 1DFT model computed with and without the flux rating. The most important design results from the model are shown, these include the minimum area required at PWWF, the applied flux, overflow rate, underflow concentration, underflow volumetric flow rate, and the minimum and operational recycle ratio. These results are available for ADWF, PDWF, and PWWF conditions. The *Design Summary* frame is shown in Figure 6.33; the results shown in this figure are for the balanced flow, settled MLE system in Section 6.1.1 and a DSVI input of 100 ml/gTSS; $X_t$ is optimised to be 6.3 gTSS/L, optimisation is discussed later in this section.

SST design and operation graphs are also generated during the model computation process; these graphs are also exported to the file directory that the PWSSD program is in. When all data has been entered and the SST specifications are calculated, State Point Analysis (SPA) graphs for different flow conditions, and the Ekama Design and Operation Chart (D&O) are also generated and are available for viewing. These charts can be accessed in the *Design Summary* section; Figure 6.34 illustrates the SPA chart for ADWF conditions and the D&O chart. In this example, because a balancing tank was used in system, the SST does not experience a PDWF, i.e. PDWF = ADWF. In the SST model, the recycle (underflow) flow rate at ADWF is set to the recycle flow rate at PDWF. Because of this, the SPA graph at ADWF is the same as the SPA graph at PDWF. This means that the SST is constantly operating at PDWF conditions, which is when SHC2 is satisfied but SHC1 is at a critical condition. However, because the PDWF is equal to the ADWF, the SST model is essentially taking the ADWF as the PDWF condition; hence, the underflow line on the ADWF SPA graph is tangential to the descending limb of the gravity flux curve. The net effect of all of this is that the SST is operating with a lower recycle flow rate and higher underflow concentration, which leads to lower operating costs. With a balancing tank, the SST area required at PWWF is also lower. These quantitative results can be seen in the *Design Summary* if the SST model is computed with and without a balancing tank. Table 6.6 shows this comparison. For the PWWF SST area required, for with and without the balancing, this was computed with an $X_t$ of 6.3 gTSS/L. Note that without the balancing the optimised $X_t$ would be this value.

Linked with the AS system design, the AS reactor volume and SST area can be optimised by having an $X_t$ that yields the most cost-effective design. If the *Optimise Xt* checkbox on the

AS system design window was checked then *Xt Optimisation Input* page in the *Design Summary* frame will be available. Section 6.2.3 discusses $X_t$ optimisation further.

**Table 6.6: Effect of balancing tank on SST design**

| | With balancing tank | | | Without balancing tank | | |
|---|---|---|---|---|---|---|
| Flow condition | Recycle ratio w.r.t Qi | Recycle flow rate ($m^3/h$) | Recycle concentration (gTSS/L) | Recycle ratio w.r.t Qi | Recycle flow rate ($m^3/h$) | Recycle concentration (gTSS/L) |
| ADWF | 0.827 | 1100.2 | 14.8 | 1.227 | 1632.1 | 12.2 |
| PDWF | 0.827 | 1100.2 | 14.8 | 0.714 | 1632.1 | 16.1 |
| | Area required at PWWF ($m^2$) = 2262 | | | Area required at PWWF ($m^2$) = 4657 | | |

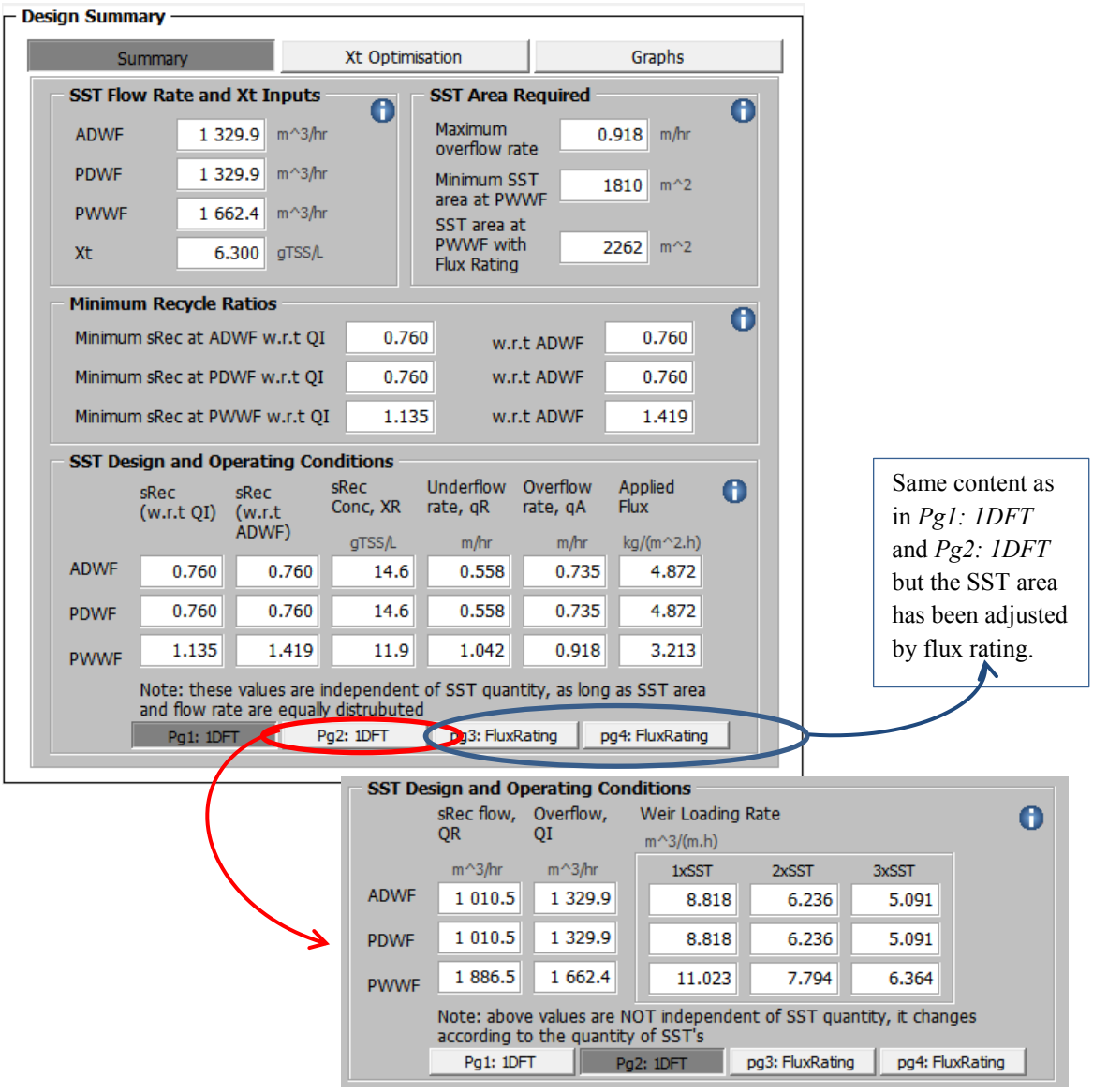



**Figure 6.33: SST – Design Summary frame**

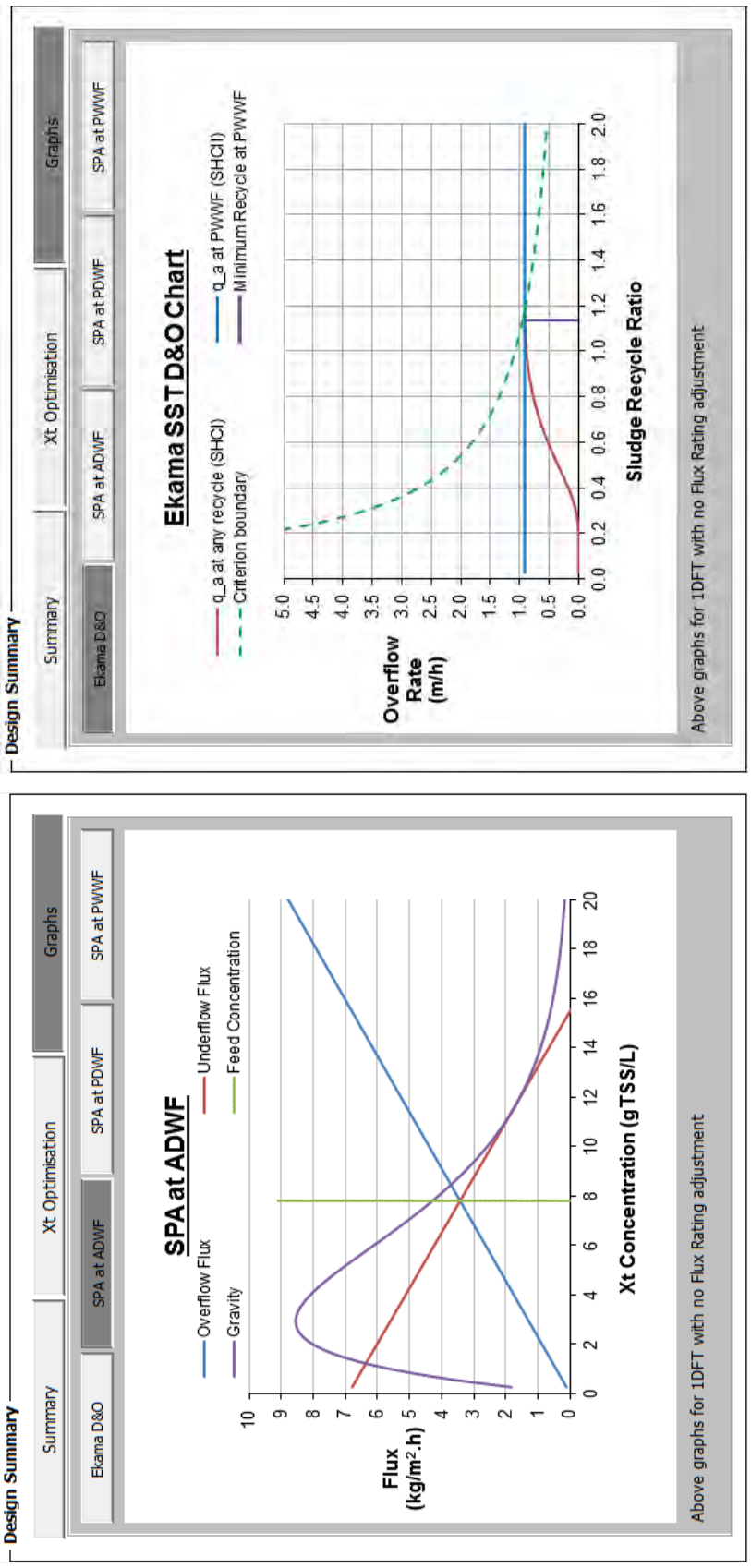



**Figure 6.34: SST – State-Point Analysis Graph and Ekama D&O Chart**

### 6.2.3 $X_t$ Optimisation

The AS models are linked to the SST model because the total particulates concentration ($X_t$) of the AS system is the feed concentration to the SST and hence an input to the SST model. A cost model to estimate the total capital cost of the AS-SST system was included. Using this cost model, the $X_t$ for the AS-SST system is determined from a cost minimization procedure. This provides an optimised AS-SST system where the calculated $X_t$ is optimised and the lowest possible total capital cost of the AS-SST system is realised (Ekama *et al*., 1997, chap. 1).

A short description of the $X_t$ optimisation model is provided. In the SST model, the $X_t$, sludge settling parameters, and influent PWWF, determine the minimum SST area required. The maximum allowable SST diameter then specifies the quantity and diameter of SSTs required. At the specified sludge age and entered wastewater characteristics, the AS system produces a fixed mass of sludge ($MX_t$) which is constantly stored in the system, the selected $X_t$ then determines the volume of the AS reactor ($V = MX_t/X_t$). The maximum allowable AS reactor volume then specifies the quantity and volume of the AS reactors. For a selected sludge settleability and PWWF/ADWF ratio, the reactor $X_t$ fixes the required SST surface area and as $X_t$ increases, the settling velocity decreases. Hence, as $X_t$ increases, the reactor volume gets smaller and less expensive; however, as determined by the 1DFT, the required minimum SST area gets larger and thus more expensive. Depending on the relative construction costs of the AS reactor and SST, there will be an $X_t$ that gives a minimum total cost.

The cost functions for the AS reactor and SST tank are exponential in form; see Equation 6.11 and Equation 6.12. The exponential equation is interpreted as the larger the spatial unit (area or volume) the lower the capital cost per unit volume or area, and *vice versa*, which provide for an economy of scale. These two equations determine the total cost of the AS-SST system. The $X_t$ that provides the lowest total costs is taken as the optimum $X_t$ for the system. In general, the spatial maximum of the AS reactor and the SST are determined by practical or construction limitations, and this needs to be considered as modularisation affects the total cost of the AS-SST system.

**Equation 6.11: $X_t$ Optimisation - AS reactor cost function**

$$Fr \times Reac\_Vol^{Er}$$

**Equation 6.12: $X_t$ Optimisation - SST cost function**

$$Fs \times SST\_Area^{Es}$$

Where Fr, Er, Fs, and Es are constants that describe the curve of the exponential cost function

The costs function is a generalised function that can cater for most scenarios, however if another type of cost function is required then this must be edited in the SST Optimisation spreadsheet. This cost function form is also used for the Cost Model (Section 6.4.4) which estimates the hypothetical cost of the entire WWTP.

It is important to note that the optimum $X_t$ is not the same for all systems, even if the Fr, Fs, Er and Es inputs to the cost model are the same. $X_t$ is highly dependent on inter alia, the sludge age, the strength of the wastewater, PWWF/ADWF ratio and sludge settleability. From the $X_t$ optimisation model, it will be found that high influent wastewater strengths (>1000 mgCOD/L) and long sludge ages (>25 days) result in high optimum $X_t$ concentrations (4-6 mgTSS/L). On the other hand, deteriorating sludge settleability and increasing PWWF/ADWF ratios result in lower optimum $X_t$ concentrations (<4 mgTSS/L)

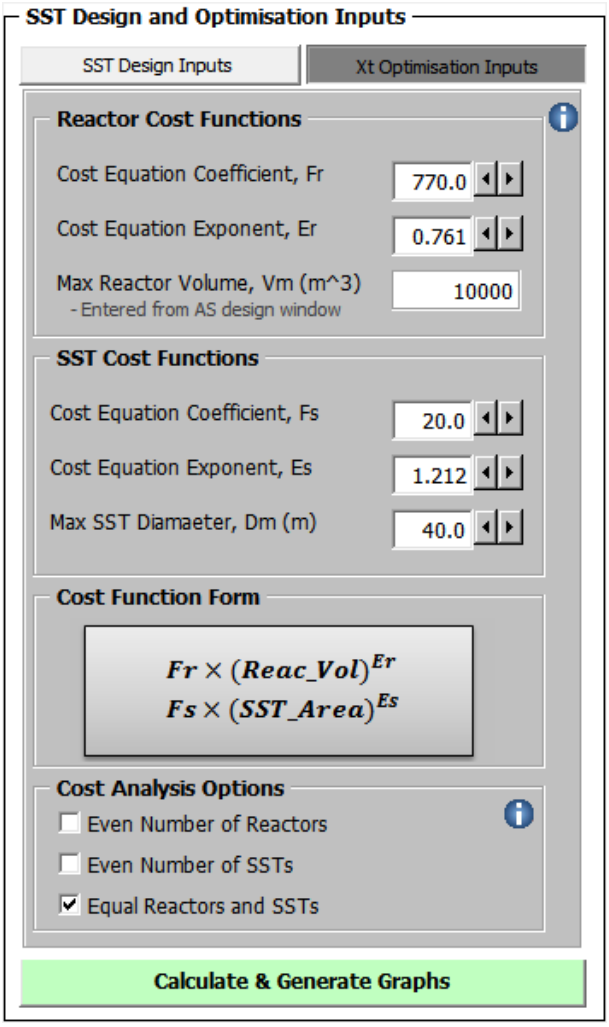



**Figure 6.35: $X_t$ Optimisation – Optimisation Inputs**

Due to the direct link between the $X_t$ optimisation model and the SST model, the inputs for the $X_t$ optimisation model are contained in the SST design window. The *Xt Optimisation Input* page is shown in Figure 6.35; this page is located in the *Design Inputs* section in the SST Design window. This page is only accessible if the *Optimise Xt* checkbox was selected in the AS design window. The inputs to the exponential cost function for the AS reactor and the SST, and the maximum AS reactor volume can be entered on the *Xt Optimisation Input* page. The maximum AS reactor volume would have been entered during the AS system design phase, therefore for consistency the AS reactor volume cannot be entered on the *Xt Optimisation Input*. The maximum AS reactor volume is automatically extracted from the AS design phase.

Three non-exclusive optimisation options for $X_t$ are available, indicated by the check boxes in Figure 6.35. These are: 1) even number of AS reactors; 2) even number of SSTs; and 3) equal number of AS reactors and SSTs. Any combination of these three can be selected. The combination specifies the number of AS reactors and SSTs required, which in turn affect the most cost-effective solution. The even numbers options will only consider an even quantity of

AS reactors or SSTs, unless only one unit is required, i.e. 1, 2, 4, 6, 8 etc. Deselecting this option will allow for odd and even quantities. The last option will only consider an equal amount of AS reactors and SSTs, i.e. symmetric AS-SST modules. It is important to note that the selection of these options only change the numerical restrictions allowed for the quantity of AS reactors and SSTs, which in turn affects the total cost of the AS-SST system; it does not change the total AS reactor volume or SST area required. The default coefficients in the AS and SST cost relationships are in no way intended to be realistic – realistic values depend on local economic conditions and construction industry costs. These are best provided by engineering consultancies and contractors.

The results from the $X_t$ optimisation are shown in the *Xt Optimisation* page in the *Design Summary* (Figure 6.36). This page shows the optimum $X_t$, total and individual AS reactor volume, and the total and individual SST area; the cost of the AS reactors and SSTs (in 1000s) are also displayed. The results page also contains the *Total Cost to Xt Graph*. The optimum $X_t$ in this example is 6.7 gTSS/L, giving 2 AS reactors and SSTs of 5685 $m^3$ and 1131 $m^2$ (diameter = 37.95 m) each for a total of 11370 $m^3$ and 2262 $m^2$. These results are for the settled MLE system in Section 6.1.1 and the DSVI and cost inputs in the Figure 6.31 and Figure 6.35.

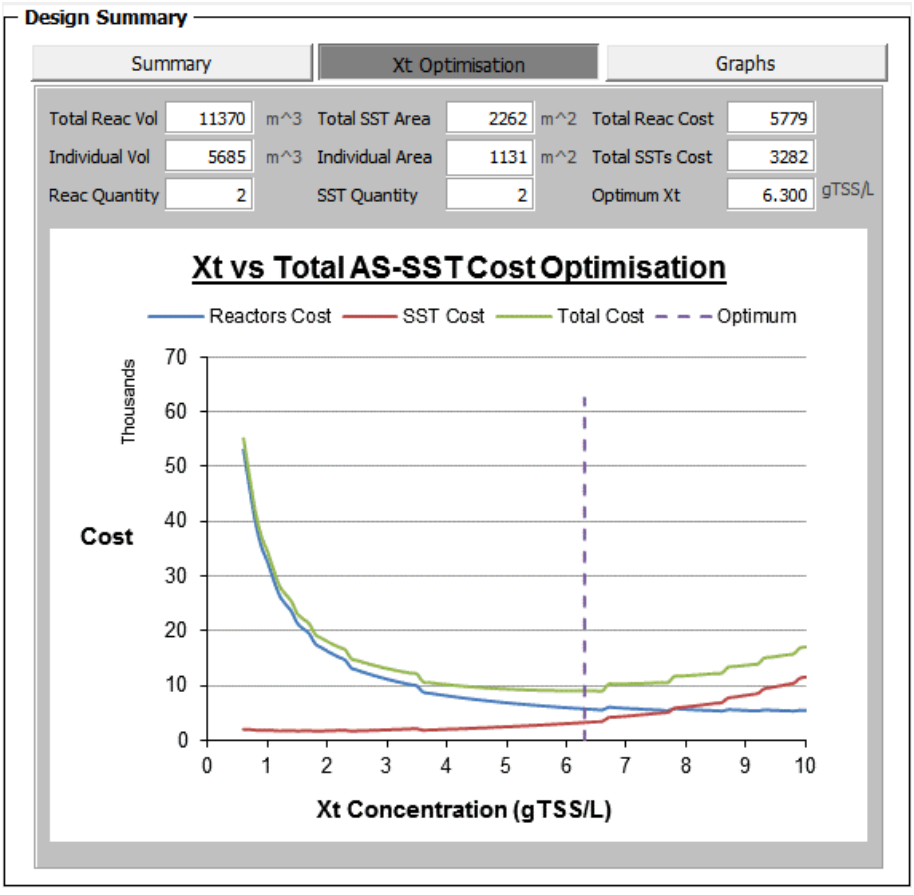



**Figure 6.36: $X_t$ Optimisation – Optimisation Summary and $X_t$ vs Total AS-SST Cost Optimisation graph**

### 6.2.4 Membrane Bioreactor

The use of membrane bioreactors is becoming more and more popular. They mitigate the need for the area-intensive SSTs and allow for high AS reactor MLSS concentrations. Negatively though, MBRs have high operational complexity, are prone to fouling if not maintained correctly, and have high capital costs and aeration energy costs if operated at high reactor TSS concentration. Nevertheless, the novel MBR technology is attractive and its usage is increasing. MBRs are not available in the PWSSD program; however, it is planned for in future editions.

In terms of the design of MBR system, the only changes required for the AS system design concerns the calculation of the process volumes. In the traditional AS system, the total particulates concentration ($X_t$) is selected for the AS system. The influent organic load and the sludge age (SRT) determine the sludge mass produced ($MX_t$), the recycle ratios and the selected $X_t$ then determines the volume requirements. As investigated by Ramphao *et al*. (2005), with an MBR system, this design procedure changes; the anaerobic, anoxic and aerobic sludge masses are selected to provide adequate N and P removal as usual; the PWWF then determines the membrane surface area required, which in turn fixes the aerobic reactor volume to contain these membranes (whether flat sheet or tubular). Then from the anaerobic, anoxic, and aerobic mass fraction, the anaerobic and anoxic volumes are fixed. With the AS reactor volume known, the SRT is then calculated to provide sufficient sludge mass production so that an adequate $X_t$ can be supplied for the MBR.

The membranes require course-bubble aeration for scouring to maintain their operating flux. If the oxygen transfer rate (OTR) of the course-bubble aeration system is insufficient to supply the peak biological oxygen demand (OD), additional fine bubble aeration systems will be required for the aerobic reactor to increase the OTR. This increases the aerobic reactor volume and hence also the anoxic and anaerobic reactor volumes (Ramphao *et al*., 2005). Therefore, with MBR systems, either the PWWF or the peak OD fixes the reactor volume.

### 6.2.5 Comments and Conclusion

The solid-liquid separation process is an integral part of the WWTP. If the secondary settling tank or membrane system is designed and operated correctly then the effluent quality, in terms of suspended solids, will be sufficiently low. For primary settling tanks, these drastically change the treatment schemes; this can be seen in the outputs of the PWSSD models. Raw wastewater systems typically have much longer sludge ages, reactor volumes, and oxygen demand. In contrast, settled WW systems have shorter sludge ages, smaller reactor volumes and lower oxygen demand, but are complex to operate due to the PS anaerobic digester.

When SSTs are used in the system, the process capacity of the AS system is largely dictated by the capacity of the SST. Furthermore, for a WWTP that receives an influent with strong diurnal variations and a high PWWF to ADWF factor, the capacity of the SST has to be significantly increased to accommodate the high PWWF. Equalizing (balancing) the diurnal

flow variation has a major impact on the hydraulic flow through the AS-SST system, reducing the peak oxygen demand and the surface area of the secondary settling tanks. Thus it is recommended to consider flow balancing tanks that equalise the influent flow in the WWTP design. Most of the variation in concentrations in the AS system, in particular the effluent ammonia concentration, are induced by the diurnal hydraulic variation, very little is induced by the dynamics of the bioprocesses themselves. Flow-balanced AS systems therefore allow for a more stable and simpler AS operation because the biological processes are not negatively affected by continuously changing organic and hydraulic loads. In considering this point, a balancing tank model has been included in the program. This is presented in Section 6.4.1.

For the purpose of steady-state design, the 1DFT is acceptable in determining the minimum SST area required, if the WWChar process was completed correctly and with sufficiently accurate input data. It is important to note that the 1DFT is incapable of predicting the ESS and SST depth. If this is required then CFD models should be used, although these also have their weaknesses for predicting the absolute effluent suspended solids (ESS) and return activated sludge (RAS, i.e. underflow) concentrations (Marais & Ekama, 2004)

Membrane systems can replace the SSTs; however, these systems have disadvantages and very specific operating requirements, some of which might not be the best choice for the particular design scenario. The membrane models are not yet available in the program; the inclusion of these models will not change the structure of the PWSSD component.

## 6.3 WAS and PS Digestion Models

Sludge treatment is an important unit process because the biodegradability of the sludge often needs to be reduced before it can be discharged to the sludge drying beds. Accompanying the activated sludge (AS) models are anaerobic digestion (AD) and anoxic-aerobic digestion (AxAeD) models, which are used for the modelling of the primary sludge (PS) and waste activated sludge (WAS) treatment systems.

Different options for WAS and PS treatment are available to the designer. The available options will depend on the chosen plant-wide system configuration. If a primary settling tank (PST) is included in the plant-wide system, then the PS generated from the PST must be treated with AD. For the WAS, unless an extended aeration system is selected, the WAS can be digested with AD or AxAeD. Mixing of the PS and WAS is allowed, but mixing is not available for a raw WW system (no PST therefore no PS available) or for an extended aeration system (no WAS treatment). AxAeD of PS is not provided for because of the high energy costs – it is better to treat raw WW or consider dual (aerobic-anaerobic) digestion of PS if disinfection is required (Messenger *et al*., 1993). Considering this inefficiency, the mixed WAS + PS can only be treated with AD. Two mixing options are allowed, complete or partial; their availability will depend on the digestion system selected for the PS and for the WAS. For complete mixing, the entire WAS flow is mixed with the PS flow. For partial mixing, only a

percentage of the WAS flow is mixed with the PS; this percentage is chosen by the designer. Table 6.7 summarises the treatment and mixing options. The different sludge mixing options are not separate steady-state models. To provide all the options above, one AxAeD model and two AD models are required: one AD model for PS, one AD model for WAS. If complete mixing or partial mixing of WAS and PS is selected, the AD of PS and AD of WAS models are computed separately and their results are combined.

However, although the options are made available, it is not recommended to anaerobically digest WAS (with or without PS). The main considerations for not anaerobically digesting WAS is the slow hydrolysis rate of the WAS biodegradable organics and the high N and P contents of the dewatering liquor. The WAS hydrolysis rate is slower than PS, thus the AD retention time (HRT or $R_h$) required to achieve good %VSS removals is longer than for PS. Therefore, when anaerobically digesting PS and WAS together, the PS is digested at a longer retention time than required. Furthermore, when anaerobically digesting PS, because the PS has low N and P contents, the N and P concentrations in the dewatering liquor from the digested PS are also low. This allows the dewatering liquor to be returned to the head of works. The N and P content of WAS is much too high to do this, especially with NDBEPR WAS which typically has a very high P content. This occurs even if the WAS is mixed with the PS.

The AxAeD and AD digester design is discussed further.

**Table 6.7: PS and WAS Treatment Options**

| Treatment option | | Available mixing options | | |
|---|---|---|---|---|
| PS | WAS | Completely mixed | Partial mixing | Separate (no mixing) |
| AD | AD | Yes | No | Yes |
| AD | AxAeD | No | Yes | Yes |
| None (raw WW) | AxAeD | No | No | Yes |
| None (raw WW) | AD | No | No | Yes |
| None (raw WW) | None (extended aeration) | No | No | No |

### 6.3.1 AxAeD of WAS

Following the procedure of Ekama *et al*. (2006b), a steady-state anoxic-aerobic digestion (AxAeD) model was developed for the digestion of WAS from a nitrification denitrification biologically enhanced phosphorous removal (NDBEPR) system. There are two biodegradable biomass groups in the NDBEPR WAS (OHOs and PAOs). These two are treated separately in the AxAeD model. Once the AxAeD model for each biomass group is computed, the results are

combined. For ND only systems, the PAO components in the AxAeD model are set to zero. In the AxAeD model, the following principles apply (Mebrahtu, 2007):

1. The unbiodegradable particulates ($X_{ui}$), the fixed inorganic particulates ($X_{Ioi}$), and the unbiodegradable soluble COD ($S_{usi}$) from the influent wastewater do not undergo any degradation or participate in any bioprocesses in the aerobic digestion. Similarly, the endogenous residue generated in the AS reactor ($X_{EH} + X_{EG}$) do not partake in AxAeD.
2. The active biomass (OHOs and PAOs) undergo endogenous respiration (which leads to).
3. The generation of additional unbiodegradable particulates (new endogenous residue).
4. Due to the loss of active biomass, a decrease in the ISS concentration associated with the OHOs and PAOs is observed.
5. The release of FSA, OP, and polyP counter-ions (Mg, Ca, K)
6. The utilisation of oxygen for the endogenous respiration process, the nitrification of the released FSA, and denitrification of produced nitrate during air off periods.

Figure 6.37 shows the AxAeD of WAS design window. This window is organised into three frames: 1) *Design Options* (**A**), 2) *Design Window* (central frame, **B**), and 3) *Design Guidance* (**C**). The *Design Options* and *Design Window* frames are the main frames that allow for interaction with the WAS AxAeD model, they are discussed in more detail in this section.

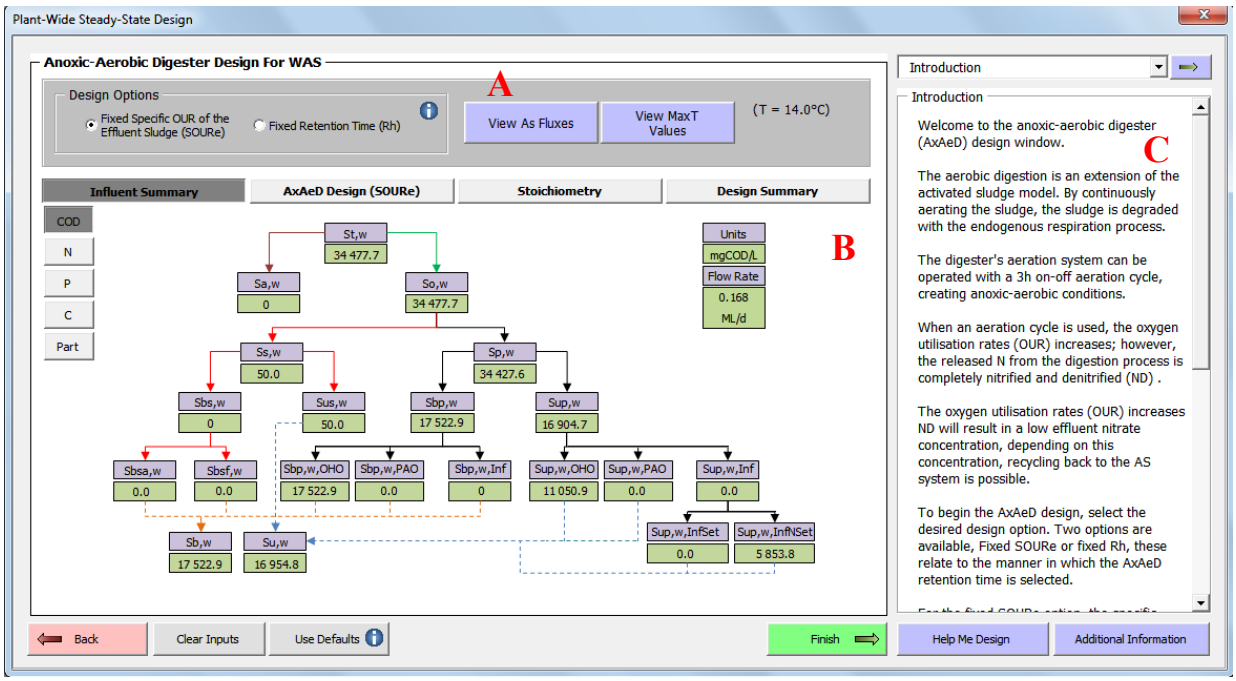



**Figure 6.37: AxAeD WAS Design**

In the *Design Options* frame (**A**), the designer can select the design scheme for the AxAeD design. Two options are available: *Fixed Specific OUR of the Effluent Sludge (SOUR$_e$)* or *Fixed Retention Time (HRT or $R_h$)*. These options pertain to how the retention time (HRT or $R_h$) of the anoxic-aerobic digester is calculated. Note that for the digesters (AxAeD and AD), the system is modelled as a completely mixed, flow-through system, thus the hydraulic retention time (HRT or $R_h$) is the same as the solids retention time (SRT or $R_s$).

For the first design option, the designer specifies the SOUR$_e$. The SOUR$_e$ is a measure of the biodegradability of the effluent sludge in terms of mgO/(gVSS.h); the lower SOUR$_e$ the more stable the sludge, however a longer AxAeD HRT is required. By specifying the SOUR$_e$, the designer indirectly determines the HRT required for the AxAeD. The US sludge guidelines recommend a SOURe < 1.5 gO/(gVSS.hr), which is interpreted in the PWSSD model to include nitrification. The HRT to achieve the specified SOUR$_e$ is calculated using a goal seek solver, much like in the ND optimisation part of the AS models. The SOUR$_e$ (which gives HRT), along with the AxAeD inputs such as the number of AxAeD in-series and the influent thickened WAS concentration, affects all the outputs of the AxAeD model; hence, it is a fundamental input for the AxAeD. The second design option allows the designer to select the HRT. This option is provided to give retention time selection to the designer because (i) while all the PolyP is released from the PAOs in 20 days, (ii) only half of the PAO biomass is digested in 20 days due to their slow endogenous respiration rate. Thus, this design option is useful if the designer has a specific HRT in mind. The selected HRT will calculate the SOUR$_e$ and determine the AxAeD performance (outputs).

The *Design Window* frame (**B**) contains multiple pages, each dealing with a particular aspect of the design. The pages in order are (1) *Influent Summary*, (2) *AxAeD Design*, (3) *Stoichiometry,* and (4) *Design Summary*. The *Influent Summary* page (1) contains the influent WAS block diagram, see Figure 6.37 above. This block diagram shows influent sludge characteristics to the AxAeD, i.e. the thickened effluent WAS concentrations from the WAS thickener. The WAS fluxes can be viewed by clicking on the *View AS Fluxes* button next to the *Design Options* frame (**A**).

The *AxAeD Design* page (2) follows the *Influent Summary* page. This page allows for the inputs to the AxAeD model to be entered (at **D**), such as the SOUR$_e$ (for the fixed SOUR$_e$ option), the HRT (for the fixed HRT option), the number of in-series digesters (N), and the WAS thickening concentration. Figure 6.38 on the next page shows the *AxAeD Design* for the fixed SOUR$_e$ option. The AxAeD design was completed for the MLE system provided in Section 6.1.1. For the fixed HRT option, the only difference is the SOUR$_e$ input is unavailable and is replaced by an input for the HRT. Note that this HRT input is for each digester in series, the total HRT is therefore the entered HRT multiplied by the number of digesters in series. Depending on the volume of the digesters and the maximum permissible AxAeD volume, the in-series digesters may need to be modularised, i.e. split into parallel in-series digesters. This modularisation function is done on the Cost and Modularisation window (Section 6.4.4).

The *%WAS Flow to the PS AD* input is located at the bottom of the *AxAeD Design* page. This input allows for a percentage of the WAS flux to be sent to the PS. Note that it is only made available if the partial mixing option is selected. For separate WAS and PS digesters, the %WAS Flow to the PS AD is 0%. If AD of mixed WAS + PS is selected, it is imperative that the designer increase the AD retention time of the mixed WAS + PS digester, this is to take account of the slower hydrolysis rate of the WAS in the AD. For NDBEPR WAS, AD should only be used for the treatment of the WAS if (i) the dewatering liquor is treated for N and P removal before return to the inlet works and (ii) struvite precipitation is catered for because with the high P content of the NDBEPR WAS will precipitate as struvite in the anaerobic digester and sludge treatment pipework.

Also on the *AxAeD Design* page is the *Design Preview* frame located on the right (**E**). This frame displays items relevant to the AxAeD design. Items are displayed for the first digester and last digester in series, and (if applicable) for all the digesters combined. The items include the effluent active fraction w.r.t to VSS ($f_{ave}$) and TSS ($f_{ate}$), the effluent VSS ($X_{ve}$) and TSS concentrations ($X_{te}$), the oxygen utilisation rate ($OUR_{td}$) and oxygen flux ($FO_{td}$) in the first, last, and all digesters combined, and the $SOUR_e$ from the last digester. The $OUR_{td}$ has been increased by 50%. Warner *et al*. (1986) showed that an intermittently aerated digester, 3h on/off, could provide complete nitrification/denitrification. This was confirmed by Mebrahtu (2007) from measurements on aerobic batch digestion tests and a continuous aerobic digester.

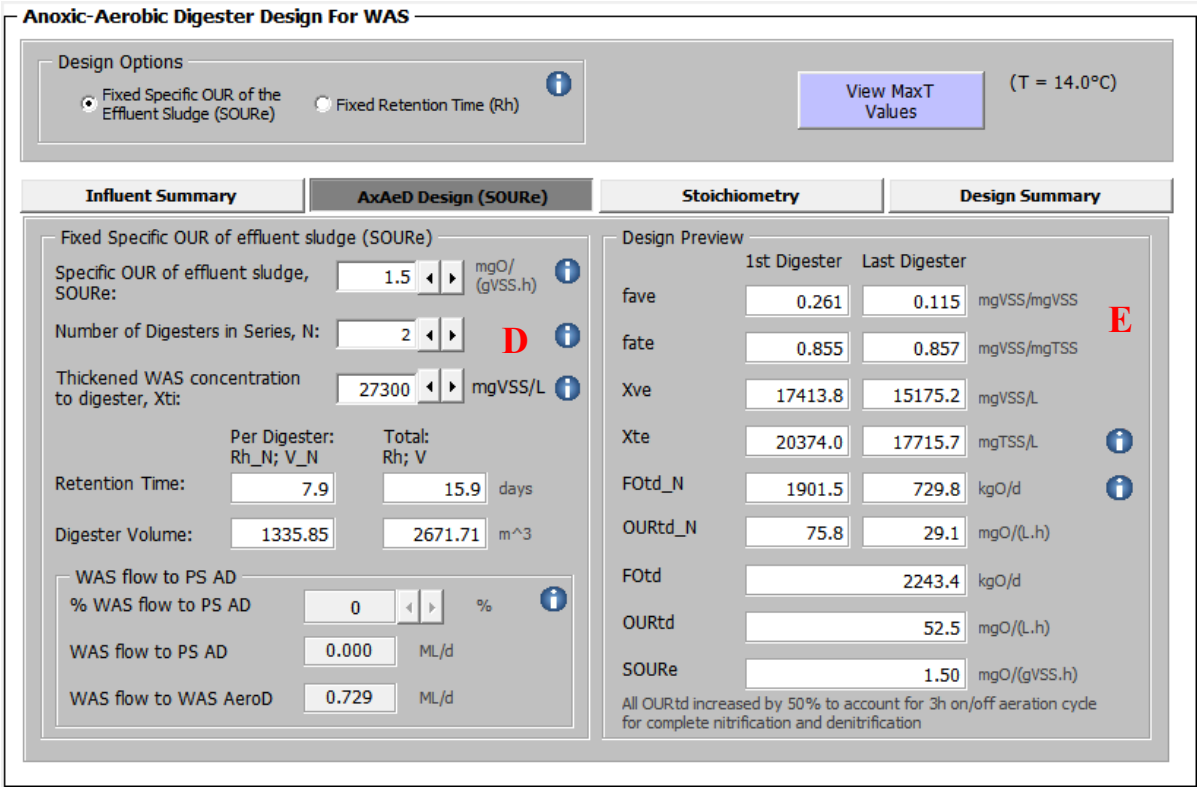



**Figure 6.38: AxAeD WAS Design – Design Option 1 (Fixed SOURe)**

Adjacent to the $X_{te}$ and $FO_{td}$ items are Blue Info buttons that will display a breakdown of the selected item. For example, the Blue Info button for the $X_{te}$ will display a breakdown of the composition of the $X_t$ (before and after thickening, and in the effluent of the first and last digester). Figure 6.39 shows the $X_t$ breakdown window. The PAO items are set to zero because of the absence of PAO biomass. Orange Info buttons are displayed on the *AxAeD Design* page if any potential design problems occur, e.g. an $OUR_{td}$ in the first reactor that is too high.

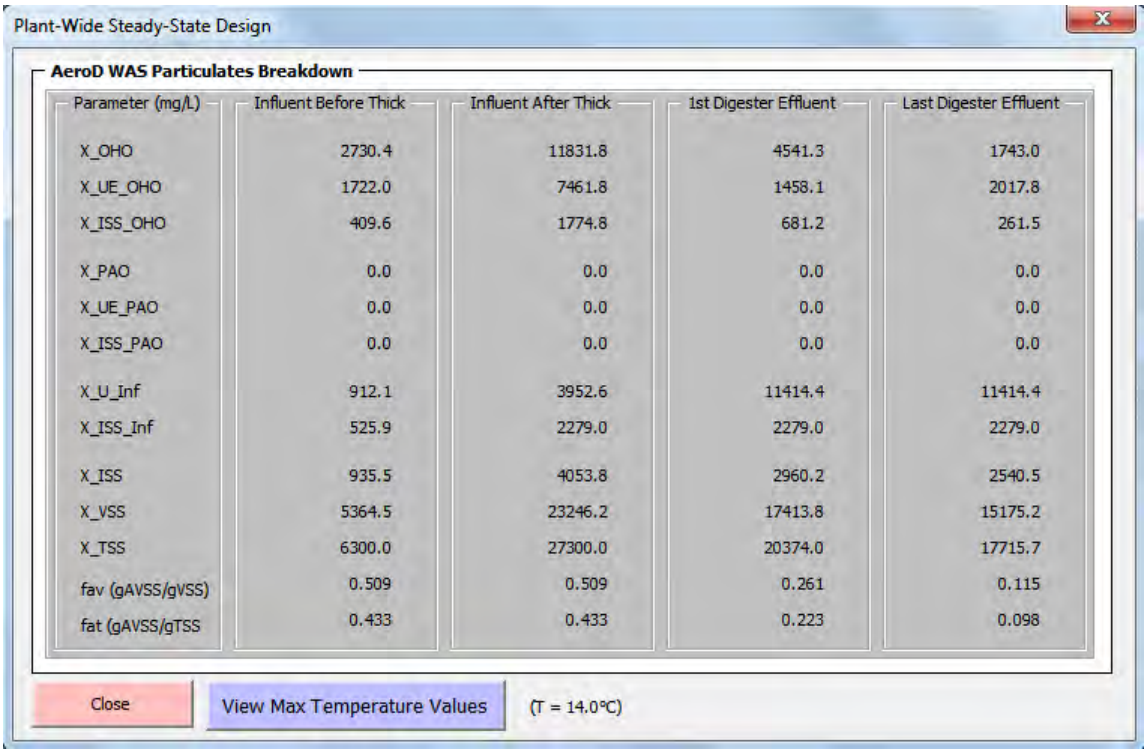



**Figure 6.39: AxAeD WAS Design – Xt Breakdown**

The *Stoichiometry* page (3), shown in Figure 6.40 on the next page, follows the *AxAeD Design* page. On this page, the bioprocess stoichiometry describing the AxAeD of the WAS is provided. The stoichiometry is available for complete nitrification and for complete nitrification + denitrification, and is obtained from Ekama (2009). The stoichiometry is important as it allows for complete tracking of the CHONP elements, and hence, an elemental mass balance of the plant-wide system. For NDBEPR WAS, the OHOs and PAOs have the same bioprocess stoichiometric equations, only for PAO polyP ($Mg_{0.27}K_{0.22}Ca_{0.12}PO_3$) is added.

The *Design Summary* page (4) is the last page in the WAS AxAeD design window and it contains all the necessary model outputs displayed in relevant frames: *General*, *Oxygen Demand*, *Effluent Solids*, *Effluent Particulates*, *Effluent Soluble*, *Sludge Stability*, and *Gas Production*. With reference to the *Design Summary* page, shown in Figure 6.41 on the next page, the polyP release during the AxAeD of NDBEPR WAS is discussed further.

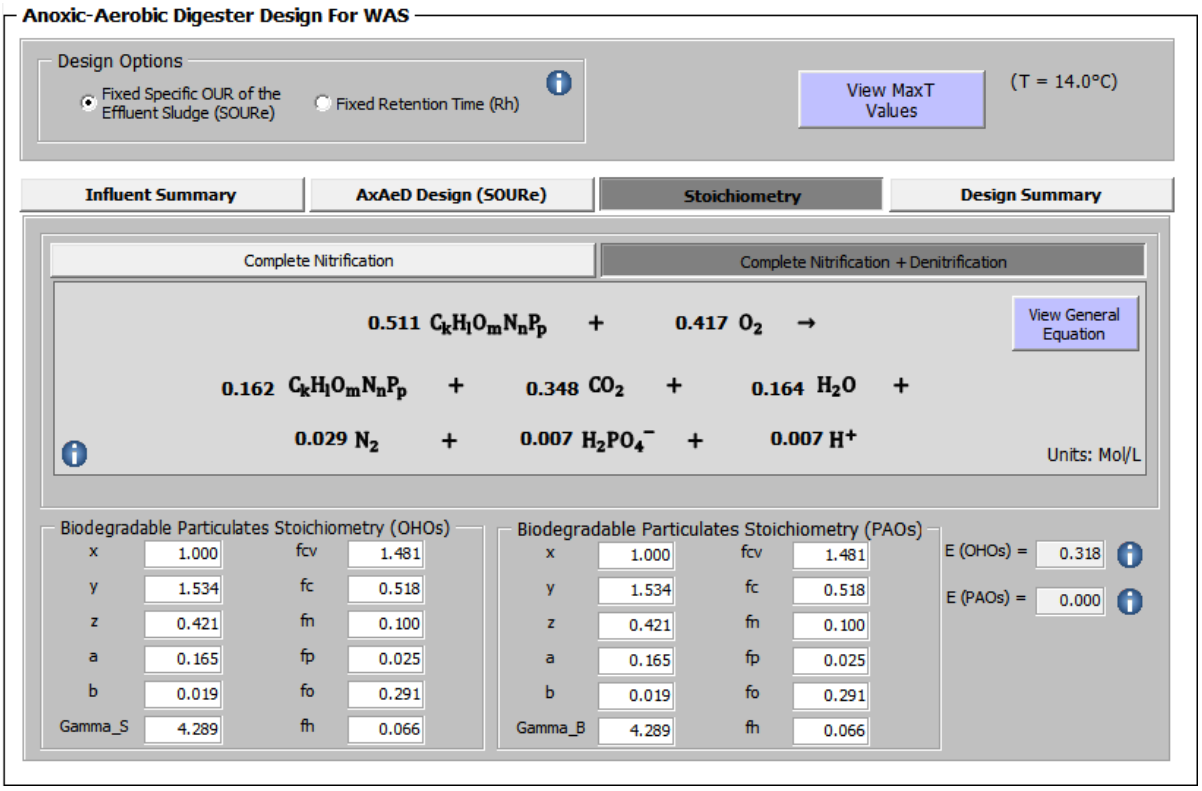



**Figure 6.40: AxAeD WAS Design – Stoichiometry**

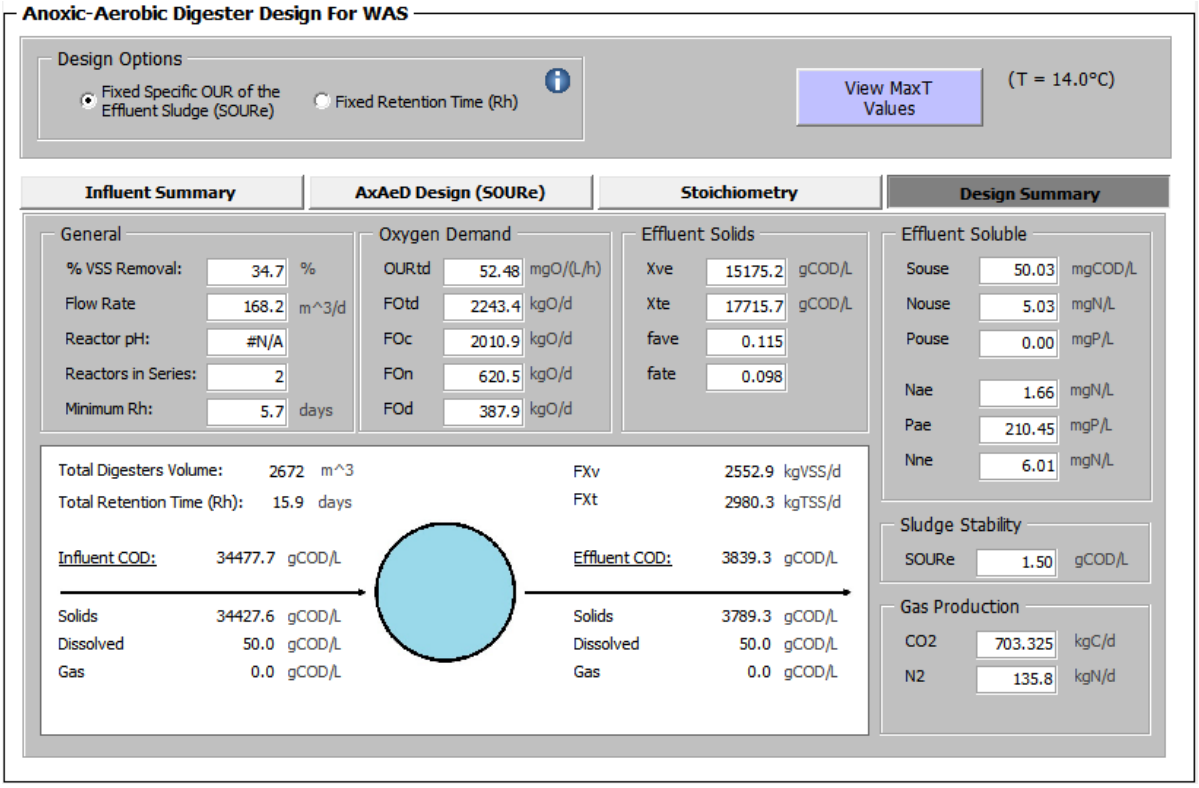



**Figure 6.41: AxAeD WAS Design – Design Summary**

Mebrahtu (2007) assumed that during the endogenous respiration of the PAOs, the stored polyP is released at the same rate as their endogenous respiration, and subsequently, mineral precipitation of the released P, Mg, and Ca occurs. This can be taken into account in the stoichiometric equations; however, the modelling of mineral precipitation is not an easy task and the research of this aspect is not complete. Vogts & Ekama (2015) showed experimentally that polyP is released 2.5 times faster than the PAO endogenous respiration rate so that after 20d aerobic digestion virtually all the polyP was released but only about half the PAO biomass digested. So in this first version of PWSSD to keep the stoichiometry simple, the cell-mass P (OrgP of the PAO and OHO) and polyP released at the same rate as their endogenous respiration rates is considered but mineral precipitation from this polyP release is not included in the stoichiometry. While of course not accurate, to some extent, releasing polyP at the PAO endogenous respiration rate compensates for mineral precipitation.

In the WAS AxAeD model, because it is assumed that no mineral precipitation takes place in the digester, all the P in the digester effluent is soluble P (in the form of OP, mgOP-P/L), therefore the effluent OP concentration ($P_{ae}$ in Figure 6.41) will be high. For a thickened WAS concentration greater than 2%, the $P_{ae}$ can be greater than 200 mgOP-P/L; in Figure 6.41, with an influent 2.73% TSS, the $P_{ae}$ concentration for the digested MLE (ND) WAS is 210.45 mgOP-P/L. If it was NDBEPR WAS, the $P_{ae}$ will be much higher (up to 500 mgP/L). For the balanced UCT system discussed in Section 6.1.2, with the same WAS AxAeD model inputs (2.73% TSS, $SOUR_e$ of 1.5 mgO/gVSS/h and 2 digesters in-series), the $P_{ae}$ is 488.23 mgOP-P/L. The $P_{ae}$ concentration is directly linked to the thickened WAS concentration. By increasing the thickening concentration, the $P_{ae}$ is concentrated due to the lower flow rate but has the same total P flux (kgP/d). For example, if 4.5% TSS were used then the $P_{ae}$ would be 341.2 mgOP-P/L for the MLE (ND) WAS, or 917.2 mgOP-P/L for the UCT (NDBEPR) WAS.

The assumption that no precipitation takes place for the AxAeD of ND WAS is acceptable, as the ND WAS will have low concentrations of Ca and Mg. However, for the AxAeD of NDBEPR WAS this is not ideal because the WAS contains concentrations of Ca and Mg conducive to mineral precipitation of calcium phosphate ($Ca_3(PO_4)_2$), calcium carbonate ($CaCO_3$) and struvite ($MgNH_4PO_4$) (Musvoto *et al*., 2000). A comparison of the modelled $P_{ae}$ and measured $P_{ae}$ for a continuous digester indicated that precipitation of the released P takes place and 1/3 of the released P was precipitated as struvite and calcium phosphate. Thus, only 2/3 of the expected released P was measured as OP (Mebrahtu, 2007). So releasing polyP at the PAO endogenous respiration rate compensates for mineral precipitation. Note that the released P cannot be fully precipitated because the constituent polyP ion (Mg, K, Ca) concentrations limits the mineral precipitation. For struvite and calcium phosphate (and calcium carbonate), this is magnesium and calcium respectively; Thus, to increase the quantity of precipitate, and hence a lower effluent OP concentration (<50 mgOP-P/L), calcium hydroxide can be dosed to the digester (Vogts & Ekama, 2015).

In terms of the modelling of the amount of mineral precipitation in the digester, this is currently absent in the AxAeD model. Ideally, in future editions, the WAS AxAeD model

should include an estimate of how much struvite and calcium phosphate is produced. This information can be displayed with the use of Blue Info buttons or additional items in the *Effluent Particulates* frame on the *Design Summary* page.

### 6.3.2 AD of PS, WAS, and WAS + PS

The steady-state anaerobic digestion (AD) model was developed according the steady-state AD model by (Sötemann *et al*., 2005a). Like the AxAeD model, the unbiodegradable particulate organics ($X_u$) and the fixed influent inorganic particulates ($X_{Ioi}$) do not undergo any degradation or bioprocesses in the anaerobic digester. There are three parts to the steady-state AD model:

1) A kinetic hydrolysis part that determines the %COD removal and methane ($CH_4$) gas production for the selected HRT.
2) A stoichiometric part that determines the gas composition in terms of partial pressure of $CO_2$ ($pCO_2$).
3) A carbonate system weak acid base (A/B) chemistry part that calculates the digester pH from the $pCO_2$ and the alkalinity generated during the AD process.

Two steady-state AD models are available in the program, one for the digestion of PS and one for the digestion of WAS. Both models are identical in terms of structure and equations, the only difference being the input sludge type, its compositions, and the hydrolysis rates. Mixing of the WAS and PS is accounted for in the program. For the AD of mixed WAS and PS (AD WAS + PS), the AD PS and AD WAS models are computed separately, the results (converted to fluxes) from the individual models are then combined to form the results for the AD PS + WAS model. The mixed WAS and PS digester is one system, thus the AD WAS and AD PS model will have the same sludge age (SRT, i.e. HRT or $R_h$) input and the same flow rate (WAS + PS). The AD model for the WAS can be used for digestion of ND WAS or for the digestion NDBEBR WAS. For NDBEPR WAS, AD is not recommended due to the complete release of polyP from the P rich NDBEPR WAS within 5 days (Harding, 2009), which results in high quantities of mineral precipitates in the digester.

A problem exists with the connection of the activated sludge (AS) model to the WAS AD model in that the outputs of the AS model ($X_t$, $X_v$, $X_{BH}$, $X_{EH}$, $X_u$ etc.) are incompatible inputs to the WAS AD model. The steady-state AD model by Sötemann *et al*. (2005a) requires the biodegradable organic inputs to be measured in mgCOD/L. Thus, to obtain compatibility, the particulate organics in the WAS ($X_{BH}$, $X_{EH}$, and $X_u$ measured as mgVSS/L) need to be converted to a COD concentration (mgCOD/L). To do this, each particulate organic group is simply multiplied by its $f_{cv}$ mass ratio (VSS/COD). For the OHO and PAO biomasses this is 1.481 mgVSS/mgCOD; for the influent settleable and non-settleable UPO ($X_{u,Inf,Set}$ and

$X_{u,Inf,NSet}$), their $f_{cv}$ mass ratios were determined during the WWChar phase. Note that because the AD WAS model does not account for the endogenous residue fraction of the OHOs ($f_{EH}$ = 0.20) and the PAOs ($f_{EG}$ = 0.25), before the OHOs and PAOs are divided by their $f_{cv}$ mass ratios, the $X_{BH}$ (OHO) and $X_{BG}$ (PAO) concentrations are reduced by $f_{EH}$ and $f_{EG}$ respectively. Concurrently, the total UPO concentration in the WAS is increased by $f_{EH} \times X_{BH}$ and $f_{EG} \times X_{BG}$. The reduced OHO and PAO biomasses, comprising only biodegradable organics, can then be multiplied by their $f_{cv}$ mass ratios, which is then the biodegradable COD source ($S_{bp}$) for the acidogens ($Z_{AD}$) in the WAS AD model. This approach is permissible because, as shown by the literature (see Section 2.1.3), the unbiodegradable organics in the influent wastewater and the waste activated sludge from fully aerobic, N removal systems, and BEPR systems, remain unbiodegradable in anaerobic systems (Ikumi *et al*., 2014).

Figure 6.42 shows the AD PS design window. The layout of this design window is similar to the AxAeD design window and consists of three parts: 1) *Design Inputs* (**A**), 2) *Design Window* (**B**), and 3) *Design Guidance* (**C**). The user-interfaces for the AD PS, AD WAS and AD WAS + PS are identical in structure, however, for the AD WAS and AD WAS + PS design windows, there are a few additional inputs regarding the thickening of the WAS and the mixing quantity of the WAS and PS. The AD PS design window is primarily discussed in this section as the other two design windows are based on the AD PS design window. The user-interface displayed for the designer will depend on the configuration of the digestion system and the selection of the mixing options: the AD WAS and AD PS user-interface is displayed if separate sludge digestion is selected, AD WAS + PS is displayed for partial or complete mixing. The AD WAS design window is not available if AxAeD WAS is selected.

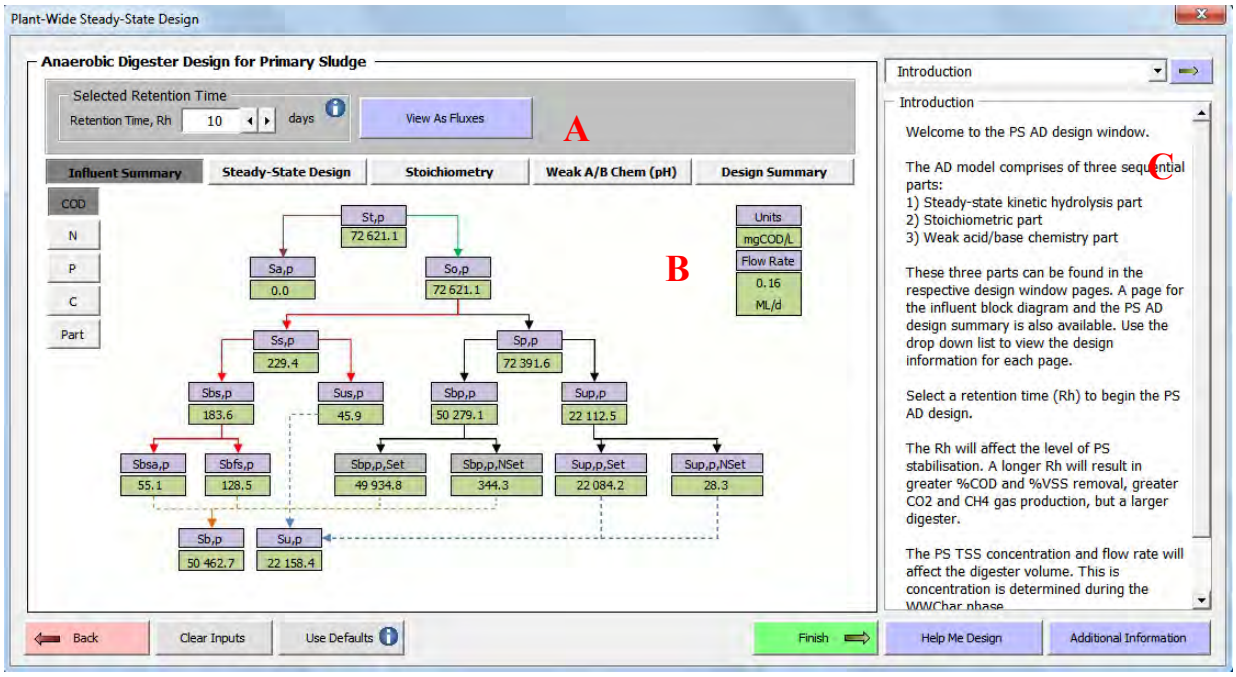



**Figure 6.42: AD PS Design**

As with the AxAeD WAS design window, see Figure 6.37, the *Design Window* section on the AD PS design window (Figure 6.42) contains different pages. These in order are the (1) *Influent Summary*, (2) *Steady-State Design*, (3) *Stoichiometry,* (4) *Weak Acid/Base Chemistry,* and (5) *Design Summary*. Figure 6.42 on the previous page shows the PS AD design window with the *Influent Summary* page (1) displayed. Here the block diagram for the FWA concentrations of the influent PS is shown, the *View Fluxes* button displays the characteristics as fluxes in kg/d.

The *Steady-State Design* page (2) shows the quantitative outputs from the kinetic hydrolysis part of the AD model. The only input for the AD model is HRT, this is located in the top frame (*Design Inputs*, **A**). A change in the HRT input will automatically update the steady-state results. Figure 6.43 below shows the *Steady-State Design* page (2). This page consists of three frames: *Influent*, *Reactor*, and *Effluent*. Note that all concentrations are displayed as gCOD/L of influent.

For the hydrolysis rates ($K_s$ and $K_m$) used in the AD PS model, these are 3.76 gCOD/L ($K_s$) and 3.34 gCOD/gCOD biomass/d ($K_m$) – obtained from (Ikumi *et al*., 2014b). These rates can be changed on the defaults spreadsheet.

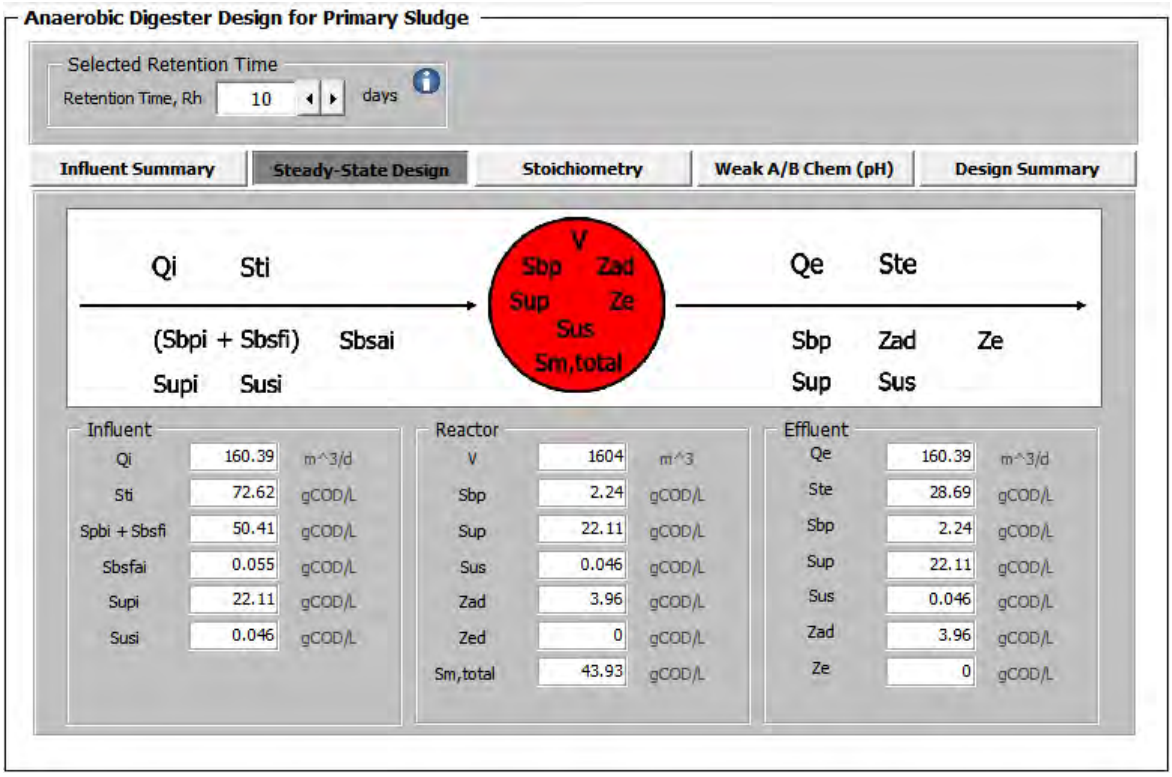



**Figure 6.43: AD PS Design – Steady-State Design**

Following the *Steady-State Design* page is the *Stoichiometry* page (3), which is shown in Figure 6.44. The *Stoichiometry* page (3) displays the stoichiometric part of the AD model. There are three pages on the *Stoichiometry* page: *Acidogenesis Process*, *Methanogenesis Process*, and *Total (Acidogenesis + Methanogenesis*). The stoichiometric equations for each process are displayed on each page. Note that in the Sötemann *et al*. (2005a) steady-state AD model, the stoichiometric equations did not include the phosphorous (P) element. P was subsequently added by Ekama (2009) and thus the stoichiometric equations used are obtained from Ekama (2009) – but the overall structure of the AD model follows closely to Sötemann *et al*. (2005a).

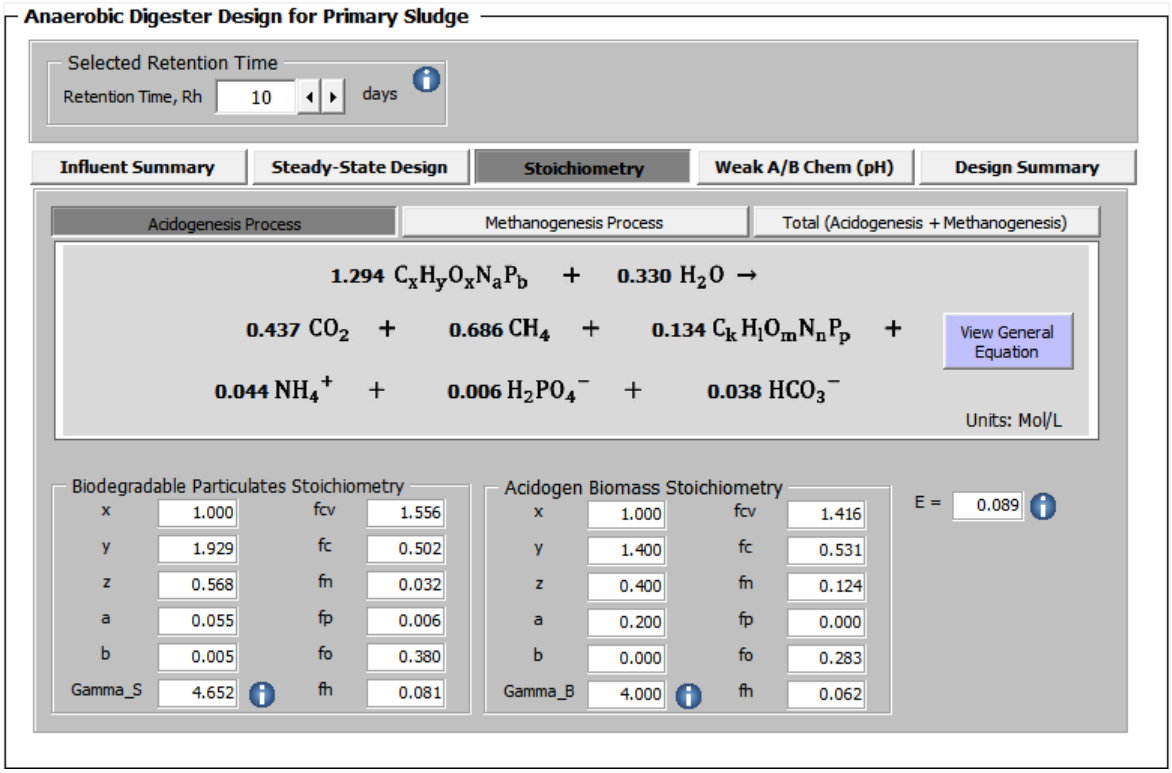



**Figure 6.44: AD PS Design – Stoichiometry**

Figure 6.45 shows the *Weak Acid Base (A/B) Chemistry* page (4). On this page, the pH predicted by the AD model is shown. A graph for showing the relationship between the fraction $CO_2$ gas composition ($pCO_2$) and reactor bicarbonate alkalinity for different pH ranges (6.0 to 8.0) is shown. This graph and its underlying equation for the pH calculation is obtained from Sötemann *et al*. (Fig. 14, Eq. 31, 2005a). The equation to calculate the pH cannot be solved explicitly, thus a goal seek solver is used. The "normal" operating range for the AD ($6.5 < pH < 7.5$) is indicated with the red rectangle. The graph can be enlarged by hovering over the graph area and clicking on the enlarge button that will pop-up. The calculation of the pH is correct for low OP concentrations (<200 mgP/L), which will usually be the case for PS digestion.

However, at higher OP concentrations as with the digestion of ND or NDBEPR WAS, the OP system begins to decrease the pH due the $H_2PO_4^-/HPO_4^{2-}$ dissociation at a pH of 7. However, because WAS also has a higher N content, which increases the total alkalinity (mgAlk/L as $CaCO_3$) in the AD, the overall effect of digesting ND or NDBEPR WAS is a pH increase. This pH behaviour is not modelled in this version of the program but will be added in future editions.

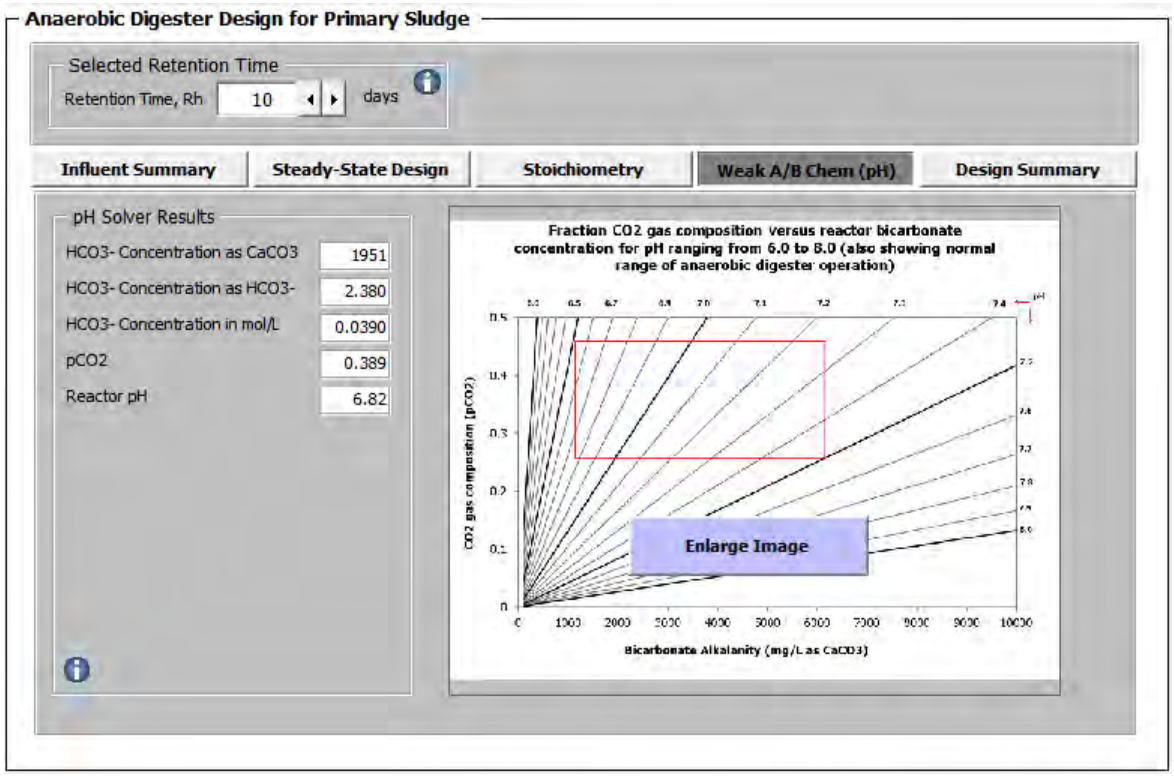



**Figure 6.45: AD PS Design – Weak A/B Chemistry**

The last page is the *Design Summary* page (5); this is shown in Figure 6.46 on the next page. Like the AxAeD WAS *Design Summary* page, important items from the outputs of the AD model are displayed. The most important item that the designer should take note of is the %COD and %VSS removal, these must conform the sludge stability guidelines that the designer is designing for. Also on this page is the gas production from the AD, this is represented in gCOD/L (for $CH_4$) and as ML/d (for $CH_4$ and $CO_2$). Avogadro's gas law is used to convert from the gas production in mol/L influent to a flux per L influent (ML/L influent). This is then multiplied by the influent flow rate to provide the total daily gas flux in ML/d.

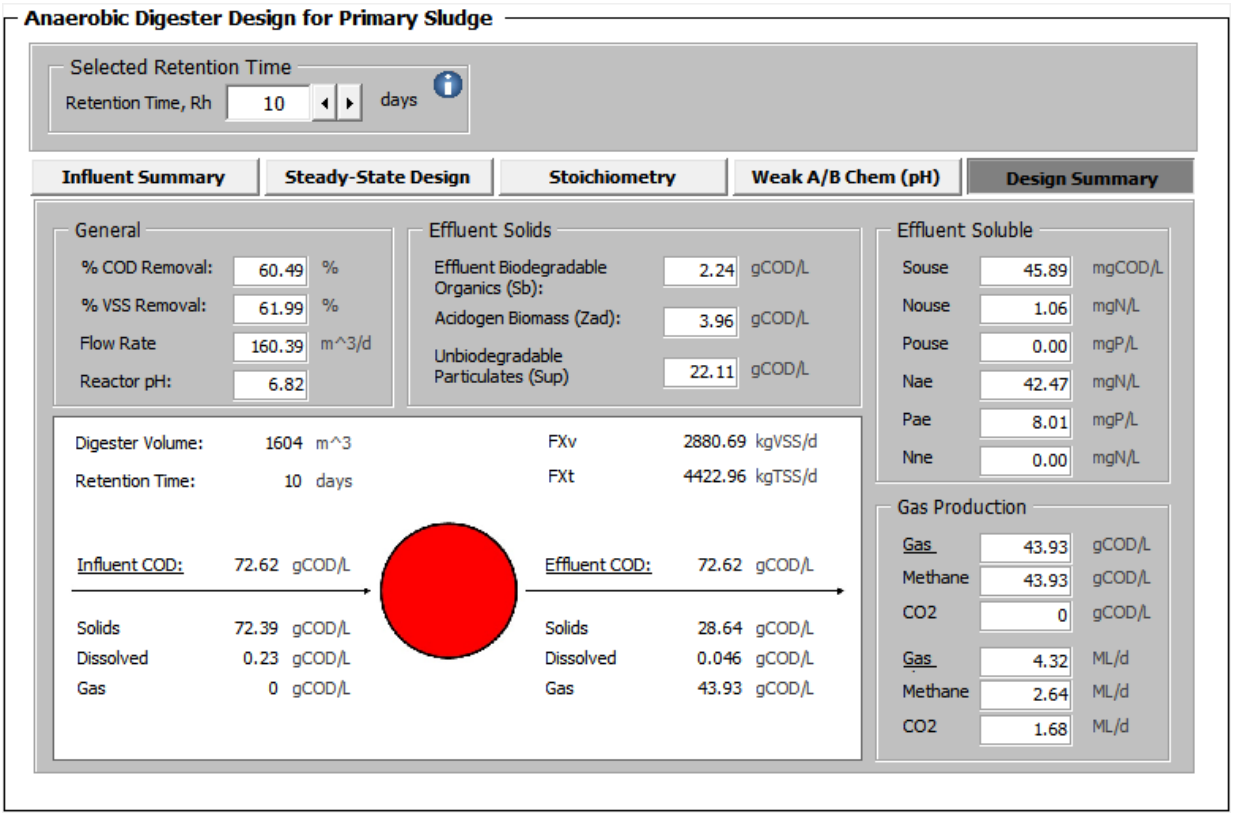



**Figure 6.46: AD PS Design – Design Summary**

The AD WAS and AD WAS + PS design windows have the same layout as the AD PS design window. Figure 6.47 on the next page shows the AD WAS window with the *Influent Summary* page activated. The AD WAS + PS design window is shown in Figure 6.48. Note that on the AD WAS + PS design window, the pages in the *Design Window* (*Influent Summary*, *Steady-State Design*, *Stoichiometry* etc.) contain pages for the combined and separate results of the AD PS and AD WAS model. In other words, the AD WAS design window contains the AD model, the AD PS design window contains the AD PS model, and the AD WAS + PS design window contains the AD WAS, AD PS, and the combined AD WAS + PS model.

There are a few points regarding the WAS thickening concentration input. For the AD WAS design window, the WAS thickening concentration is a required input. For the AD WAS + PS design window, if the complete mixing option is selected then the WAS thickening concentration is also a required input (this is the option shown in Figure 6.48). If the partial mixing option is selected, i.e. AxAeD WAS is selected, but a portion of the WAS flow is sent to the PS digester (AD WAS + PS), the WAS thickening concentration is not an available input on the AD WAS + PS design window, and must be specified on the AxAeD design window. This is because the WAS thickening concentration has a major impact on the design of the aeration system of the AxAeD, thus the WAS thickening concentration input is more important for the AxAeD WAS design than for the AD PS + WAS design. However, when considering

the AD system, the more concentrated the WAS (or PS) the better because it decreases heating requirements (saves gas/energy) and increase AD SRT (decreases flow). Thus it is beneficial to have the highest possible thickened WAS concentration for the partial mixing scenario.

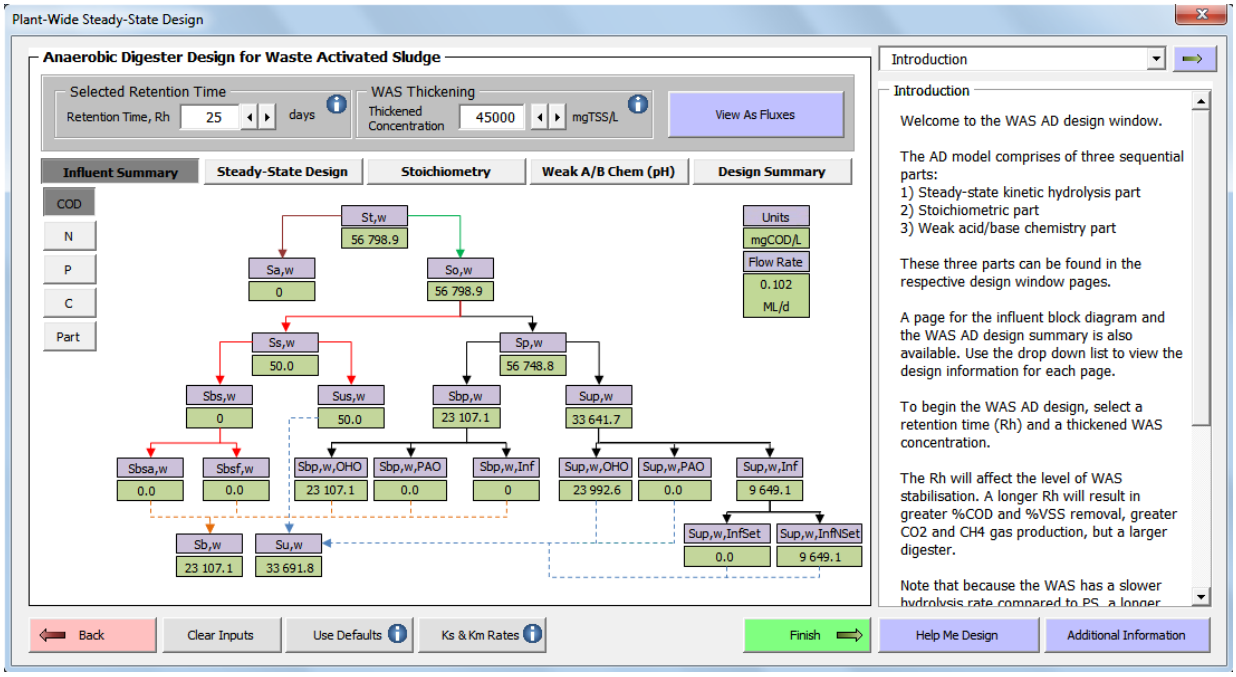



**Figure 6.47: AD WAS Design**

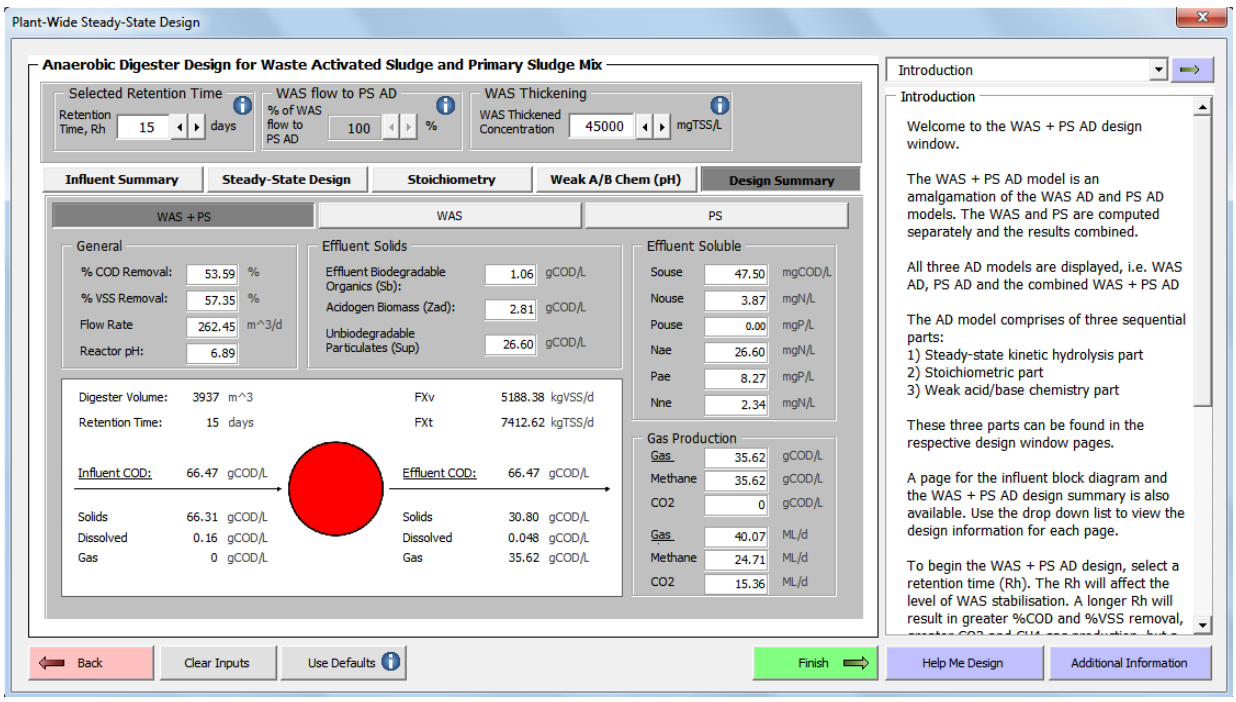



**Figure 6.48: AD WAS + PS Design**

For a partial mixing configuration (AxAeD WAS and AD WAS+ PS), the *% WAS flow to the PS AD* is an additional input on the AD WAS + PS design window. This percentage will determine the quantity of WAS mixed with the PS, i.e. the flux of WAS sent to the PS digester. The percentage must be between 0% and 100% for the partially mixed WAS + PS digester. The *% WAS flow to the PS AD* value will affect the %COD and %VSS removal. In interacting with the WAS + PS model, it was found that an increase in the *% WAS flow to the PS AD* value, i.e. more WAS sludge treated via AD, will decrease the %COD removal and also decrease the %VSS removal. The reason for this is due to the lower %Removals experienced in anaerobically digesting WAS, because of the slower hydrolysis rates. Therefore, by increasing the fraction of the WAS in the WAS + PS mix, the blended sludge's "overall" hydrolysis rate decreases; and thus for a specified retention time, the %COD and %VSS removal decreases. This decrease in VSS removal can be compensated for by increasing SRT. Note that for a completely mixed configuration (AD WAS + PS only), this percentage is 100% and cannot be changed.

The hydrolysis rates (Monod Kinetics, $K_s$ and $K_m$) used in the AD WAS model are 0.408 gCOD/L ($K_s$) and 2.049 gCOD/gCOD biomass/d ($K_m$) for the ND only WAS (MLE systems). For NDBEPR systems, the NDBEPR WAS consists of OHO and PAO biomass; the hydrolysis rates of 0.607 gCOD/L ($K_s$) and 2.465 gCOD/gCOD biomass/d ($K_m$) are used. These rates are obtained from Ikumi *et al*. (2014). Note that for the AD of NDBEPR WAS, there are two biodegradable organic sources (OHOs and PAOs); however, the model treats this as one combined source. This is because separate $K_s$ and $K_m$ rates for the OHOs and PAOs are not known, thus only lumped $K_s$ and $K_m$ rates are available. Therefore, the AD model cannot compute the digestion of the OHOs and PAOs separately. However, in foresight, separate computation of the OHOs and PAOs is made available in the AD WAS model. If future research provides separate $K_s$ and $K_m$ rates for the OHOs and PAOs, then the two groups can be computed separately in the AD model, the separate results can then be combined. To enable this option, the separate Ks and Km rates must be entered in the defaults spreadsheet, and then the separate digestion of the OHOs and PAOs can be "switched on".

There is an important spreadsheet (WAS_Char) that links the AS system with the WAS digestion models (AxAeD and AD). In each AS model, the WAS fluxes are computed and the COD, N, P, and C fluxes of the WAS particulates are computed. These fluxes are linked to the WAS_Char spreadsheet. This spreadsheet functions as an intermediary: it collects all the WAS fluxes from the AS systems, and then selects the "correct WAS fluxes" based on the AS configuration selected (MLE, UCT, or JHB). The "correct WAS fluxes" are then linked to the AxAeD and AD models. The WAS thickening and the excess liquid from the thickening process is administered on this spreadsheet. In short, if any new AS systems are added in the future, to link the system to the WAS digestion models, the WAS_Char spreadsheet needs to be updated to include the WAS fluxes from the new AS system. Likewise, if a new WAS digestion model is added to the program, the WAS inputs to that model can be obtained from the WAS_Char spreadsheet.

### 6.3.3 Comments and Conclusion

Sludge digestion is important for the plant-wide design because the PS and WAS needs to be stabilised before it can be discharged to the sludge drying beds. However, depending on the system configuration, sludge digestion might not be necessary, for example if the designer wants a raw WW system with extended aeration then WAS sludge treatment can be avoided by having a long design sludge age (e.g. ±30 days) and hence a sufficiently stable WAS ($<0.15f_{av}$). This length selection of this long sludge age and its associated WAS $f_{av}$ will of course depend on the influent wastewater characteristics and the design temperature.

Different options for WAS and PS treatment are available to the designer. The available options will depend on the chosen plant-wide system configuration. If a primary settling tank (PST) is included in the plant-wide system, then the PS generated from the PST must be treated with AD. For the WAS, unless an extended aeration system is selected, the WAS can be digested with AD or AxAeD. Mixing of the PS and WAS is allowed, but mixing is not available for a raw WW system (no PST therefore no PS available) or for an extended aeration system (no WAS treatment). However, although the options are made available, it is not recommended to anaerobically digest WAS (with or without PS). Mineral precipitation will occur in the AD due to the conducive high N and P content of the WAS (ND or NDBEPR). For the AxAeD of NDBEPR WAS this will also transpire. Research and modelling of the mineral precipitation in this area is not currently complete and modelling of the amount of precipitation formed is not available in the current version of the program. However, in future editions, an estimate of the amount of struvite and calcium phosphate precipitates formed in the AD and AxAeD systems will be useful. This information will also aid in better predicting the behaviour of the pH in the AD.

## 6.4 Supplementary Models

Expanding on the theme of a plant-wide WWTP design, commonly implemented unit processes in current WWTP's are also included. In addition to this, because the capital costs are also an important aspect in design, a cost model is also included. The following supplementary models are available and these are discussed further in this section:

- A balancing tank for equalisation of the influent raw WW
- Aeration model for the mechanical surface aeration system
- A hypothetical cost and modularisation model

### 6.4.1 Balancing Tank

When creating a wastewater profile, of the WWChar methods available, the Direct Input method (Section 5.1) assumes a constant flow rate and wastewater characteristics, therefore it has no diurnal flow pattern. For a balancing tank, due to the diurnal flow pattern requirement, if the wastewater profile used in the plant-wide design is created from the Direct Method, then the balancing tank model is not available.

The balancing tank precedes the AS system; for a settled WW system where a PST is included, the balancing tank follows the PST. A balancing tank is a simple flow-in, flow-out, storage structure that equalises the influent diurnal flow. It is an optional unit-process that has no impact on the total daily organic load on the system; however, it eliminates the diurnal flow pattern and therefore mitigates any peak hydraulic loads, thus improving SST and AS process performance. It also changes the requirements for the aeration system; no peak factor is applied to the average oxygen utilisation rate (OUR), thus reducing the aeration capital costs and operation energy costs of the system.

The PSTs usually precede the balancing tank to avoid excessive solids deposition on the balancing tank floor. However, if the balancing tank is controlled with a computer (Dold *et al*., 1982, 1984; Garrard, 2014), its filling and emptying can be programmed so that at least daily the deposited solids are scoured off the tank floor and removed from the tank. The PSTs themselves also provide some load attenuation but not as effective as balancing tanks of course. Hence, for settled WW systems, the amplitude of the TOD load wave is reduced by 25%. The balancing tank also affects the PWWF:ADWF factor; when it is applied this factor can be assumed to be between 1.10 and 1.25:1 due to the imperfect load balance with hydraulic balancing. The effect of balancing the influent flow is shown in Table 6.6 in Section 6.2.2.

**Table 6.8: Effect of the balancing tank and the PST on peak and flow factors**

| System Type | Raw wastewater | Raw wastewater | Settled wastewater | Settled wastewater |
|---|---|---|---|---|
| Balancing Tank | False | True | False | True |
| PST | False | False | True | True |
| adjustment to aL | No adjustment | No adjustment | 0.75×aL | 0.75×aL |
| Peak OUR Factor | 1+0.28×aL | 1+0.28×aL | 1+0.28×(0.75×aL) | 1+0.28×(0.75×aL) |
| PWWF:ADWF | No adjustment | 1.25:1 | No adjustment | 1.25:1 |
| PDWF:ADWF | No adjustment | 1:1 | No adjustment | 1.1 |
| ADWF:ADWF | 1:1 | 1:1 | 1:1 | 1:1 |

Where:
- aL = amplitude of the TOD load wave = (Peak TOD/Average TOD) – 1; peak and average TOD in kgTOD/h
- 0.28 is the dampening factor applied to the OUR for BNR systems

There is only one input for the balancing tank model – a safety factor. This safety factor increases the calculated volume required, hence allowing for any shock loads or uncertainties to be accommodated. There are few outputs from the balancing tank model, namely: the volume required (with and without the safety factor applied), the time at which the minimum and maximum volume can be expected, and a hydrograph of the balancing tank. A screen capture of a completed Balancing Tank design window is shown in Figure 6.49. The balancing tank is designed for dry weather conditions. Using the DFData diurnal flow pattern (Section 5.2), the required volume without a safety factor is 5541.7 $m^3$. For a safety factor of 1.25, the required volume is 6927.1 $m^3$. The minimum and maximum volume time occurs at 08AM and 10PM respectively. From balancing tank control modelling (Dold *et al*., 1982, 1984; Garrard, 2014), a balancing tank hydraulic retention time of 4 hours based on ADWF can almost completely equalize the diurnal hydraulic flow. At shorter retention times than 4h, the control algorithm will minimize hydraulic variation within the balancing tank volume available.

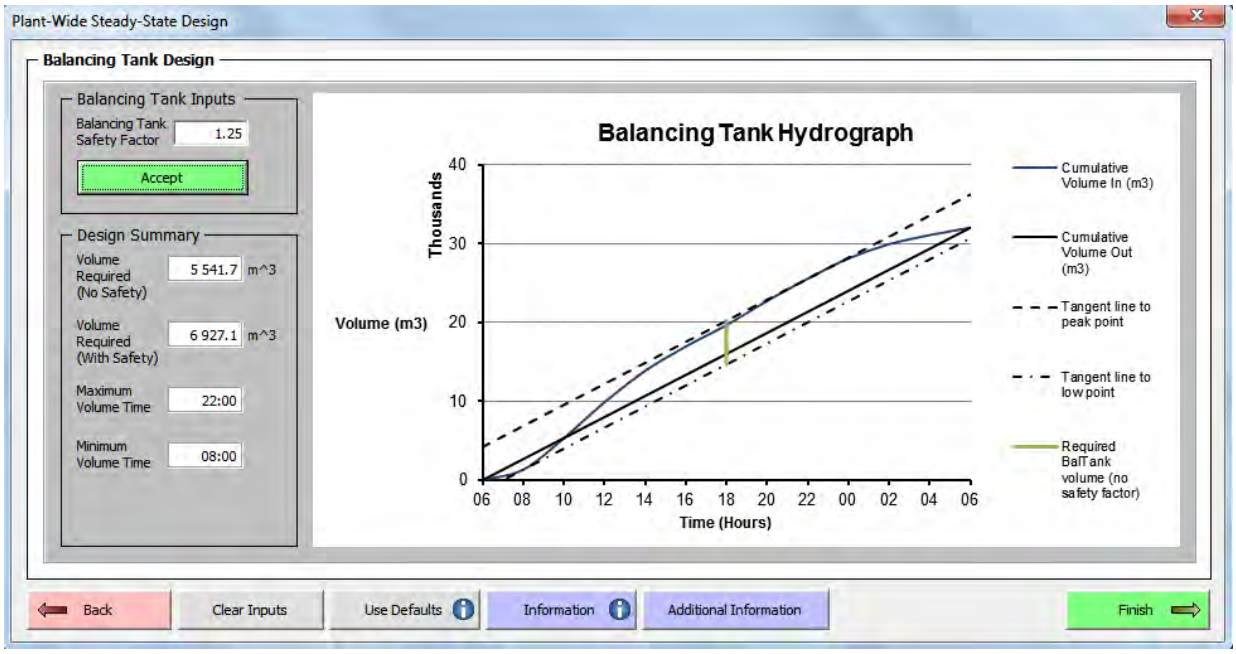



**Figure 6.49: Balancing Tank Design**

In the balancing tank model, the hourly flow variation ($m^3/h$) for the average dry weather flow (ADWF) condition is scaled up to the peak wet weather flow (PWWF) condition using the PWWF factor. This PWWF factor was determined during the WWChar phase. The cumulative volume into the balancing tank is then plotted on a hydrograph (blue line). The total volume in for that 24h period must be equal to the total volume out; therefore, by dividing the total volume in by 24 hours, the hourly flow rate out of the balancing is determined. This hourly flow rate out should be equal to the average of the PWWF. The cumulative volume out is also plotted on the hydrograph (solid black line). To determine the balancing tank volume required, the cumulative volume out line is extended, with the same gradient, to the peak and minimum of the cumulative volume in line (blue line). The difference between the peak and minimum lines (dashed lines) is the volume required for the balancing tank.

The balancing tank model available in this program is a simplistic model to determine the volume requirements. If this volume is already known then a more detailed balancing model, by Dold *et al*. (1982, 1984) and Garrard (2014) can be used. This model utilises an algorithm to determine the optimum outflow profile, and is essentially a dynamic balancing tank model. The version by Garrard (2014) is written in the Excel/VBA environment. Even though the primary purpose of Garrard's (and Dold's) balancing tank model is to calculate and set the outflow rate on real balancing tanks in real time. With some adjustments to fit the structure and appearance of the PWSSD program, Garrad's version can be added in future editions.

### 6.4.2 Aeration

Aeration requirements for the AS aerobic reactor and the WAS aerobic digester (AxAeD) can be calculated using an aeration model. The aeration model is useful as it estimates the required total power output from the aerators. This allows the aerator sizes to be selected appropriately; if this is not done then the AS and WAS digestion process in terms of COD and N removal will be inhibited because enough oxygen supply does not supply the carbonaceous COD ($FO_c$) and nitrification ($FO_n$) oxygen demands.

The aeration design window contains a *Model Inputs* and *Design Summary* frame that contains the aeration model inputs and results for both the AS aerobic reactor and WAS AxAeD. If a WAS AxAeD is not available, i.e. system is an extended aeration system or a WAS AD is used, then the WAS AxAeD inputs and results will not be available. The aeration design window also contains the *Design Guidance* frame and all the relevant information about the model inputs and the aeration model is displayed there. This window is shown in Figure 6.50 on the next page.

Numerous aerations systems can be used; the most common are mechanical surface aeration systems that dissolve oxygen into the wastewater by agitation, and diffused bubble systems that disperse oxygen into the wastewater with submerged diffusers. In general, compared to mechanical aerators, bubble aerators allow for a greater rate of oxygen transfer and greater oxygen transfer efficiency, however they are more complicated in terms of operation and design. At this stage, only a mechanical aeration model has been included in the aeration design; bubble aeration systems can be included in future editions. For the mechanical aeration model, empirical equations are used to calculate the barometric pressure from the site altitude and saturated vapour pressure, and the dissolved oxygen concentration from the temperature and barometric pressure. A summary of the aeration model inputs is presented in the list below:

- Site altitude (Alt)
- Impurities correction factors for $K_{La}$ (alpha, $\alpha$) and dissolved oxygen (beta, $\beta$)
- Standard oxygen transfer rate ($R_{std}$)
- Dissolved oxygen level required in bulk liquid ($C_L$)
- Line to shaft efficiency of the mechanical equipment (Eff)
- Number of aeration compartments (for the aerobic AS reactor)

The inputs listed above (except for the last point) apply also to the WAS AxAeD and are contained in the *AS Aerobic Reactor* and *WAS Ax-Ae Digester* input pages. A third page, *OUR Requirements*, contains the $OUR_{td}$ at minimum and maximum temperature (MinT and MaxT) for the AS system and the WAS AxAeD. These inputs cannot be changed, as they are outputs

from the AS and WAS AxAeD models. Of the two temperatures, the highest $OUR_{td}$ determines the aerator sizes for the aeration system. The left figure in Figure 6.51 shows the *AS Aerobic Reactor* input page, the right figure in Figure 6.51 shows the *OUR Requirements* page.

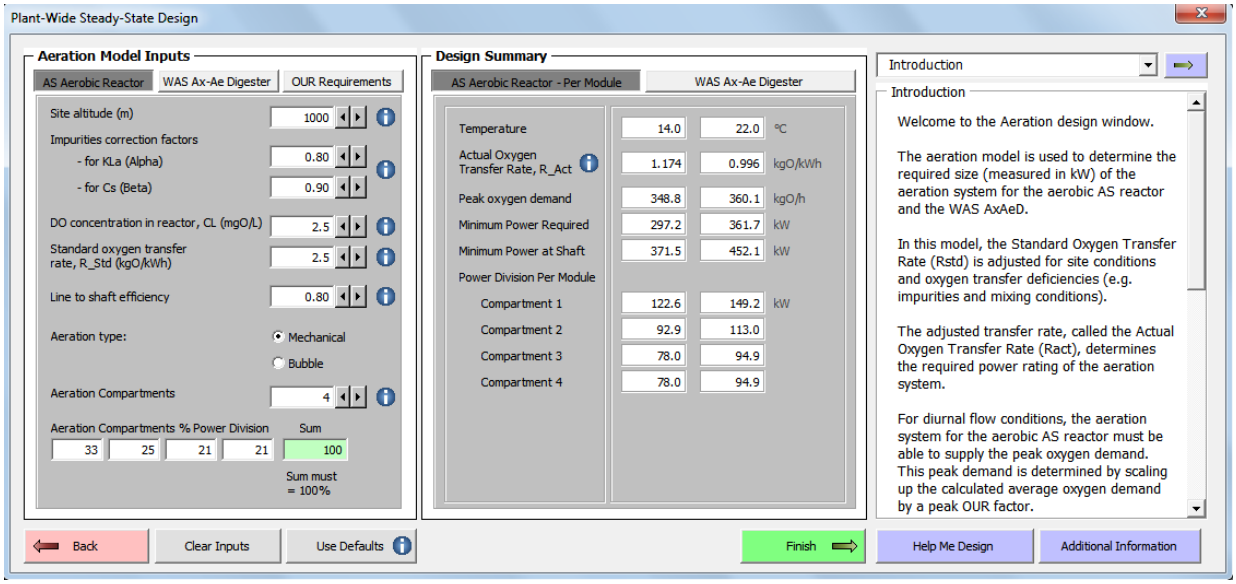



**Figure 6.50: Aeration Design**

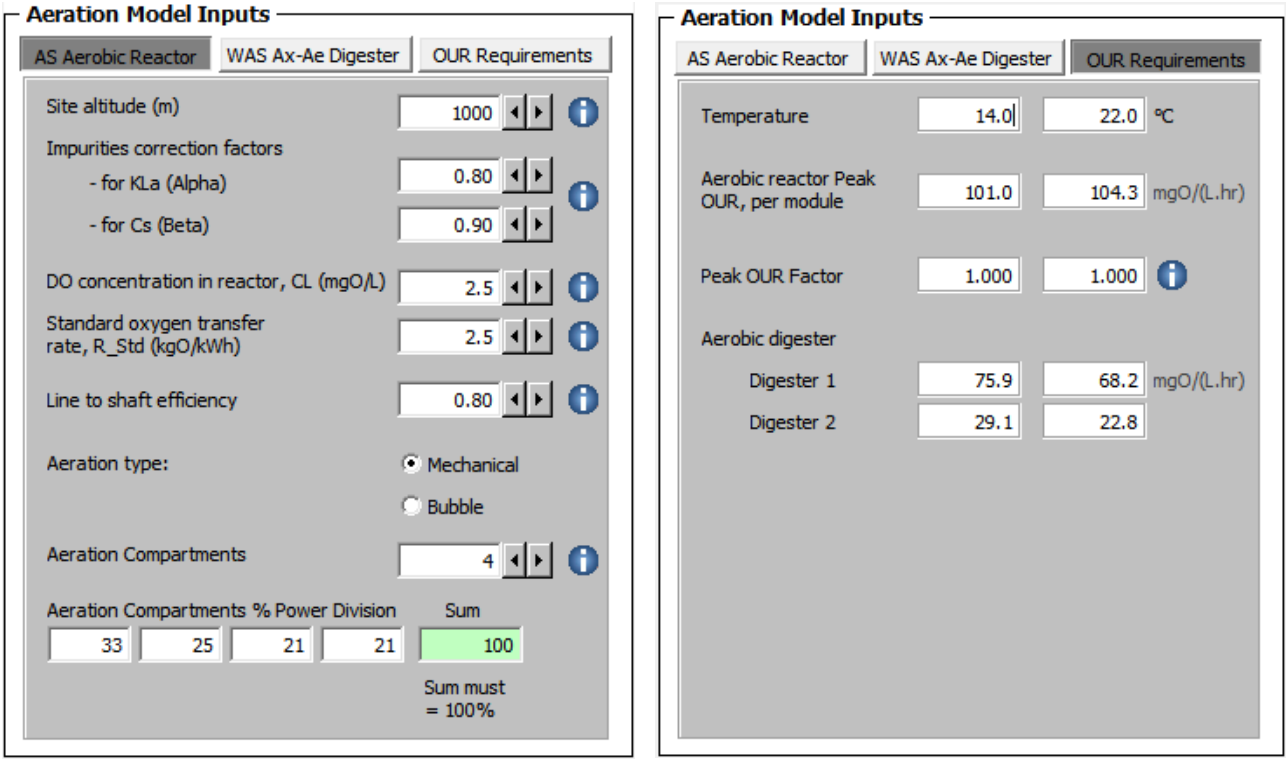



**Figure 6.51: Aeration Design – Aeration Model Inputs and OUR Requirements pages**

The peak OUR factor applied to the $OUR_{td}$ for AS system is also displayed in the *OUR Requirements* page. In this example, because flow balancing is applied, this factor is 1.00. A breakdown of how this factor is calculated is shown in Table 6.8 in Section 6.4.1. Note that the WAS AxAeD $OUR_{td}$ is increased by 50% to account for the intermittent aeration cycle for complete denitrification. The $OUR_{td}$ for each WAS digester in-series is displayed on the *OUR Requirements* page. The first digester's $OUR_{td}$ is important for the design of the WAS digester. Due to first order kinetics, the proportion of the $FO_{td}$ in the first digester increases as the number of digester in series increases. At the same time, more digesters in series results in a reduced total retention time and total volume. Hence, the $OUR_{td}$ of the first digester increases with increasing number of digesters in series. However, the number of digesters in series is limited by the maximum oxygen transfer rate of the aeration system, which is typically 100 – 125 mgO/(L.h).

Using the flow balanced settled MLE and WAS AxAeD design examples presented in Section 6.1.1 and Section 6.3.1, the $OUR_{td}$ for the AS system is 104.3 mgO/(L.h) at MaxT. For the WAS AxAeD, it is 111.0 mgO/(L.h) for the first digester, and 42.6 mgO/(L.h) for the second (last) digester, both digesters $OUR_{td}$ are at MinT. A discussion to why the $OUR_{td}$ is higher at MaxT for the AS system and higher at MinT for the WAS AxAeD is provided.

In the AS system, the volume of the AS system is designed for the minimum temperature (MinT) because the endogenous respiration process is slower and thus the sludge mass production is higher at MinT. With the reactor volume determined for MinT, the peak $OUR_{td}$ at the maximum temperature (MaxT) can be determined. This peak $OUR_{td}$ at MaxT is higher than the $OUR_{td}$ at MinT because the endogenous respiration rate ($b_{HT}$) is faster at MaxT, thus resulting in a higher oxygen demand and a lower active fraction ($f_{av}$) of sludge mass. This principle also applies to the WAS AxAeD: the retention time (HRT) and hence the AxAeD volume is defined by the MinT condition due to the lower $b_{HT}$ at MinT. To achieve the required specific OUR ($SOUR_e$) [usually 1.50 gO/kgVSS/h including nitrification], the AxAeD HRT at MinT is longer than at MaxT. This is attributed to the slower $b_{HT}$, i.e. slower rate equals longer HRT to achieve the required $SOUR_e$. Thus the volume of the WAS AxAeD is determined at the MinT, because the MinT has the longer HRT (and the higher influent TSS flux from the AS reactor). However, from the AS system, the flux of the WAS and its $f_{av}$ is lower at MaxT than at MinT. Therefore, when operating the WAS AxAeD at MaxT, the lower WAS flux and influent active fraction results in the total oxygen demand being lower than when operating at MaxT. This effect occurs even though the $b_{HT}$ is faster at MaxT, resulting in a higher oxygen consumption per influent unit of VSS.

Although, this does not necessarily mean that the required power supply of the aeration system for the WAS AxAeD is always higher for the MinT condition. Whether it is for the MaxT or MinT condition will depend on the actual oxygen transfer rate ($R_{act}$), which is also dependent on temperature and site altitude. The $R_{act}$ decreases for increasing temperature and the power required is the peak oxygen demand divided by $R_{act}$. Thus if the $R_{act}$ at MaxT is significantly different to the $R_{act}$ at MinT, a situation can occur where the power required at

MaxT is higher than at MinT, even though the peak oxygen demand (and $OUR_{td}$) at the MaxT is lower than at the MinT.

The aeration model results are shown in Figure 6.52. The results are shown for the design at MinT and MaxT and include the actual oxygen transfer rate, the power requirements per AS module and AxAeD with and without the mechanical efficiency applied. For the WAS AxAeD, the results show that at MaxT, the peak oxygen demand is lower than at MinT (**A**), and that the there is no significant difference between the $R_{act}$ for the two temperature conditions (**B**). The result is that the power requirement of the aeration system is higher at the MinT condition (**C**).

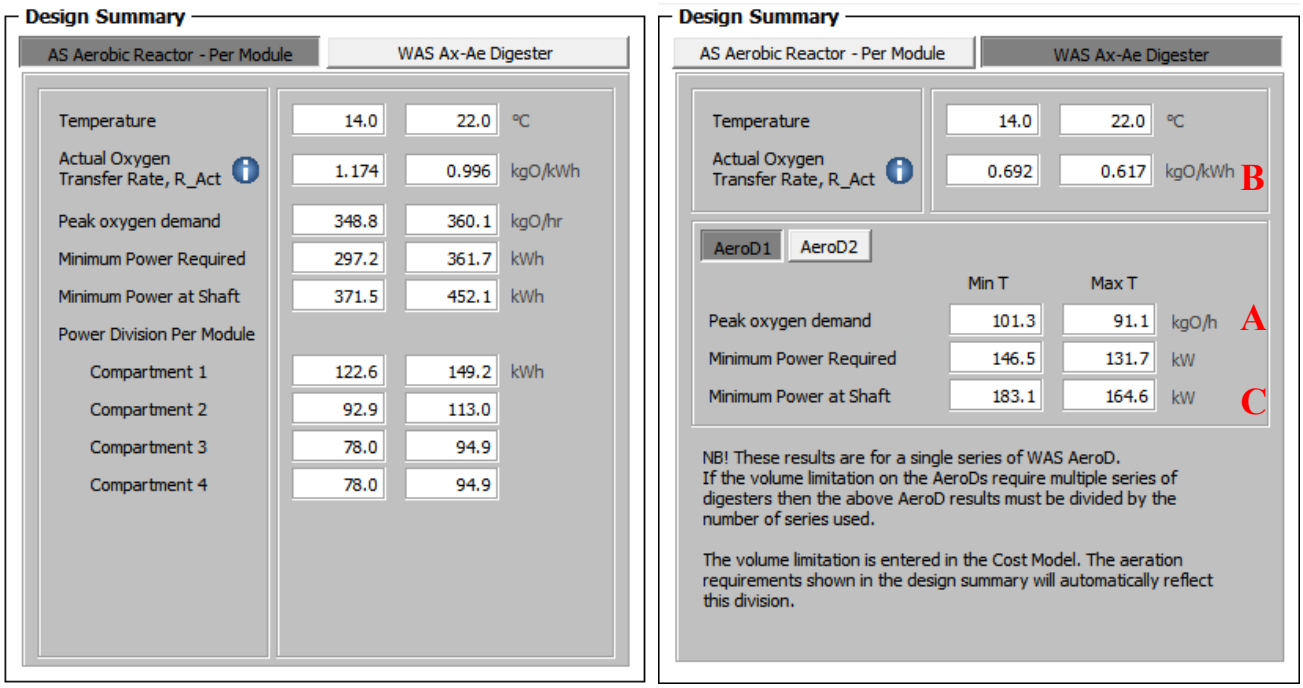



**Figure 6.52: Aeration Design – AS Aerobic Reactor and WAS AxAeD Design Summary pages**

The aeration results for the WAS AxAeD are for completely mixed in-series digesters. The number of in-series digesters is selected in the AxAeD design window; each digester has the same volume. If the in-series digester volume exceeds the maximum volume of a single digester* then the in-series digesters need to modularised, i.e. split into identical parallel modules. If this is done then the aeration results must also be divided by the number of parallel modules required. This is permissible because the oxygen demand and AxAeD volumes are divided equally; hence, the power requirements are also equally divided. This of course assumes that the WAS flow rate is also equally divided between the modules. This division is only relevant when selecting the aerator sizes, it does not affect the total power requirements determined by the aeration model, i.e. the total power required is independent of the number of

* The maximum volume for the AxAeD is selected in the Cost and Modularisation window.

modules of AxAeD. However, in most scenarios splitting the AxAeD into multiple modules is not required as the AxAeD volumes are quite small. Therefore the aeration design window for the WAS AxAeD focuses more on the total power requirements for a single AxAeD module. The maximum AxAeD volume, which determines if multiple modules are required, and the selection of aerator sizes are made in the Cost and Modularisation window (Section 6.4.4). This is because it pertains more to the cost of the system. The standard aeration power ratings of the different mechanical surface aerators are 40, 55, 65, 80, 95, and 110 kW.

However, for the AS system, modularisation is often used, and because the maximum AS reactor volume was already entered during the AS system design phase, the aeration results for the AS aerobic reactor are for each AS module. The aeration results shown for the AS aerobic reactor must not be divided by the number of AS modules in the AS system. When modularising the AS system, the same principles for modularising a single series of AxAeD are applied. For multiple AS modules, the total power required per AS module is simply the total power required for the entire AS system divided by the number of AS modules. This has already been completed in the background and taken into consideration in the aeration model.

The effect of modularisation on the aeration requirements is illustrated in Figure 6.53; the results from the MLE and WAS AxAeD design examples, presented in Section 6.1.1 and Section 6.3.1, are used.

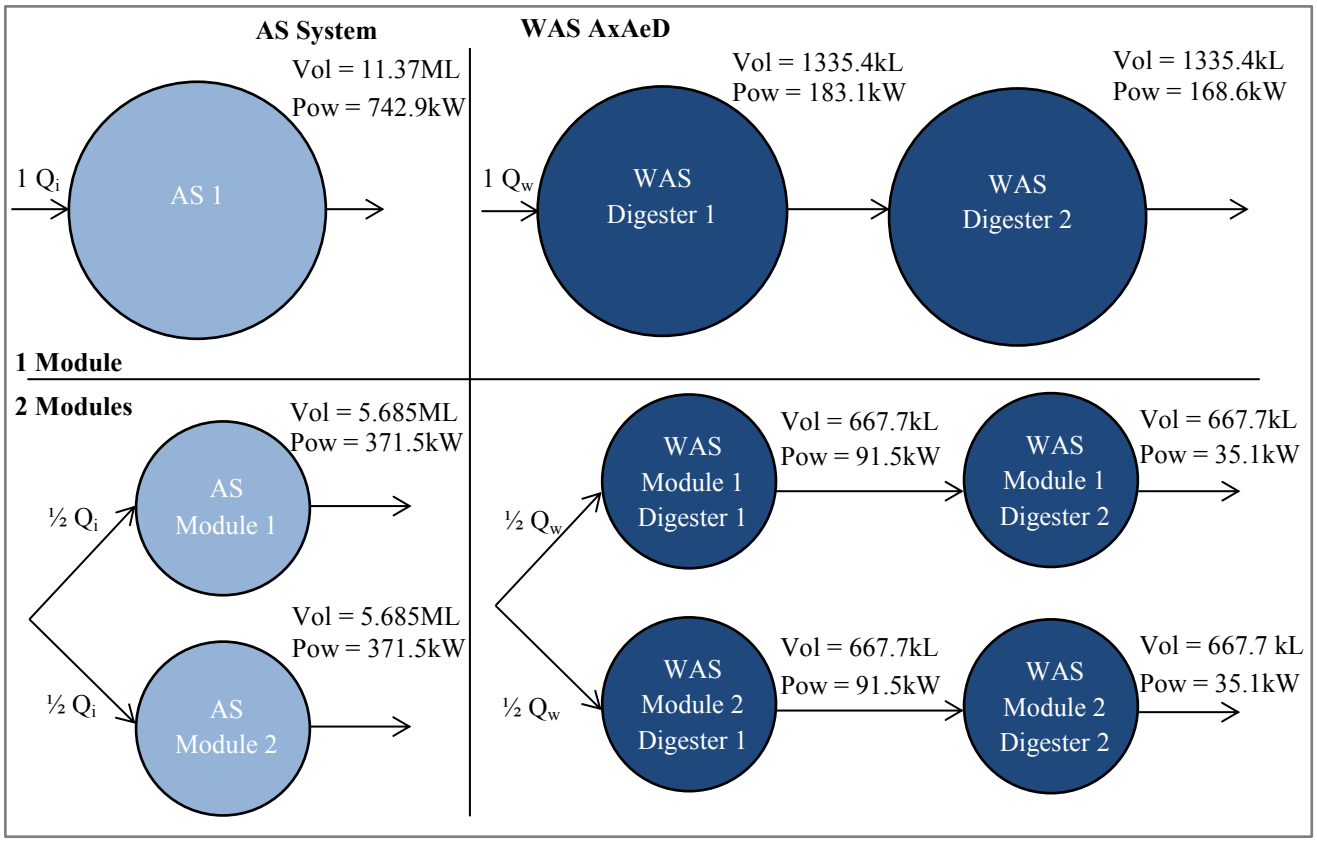



**Figure 6.53: Aeration Power Distribution for AS Modules and WAS AxAeD Series**

### 6.4.3 Dissolved Air Flotation

Dissolved air flotation (DAF) is often used for the thickening of WAS. In this unit process, pressured air is discharged into the bottom of a flotation unit; the WAS particulates attach to the air bubbles and rise to the surface of the unit where it is scraped off by a scraping mechanism. The WAS is thickened to 4-6% TSS in this manner (Bratby *et al*., 2008). DAF is not currently available in the PWSSD program, but a steady-state model exists (Bratby & Marais, 1976; Bratby, 1978). This model determines the number of DAF units required, the pressure requirements, scraping dimensions etc.

### 6.4.4 Cost and Modularisation Model

The cost and modularisation model (CostMod) is a simple model that estimates the total capital costs of the system. An aspect of the CostMod has already been introduced in the $X_t$ Optimisation part of the AS system and SST design. The $X_t$ Optimisation part utilises the CostMod to determine the optimum $X_t$ for the AS-SST system.

Before a cost estimate can be produced, the number of modules for each unit process needs to be determined. In general, a unit process is modularised into identical parallel modules if the total spatial requirement for that unit process exceeds the maximum spatial limitation, i.e. the physical structure needs to be split into two or more identical parts because a single structure cannot be built. Alternatively, unit processes are also modularised so that maintenance is easier. The Cost and Modularisation Window (Figure 6.54), allows for the entry of the spatial limitation (volume, area or diameter) for each unit process. From these input, the number of modules for each unit process is determined.

For the cost part, a cost coefficient and exponent is entered for each unit process (AS, SST, PST, AD etc.), these parameters describe the exponential cost function for that unit process (Equation 6.13). The total cost of the system is then sum of the cost of each unit process. For the surface aeration system, the cost function for the aerators is in the same form as Equation 6.13. The only difference is that the *Spatial_Requirement* variable is the power output of the surface aerators (40, 55, 65, 80, 95, and 110 kW). The aerator combinations that will supply the required power output must be selected manually. This is because there is no explicit solution in selecting the best combination. When selecting the sizes (kW), it is recommended that similar aerator sizes be selected so that maintenance of the aeration system is easier. A tool to help select the aerator combinations has been created (Figure 6.55); the tool instantaneously calculates the cost and the power supplied by the aerator combination.

**Equation 6.13: Cost Model – generalised cost function**

$$N \times F \times (\text{Spatial\_Requirement})^{E}$$

Where N is the number of modules and F and E describe the curve of the cost function

The outputs from the cost model are purely hypothetical and the quality of the estimation depends entirely on the inputs to the cost functions for the AS system, SST, PST, digesters etc.. The purpose of the cost model is not to estimate the total cost to the nearest cent, but to provide a basis to compare the total costs of different systems. In practice, more detailed cost analyses are conducted and each consulting firm will have their own cost functions and methods of analysis, the Specifications Summary (Section 6.5.2) can be used for these custom cost estimations.

The Cost and Modularisation window and Aerators Selection window are shown in Figure 6.54 and Figure 6.55. For the flow-balanced, settled WW, balanced MLE system, with PS AD, and WAS AxAeD treatment, four AS aerobic reactor compartments were selected during the aeration design, giving power requirements of: 149.2 kW, 113.0 kW, 94.9 kW and 56.8 kW. The selected aerators are (1×40 kW + 2×65 kW), (2×65 kW), (1×40 kW + 1×65 kW), and (1×40 kW + 1×65 kW), giving total power output of 170 kW, 130 kW, 105 kW and 105 kW. For the two in-series WAS AxAeDs, the power requirements were 183.1 kW and 70.3 kW, the selected aerators are (2×65 kW + 2×40 kW) and (1×40 kW + 1×65 kW), giving a total power output of 210 kW and 105 kW.

The modularisation part can be used without the cost estimation. To do this, check the *Do Not Estimate Costs* checkbox – this will not override the cost estimation for the $X_t$ optimisation part. If modularisation is not required, then enter sufficiently large spatial limitations into the *Max Measurement* textboxes.

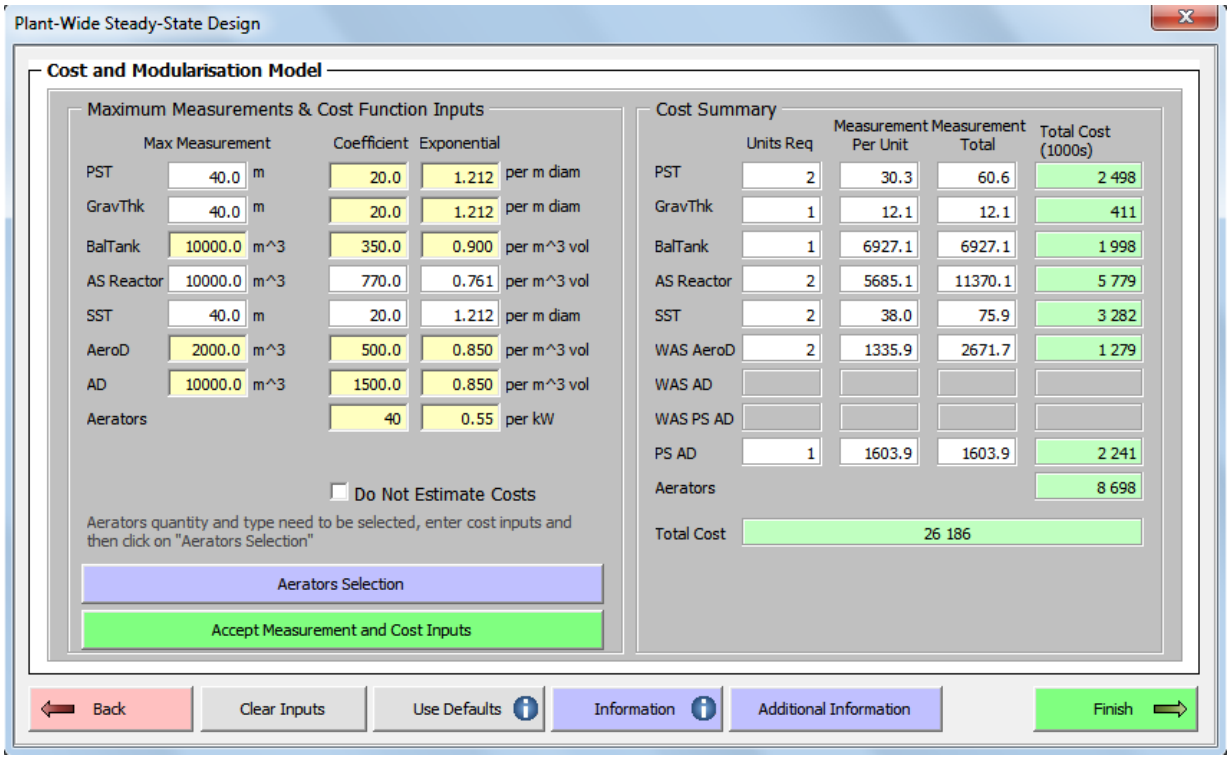



**Figure 6.54: Cost and Modularisation window**

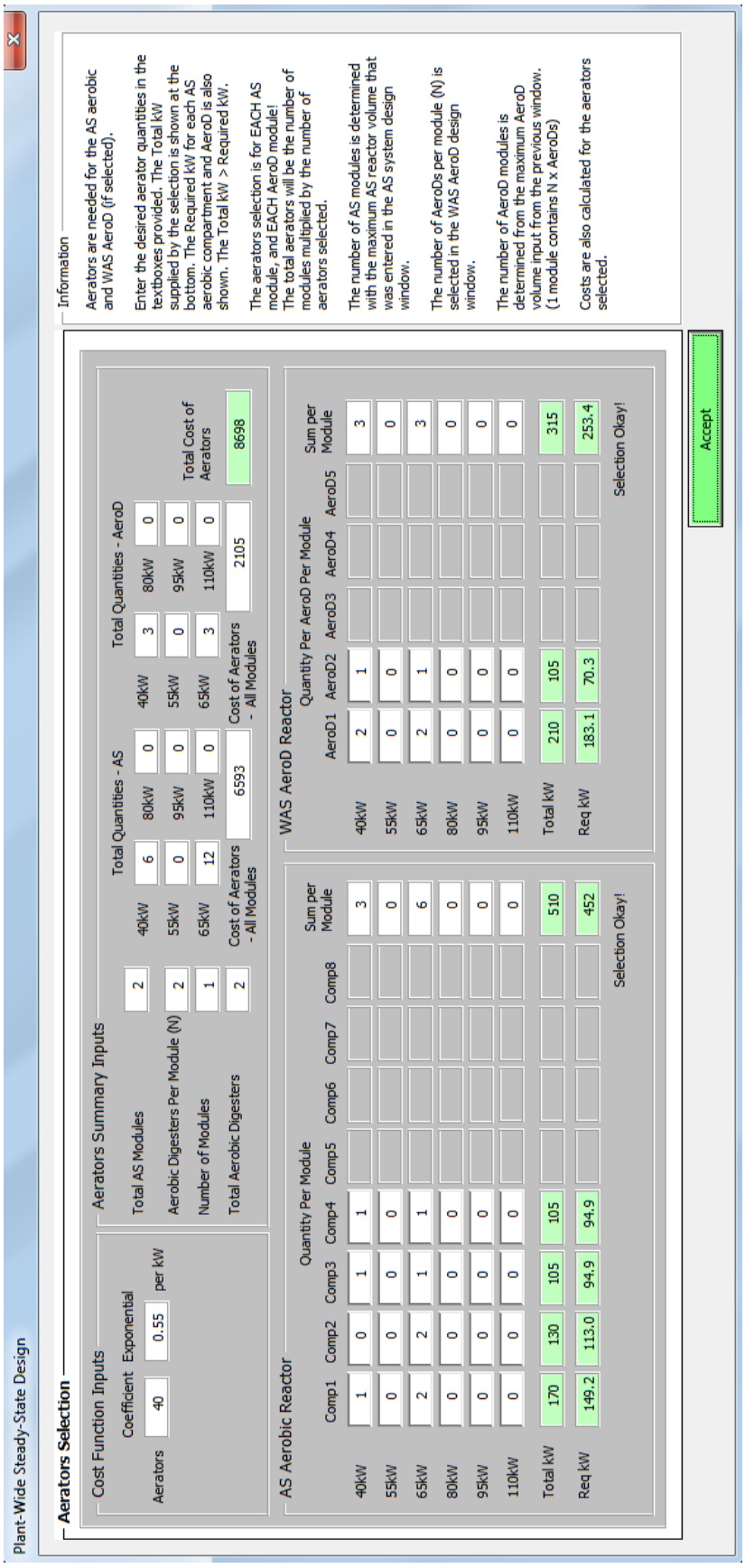



**Figure 6.55: Cost Model – Aerators Selection**

### 6.4.5 Comments and Conclusion

In general, any model that can be written in a spreadsheet can be added to the PWSSD component. The user-interfaces for the models are simply windows that capture and display data. The spreadsheets (and VBA), that run in the background, provide the computational power to compute these models. Supplementary models do not even have to be hosted inside the PWSSD program, VBA code can be written to export or import data and to link the PWSSD program with an external application.

For future editions, a thickening model for the WAS will be incorporated. Thickening using dissolved air flotation (DAF) was identified, and a model for the DAF thickener design is available (Bratby & Marais, 1976; Bratby, 1978). The aeration model can be expanded to include alternative aeration methods, such as bubble aeration. These supplementary processes are important for the design of the WWTP and thus should be looked at in future additions of the program. Other potential models, which have or are being written in Excel/VBA, which can be added to the program include a dynamic balancing tank model and the UCTOLD (Dold *et al*., 1980) and UCTPHO (Wentzel *et al*., 1988; Wentzel *et al*., 1989a; Wentzel *et al*., 1989b) dynamic models. The UCTOLD (for N removal) and UCTPHO (for P removal) dynamic simulation models are written in the old Pascal language. If these are rewritten in VBA, they can be added. Adding these two dynamic models will provide a major improvement to the PWSSD program as they can be used to determine the peak OUR rather than generalised empirical values. With UCTOLD and UCTPHO, it is envisioned that when the steady state design is completed, the dynamic response of the designed AS system can be checked simply by clicking "simulate" without entering any new data. This is possible because all the inputs required are transferred seamlessly from the steady state calculations (provided a diurnal wastewater flow and load pattern was entered in the WWChar).

The PWSSD program is not limited to the currently available models. The structure of the PWSSD component has been set up in a flexible manner, and thus the addition of a new models is not a complicated process, however it can be time consuming depending on how many links must be created (between upstream and downstream processes). To add a new model, a new spreadsheet model must be set-up and the inputs must be linked to it. These inputs can be outputs from existing models, such as the AS models, or it can be captured from the user with a user-interface, created using VBA. To finish integrating the new model, the outputs must then be linked to the downstream processes or the respective summary pages (discussed further in Section 6.5).

## 6.5 PWSSD Design Summary

The PWSSD Design Summary window concludes the PWSSD component. It summaries the inputs used for the steady-state models in one window, and displays a summary of the results from the steady-state models for each unit process. The results are displayed in the respective

pages for each unit process. Depending on the system configuration, the wastewater block diagrams for the influent raw WW, settled WW, PS, WAS, and PS, and WAS+PS mix are also shown. This window is large and thus has been split into three figures, Figure 6.56 to Figure 6.58, each showing a third of the window. At the bottom of each summary page, a *View Model* button is available. This displays the model spreadsheet for the respective unit process selected. On each spreadsheet, the entire steady-state model outputs can be viewed and exported to a new Excel workbook where it can be externally manipulated and printed (if screen prints as in this thesis are unacceptable). At the bottom of the PWSSD Design Summary window, the *View Full Wastewater Profile* button displays the WWChar Summary window; the *Design Report* button transfers the information on this window to a new Excel workbook, where it can be used externally.

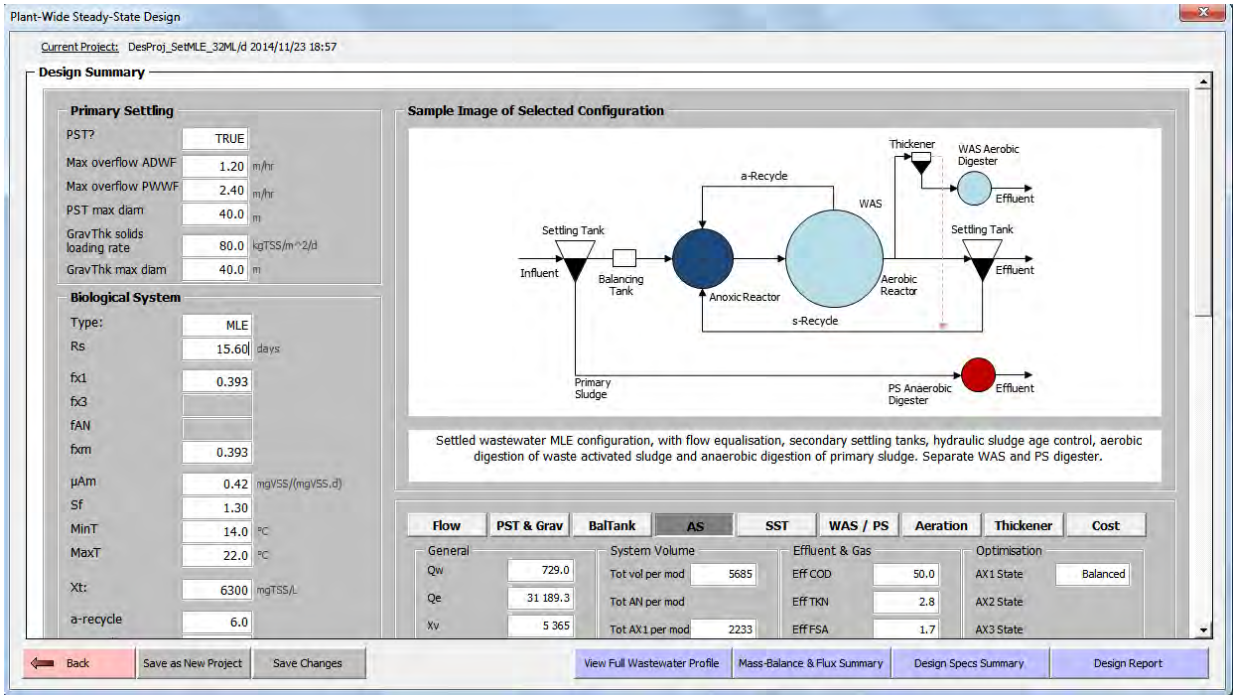



**Figure 6.56: PWSSD Design Summary – Top third of window**

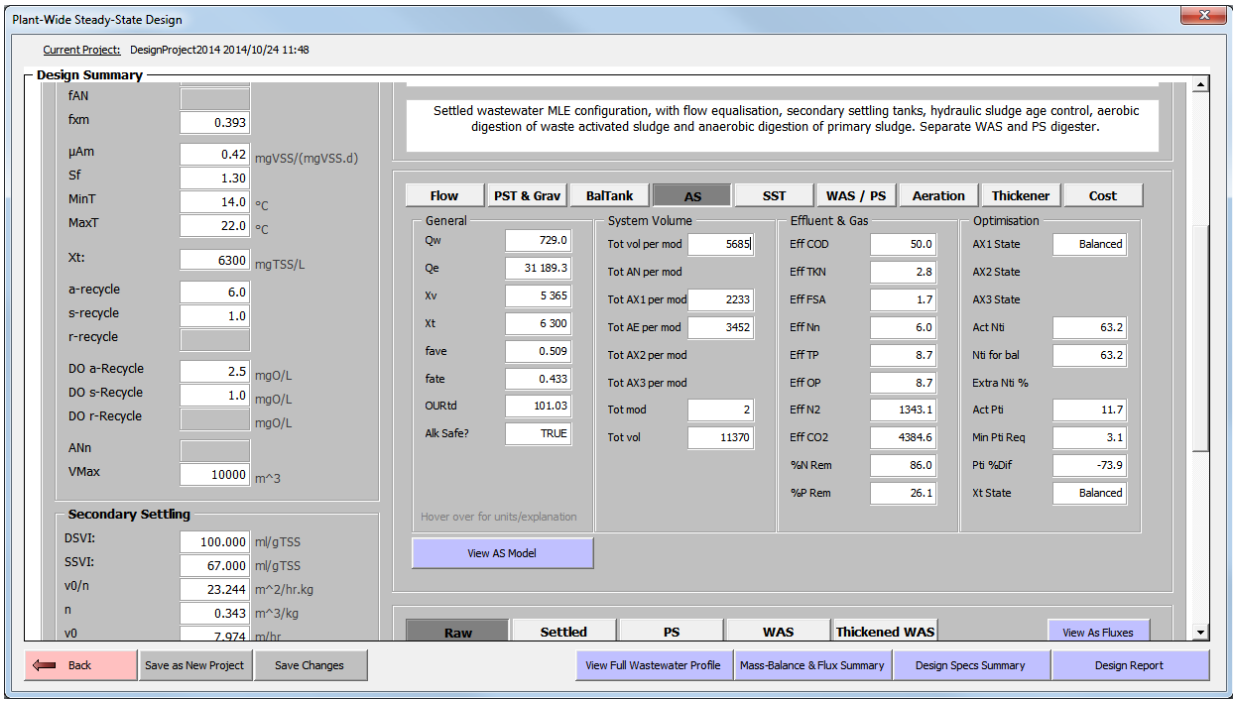



**Figure 6.57: PWSSD Design Summary – Middle third of window**

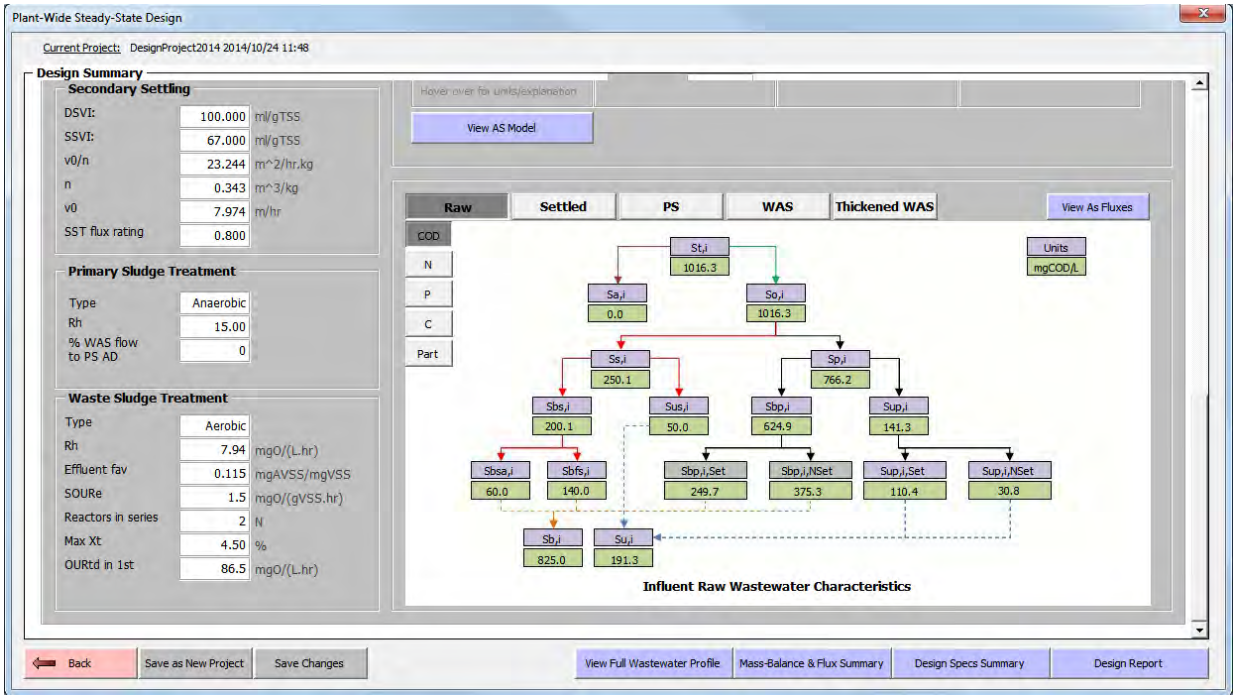



**Figure 6.58: PWSSD Design Summary – Bottom third of window**

Also at the bottom of the PWSSD Design Summary window, the *View Flux Summary* and *View Specifications Summary* buttons display the Flux Summary and Specifications Summary of the design. The Flux Summary shows a plant-wide mass balance of the COD, C, N, P, and TOD constituents, which allows the solid, liquid, and gaseous influent and effluent fluxes to be quantified. The Flux Summary is discussed further in Section 6.5.1. The Specifications Summary is a graphical summary of the plant-wide design; it shows the design results overlaid onto an image of the system. Examples of these results include the reactor volumes, reactor concentrations, recycle ratios, settling tank dimensions, and overflow rates. The Specifications Summary is discussed further in Section 6.5.2. The Flux Summary and Specifications Summary can be exported to a new Excel workbook where it can be externally manipulated, printed, saved etc.

### 6.5.1 Flux Summary

For the steady-state AS models and the sludge digestion models a stoichiometric part for mass-balancing (COD, C, H, O, N, P) and calculation of gas production is included. The stoichiometric part allows for tracking of the various constituents from their entry into the system to their solid, liquid, or gas exit routes. When the mass balances of each unit process are linked together, a plant-wide mass balance is formed allowing the designer a bird-eye of view of the behaviour of each constituent.

In order to create the plant-wide mass balance tool, the steady-state AS models had to be extended with the bioprocess stoichiometry as presented by Ekama (2009). This stoichiometry allowed for the prediction and tracking of the solids, liquids, and gas exit streams of the C, H, O, N, P, and COD for anaerobic, anoxic, and aerobic treatment processes. Mass balances for each unit process could be computed (AS, sludge digestion, PST, thickening etc.); in order to create a plant-wide mass balance, the individual mass balances where combined and presented in one graphical summary. This is permissible because when doing a plant-wide design, by using the outputs of one process as the inputs to another, a plant-wide mass balance is inherently performed.

The mass balance is computed in the background as soon as the user starts the plant-wide design. Beginning with the WWChar process, the mass ratios ($f_{cv}$, $f_n$, $f_p$, $f_c$, $f_o$, and $f_h$) of the wastewater constituents are calculated. These ratios are then transformed to the x, y, z, a, and b components which quantify the stoichiometric composition of the various wastewater organics. The biomass (OHOs or PAOs) formed from these organics has a predefined stoichiometric composition ($C_kH_lO_mN_nP_p$) and mass ratios. For the activated sludge model, as the inputs to the steady-state model are entered, the steady-state model is computed. This model calculates the WAS and effluent streams; from the mass ratios of the influent wastewater, and as well as the mass ratios of the biomass formed, the COD, N, P and C fluxes in the WAS and effluent can be calculated. At this stage a mass balance can be applied to COD, N and P (and TOD), but for the C mass balance, the $CO_2$ gas production needs to be calculated. This production is not possible

from the AS sludge model; however it can be calculated using the bioprocess stoichiometry model by Ekama (2009).

In order to use the bioprocess stoichiometry model, the fluxes of the biodegradable organics utilised in the different process zones (aerobic, anoxic, and anaerobic if a BEPR system is used) must be quantified, this is because in each zone there are different electron acceptors, donors, reactants, and products. This quantification can be done from the steady-state AS model by evaluating the denitrification capacity of each organic type. For the BEPR systems, the VFA uptake in the anaerobic zone is also used. Once the fluxes of the biodegradable organics utilised in each process zone is known, the solids, liquids, and gas production can be predicted using the stoichiometric equations for each process zone. The $CO_2$ gas production, which is predicted from the stoichiometry, can then be used to compute a C mass balance. Other outputs from the stoichiometric model, particularly the biomass produced, N2 gas released, and the $O_2$ consumption, can be compared to the outputs from steady-state AS model, thus allowing the arithmetic of the model to be checked.

The above mass balance process is also applied to the AxAeD and AD steady-state models. In the AxAeD model, WAS is digested in an aerobic digester. Due to the similarities between the AxAeD of WAS and the steady-state aerobic AS model, the stoichiometric models are similar – the only difference is that in the AxAeD of WAS model, the only bioprocess that occurs is the endogenous utilisation of biomass. In the AxAeD of WAS, the process can be either aerobic only, or anoxic-aerobic. In the first scenario, nitrification occurs and nitrate is a product of the AxAeD process. In the second, in line with the benefits of denitrification, if the AxAeD is intermittently aerated, as shown by Warner *et al*. (1986), complete nitrification and denitrification is achieved, and N2 is as product of the AxAeD process, with some saving in oxygen demand. The stoichiometric computations for both scenarios are included in the background; however, for simplicity and emphasis, the nitrification-denitrification scenario is ultimately used for the mass balance. In the AD model of PS, or WAS, or WAS and PS mix, the same mass balance computation is applied. The only difference is that a different stoichiometric equation is used. For the WAS and PS mixed AD model, the digestion of WAS and PS are computed separately and the results of the calculations are combined. For the mass balance of the WAS and PS mixed AD model, this principle is also applied. The in-situ pH is calculated for the individual PS and WAS ADs based on zero mineral precipitation but including effect of the OP system, which becomes significant with the release of P from BEPR WAS.

The plant-wide mass balance can be viewed when the design is finished. On the design summary window, the *View Flux Summary* displays the plant-wide mass balance. An accompanying window is also displayed. This window controls the mass balance that is displayed: COD, N, P, C, or TOD. Generally, an H and O mass balance is not required and thus has been omitted. The COD, N, P, C, and TOD mass balances can be viewed as fluxes in kg/d, as a % of the influent raw WW flux, or as a % of the influent flux to that unit process; the buttons on the Flux Summary Controls window are used to do this. The Flux Summary is

displayed in Figure 6.59. This is for the flow-balanced, settled WW, balanced MLE system, with PS AD, and WAS AxAeD treatment. The fluxes are displayed as a % of the influent raw WW flux; from the summary, it can be seen that of the 100% COD flux entering the WWTP, 4.8% exits as soluble COD from the AS system, 11.6% exits as solids from the WAS AxAeD, 13.6% exits as solids and 22.1% as methane gas from the PS AD. The balance of the COD (electrons) exited with water produced resulting from oxygen consumption via 4 ($e^- + H^+$) + $O_2$ = $2H_2O$. Element (CHONP) and COD mass balances are checked over each unit operation and the entire WWTP.

### 6.5.2 Specifications Summary

The ultimate goal of a plant-wide steady-state design is to generate the WWTP specifications, such as reactor volumes, flow rates, aeration requirements, SST areas etc. These specifications are important for a summary layout or performance assessment of a designed or existing WWTP. Also for dynamic simulation models, these specifications are often the first inputs that must be entered into the simulation models.

The specifications are summarised in a graphical summary, which is very similar to the Flux Summary; the only difference is the type of data displayed. The structure of the Specifications Summary is the same as the Flux Summary, because the models are calculated as soon as the inputs are entered, the Specifications Summary simply collects those outputs and displays it graphically. To avoid clutter, the most relevant data is presented in the summary; the goal behind this summary is that the designer can simply print it and include it in a design report to provide a plant-wide overview of the system design. An export function is thus also included. This summary can be accessed from the PWSSD Design Summary window with the *Specifications Summary* button. Figure 6.60 shows the Specifications Summary for the flow-balanced, settled WW, balanced MLE system, with PS AD, and WAS AxAeD treatment.

A spreadsheet and VBA code controls the items displayed on the Specifications Summary. Any output or item generated from the steady-state models can be displayed (or removed) by adjusting this spreadsheet and code.

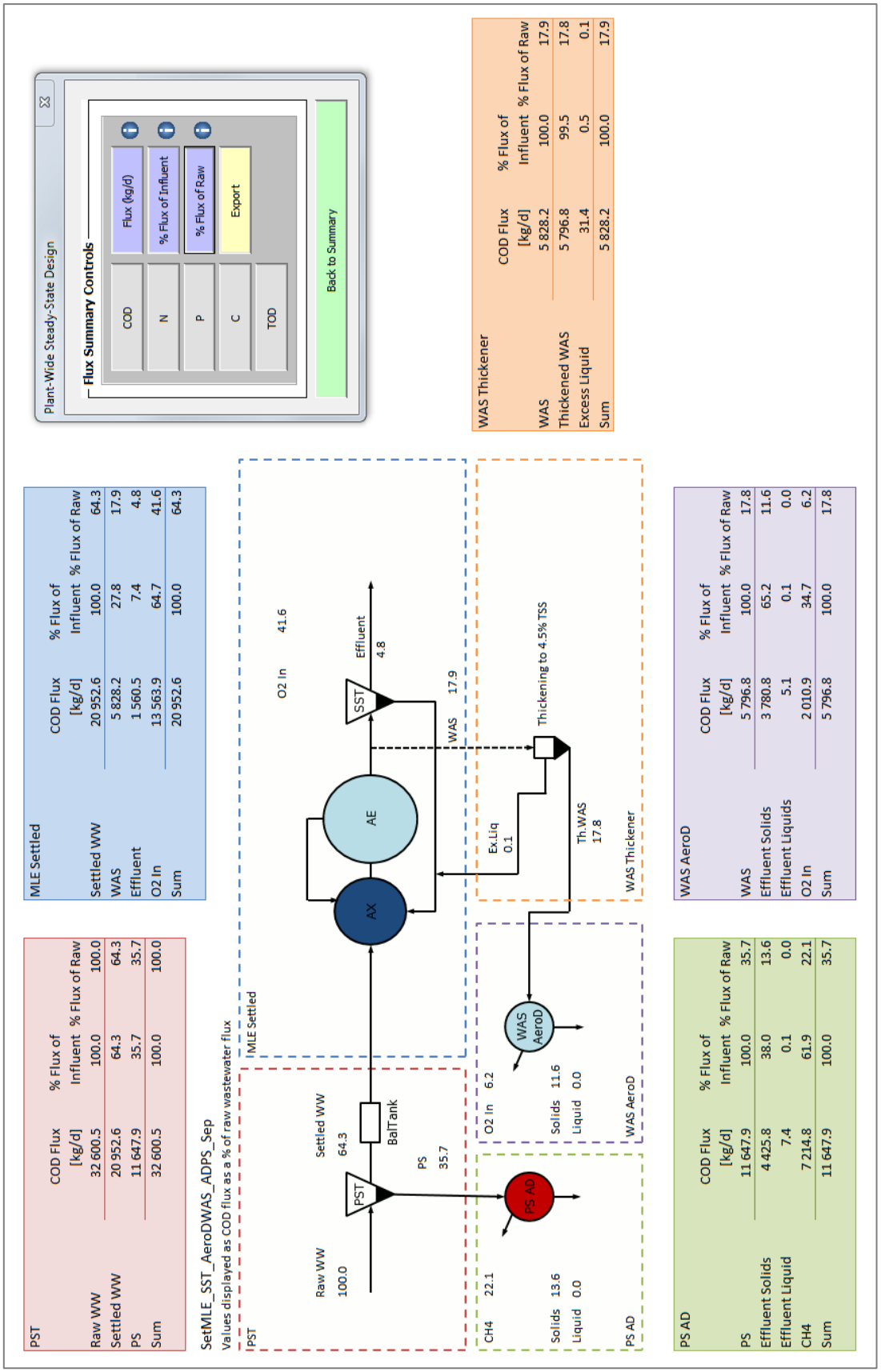



**Figure 6.59: Flux Summary – COD flux summary for the flow-balanced, settled wastewater, balanced MLE system, with PS AD, and WAS AxAeD treatment**

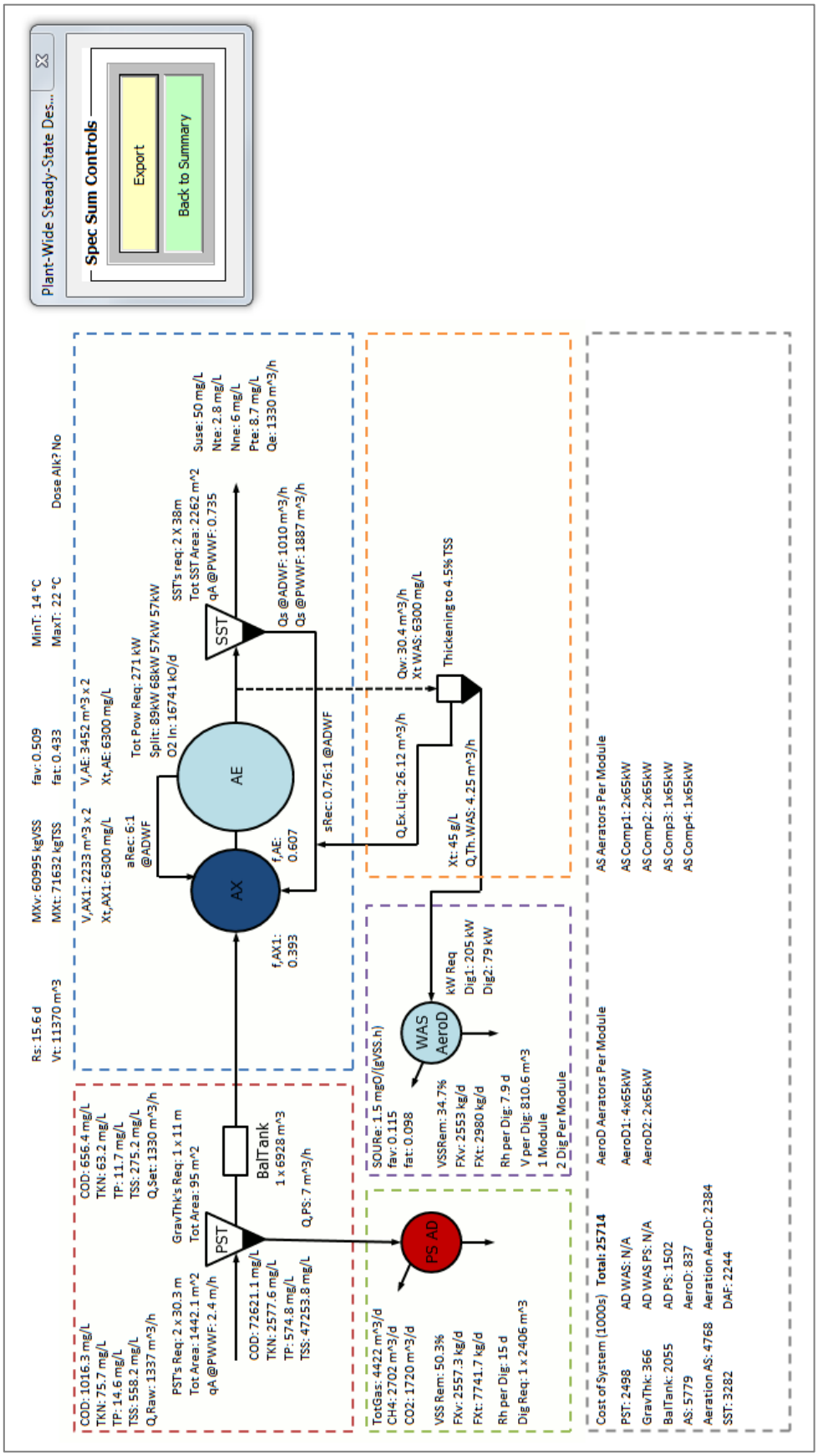



**Figure 6.60: Specifications Summary – Design summary for the flow-balanced, settled wastewater, balanced MLE system, with PS AD, and WAS AxAeD treatment**

## 6.6 PWSSD Navigation

This section covers the navigation around the PWSSD component. A flow chart of the component is presented in Section 6.6.7 WWChar Flow Chart.

### 6.6.1 PWSSD Landing

The PWSSD Landing window is the starting window for a plant-wide design. There are three buttons on this window: *Create New Project, Return to Current Project, Load Saved Project*. This window is shown in Figure 6.61.

The *Create New Project* button starts a new design. Any existing design is cleared when starting a new design. Furthermore, wastewater characteristics are required, therefore when starting a new design a wastewater profile must be created, the WWChar Landing window is displayed and a new profile can be created using one of the WWChar methods provided in the WWChar component (Chapter 5 Program Design Part C: Wastewater Characterisation). Alternatively, if a completed profile exists, it can be loaded in into the new design project.

The *Return to Current Project* button returns the back to the current project; and the *Load Saved Project* calls up a previously saved project, complete or incomplete. This is an interval save feature like WWChar Save Data as discussed in Section 5.7.4.

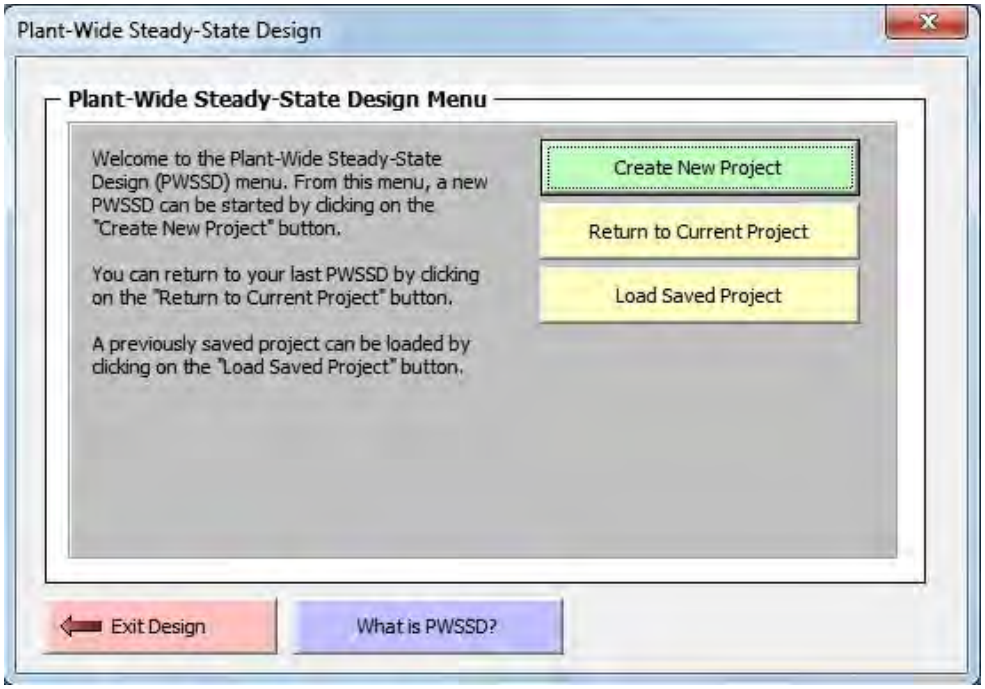



**Figure 6.61: PWSSD Landing**

### 6.6.2 PWSSD System Configuration

The PWSSD System Configuration window, Figure 6.63, follows the PWSSD Landing window. On this window the configuration of the AS system can be selected: MLE, UCT or JHB, selection of the 4-stage and 5-stage will also be provided on this window in the future. The unit processes linked to the AS system can also be selected on this window, namely PST, flow balancing, PS and WAS sludge treatment, sludge mixing, and the WAS flow location. The *Blue Info* buttons display information in the *Design Guidance* frame. The majority of this information is about the different configuration options of the AS system and unit processes, such as its pros and cons, why it is used, and what impact it has on the design of the system.

This window also contains a summary of the wastewater profile used for the design. The most important wastewater characteristics are shown, namely ADWF, total COD, $f_{S'up}$, $f_{S'us}$, $f_{Sb's}$, TKN, FSA, TP, OP, TSS, ISS, and UPO mass ratios. The full wastewater profile containing all the characteristics and flow rates at the different time intervals can be viewed by clicking on the *View Full Profile* button that opens the WWChar Summary window (Section 5.6). The *Load Saved Profile* and *Create New Profile* buttons allow a different profile to be used in the project.

The *Save as New Project* and *Save Changes* relate to the internal save feature, *Save as New Project* saves the current design so that it can be loaded at any time. *Save Changes* is applicable to an already saved or a loaded project; it updates the saved project with any changes made to the design of the system.

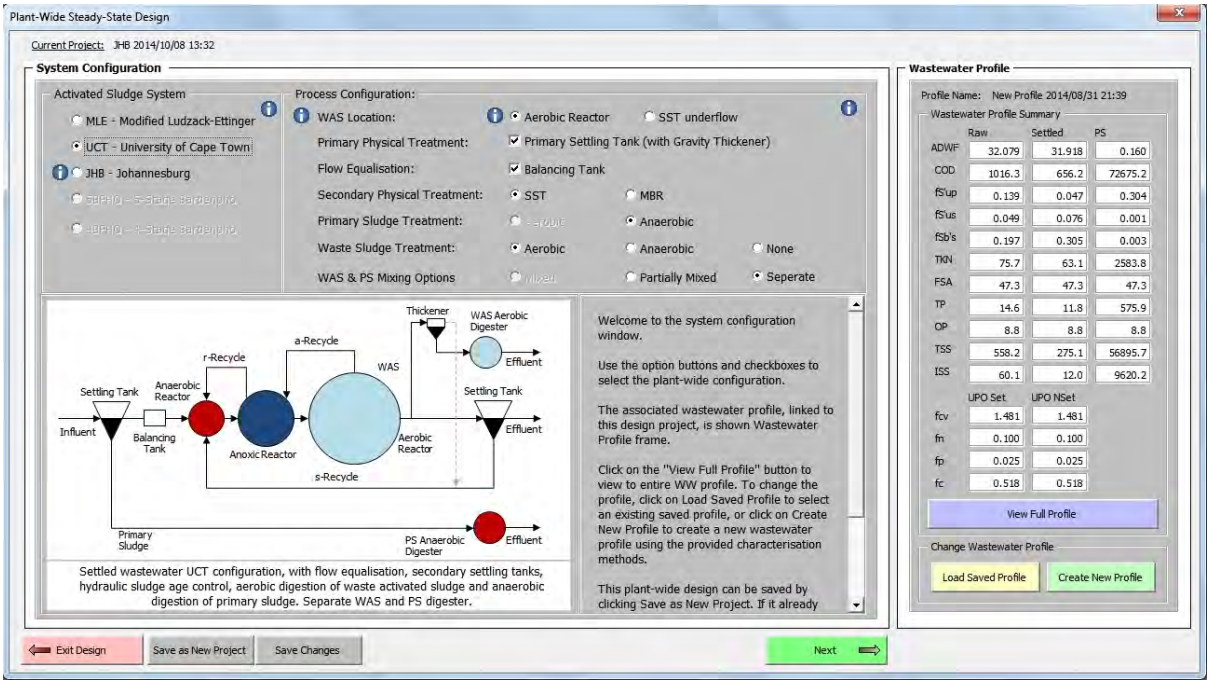



**Figure 6.62: PWSSD System Configuration**

### 6.6.3 PWSSD System Design

The PWSSD System Design window follows the PWSSD System Configuration window. On the PWSSD System Design window, the different design windows, as shown in Sections 6.1 to 6.4, for the different unit process can be accessed.

The unit processes are organised into different pages, each page contains a summary of the inputs entered for its respective steady-state model, and as well as some important information in using the model or on the design of that unit process. On each page, there is a button that allows the design window to be opened. Upstream unit processes must be completed before downstream unit processes can be designed, for example, the designer will not be allowed to design the aeration system if the design of the AS system or the AxAe digester is incomplete.

The *Finish* button opens the PWSSD Design Summary window; before the summary window is opened, the model inputs are checked, any incomplete unit processes or invalid inputs will deny access the PWSSD Design Summary.

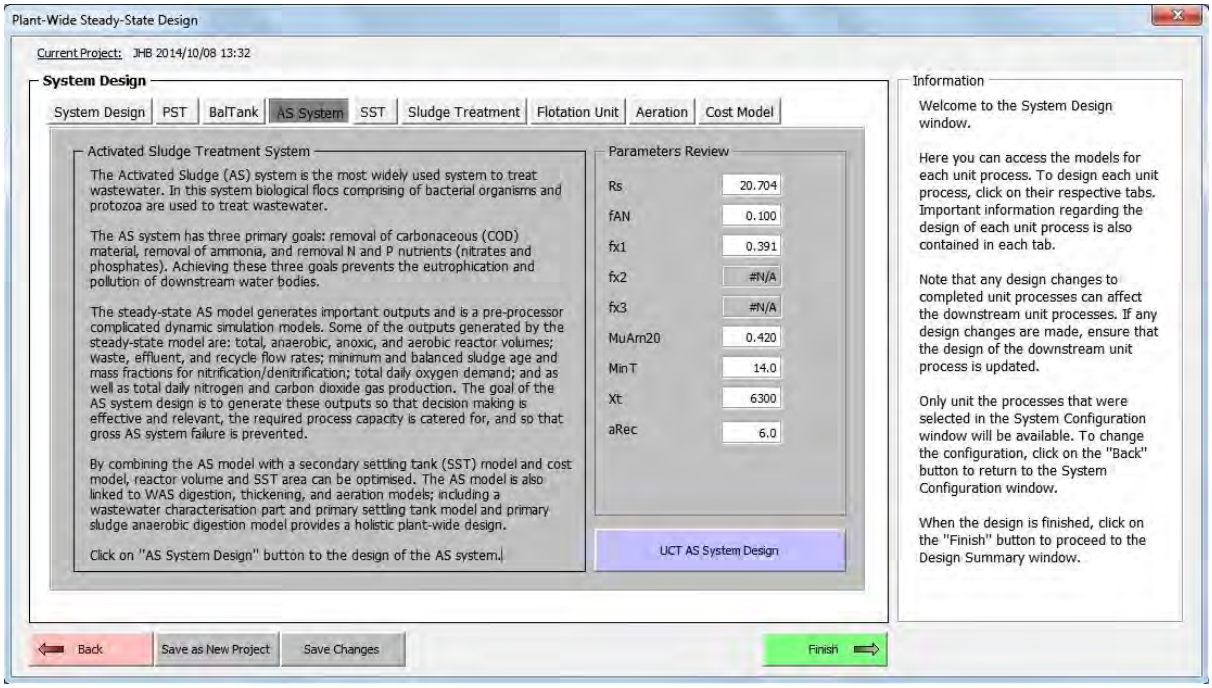



**Figure 6.63: PWSSD System Design**

### 6.6.4 PWSSD Load

The PWSSD Load window, allows a saved project to be loaded. This window is displayed when the *Load Saved Project* button is clicked on the PWSSD Landing window (Figure 6.61). Like the WWChar Load window, the PWSSD Load window contains a *Delete Project* and *Duplicate Project* button for deleting and duplicating the selected saved design project.

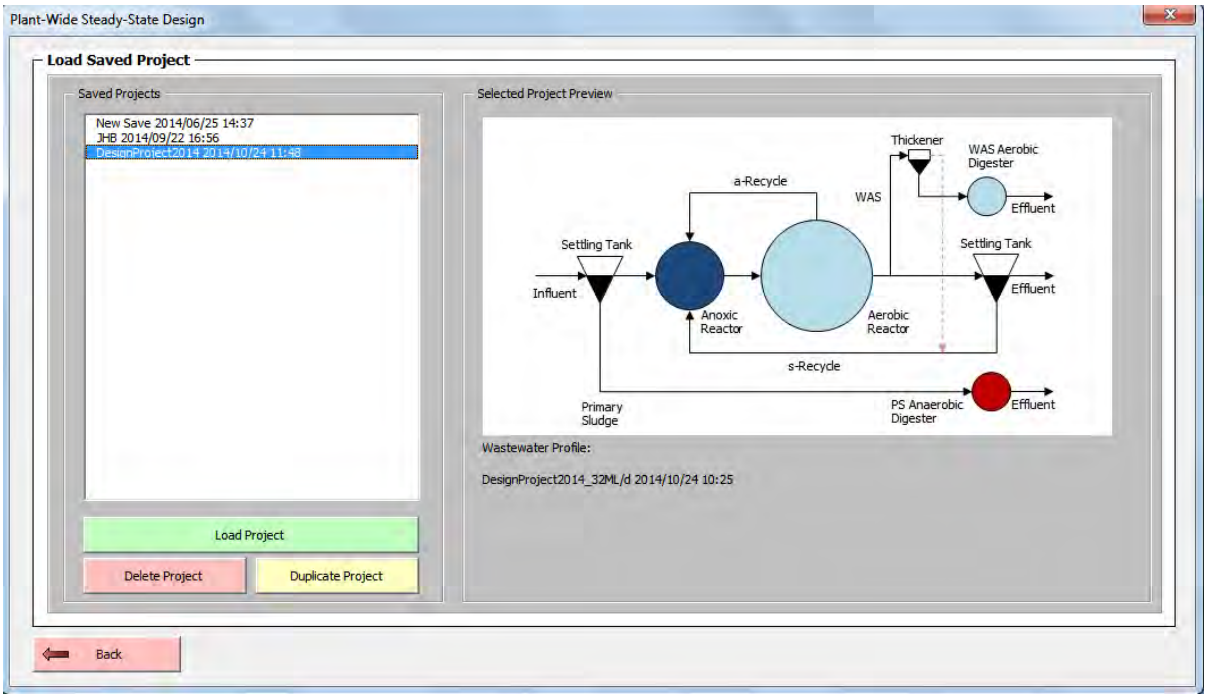



**Figure 6.64: PWSSD Load**

## 6.6.5 PWSSD Save

The PWSSD Save is an internal feature of this program. The current inputs for the current design project are transferred to the Model_SaveData spreadsheet. When called upon, this data is transferred back to the models allowing for the continuation of a previous design project.

The WWChar component is separate from the PWSSD component, a design project can be deleted without deleting the wastewater profile linked to it, and the opposite is also true. Therefore, when a design project is saved, only the name of wastewater profile used for that design project is saved. Then when loading that design project, an index containing all the saved wastewater profiles is checked for the saved wastewater profile name associated with that design project. If it exists in the index, then that wastewater profile exists in the WWChar_SaveData spreadsheet, thus the wastewater profile is also loaded with the design project. If it does not exist because it has been deleted, then a new profile must be created or an existing profile must be loaded in place of the missing profile.

## 6.6.6 PWSSD Model Inputs

In order to link the models the user-interface, a location to store the input data is required. The PWSSDD spreadsheet, which stands for Plant-Wide Steady-State Design Decisions, performs this function. In each user-interface that contains data entry, when the data is entered it is transferred PWSSDD where the data is collected and organised. Preliminary calculations are computed and an input check is performed. This input check inspects the entered data; any

incorrect inputs, for example, negative numbers or non-numeric inputs are flagged and the input check fails. When this occurs, a warning message is sent to the designer via the user-interface. Depending on the type of input that failed, the user might not be able proceed with the models unless it is corrected.

### 6.6.7 PWSSD Flow Chart

The PWSSD flow chart is shown in Figure 6.65. This flow chart outlines the different routes the designer can take when using the PWSSD component. The primary windows are the PWSSD System Configuration and the PWSSD System Design windows. With these windows, the designer can navigate into or out of the WWChar component, and access the various design windows for the unit processes.

## 6.7 PWSSD Conclusion

The PWSSD component allows for the holistic design of a WWTP. Combined with the WWChar component, the PWSSD component can provide meaningful and quantitative design information. This information is vital for the decision-making and can be linked to dynamic simulation software.

The strength of the steady-state models is it comprises of explicit algebraic equations, which allows for relatively easy and quick computation. In interacting with the design windows, this strength is shown by the seamless generation of outputs as model parameters are changed. With the aid of the graphical Flux and Specifications summary tools, the most important design information from the models, such as fluxes, volumes, areas, and flow rates, are conveniently displayed to the designer.

There is much more that can be added to the PWSSD component. Due to flexible structure of the program, Excel, and VBA, various other tools and models can be added to the PWSSD component. Currently, the UCT WRG has projects involving the translation of the UCTOLD and UCTPHO dynamic AS models into VBA code. A dynamic balancing tank model, based on Dold *et al*. (1982, 1984), has also been developed by (Garrard, 2014). In addition to these items, alternative activated sludge configurations (such as the 3-Stage, 4-Stage, and 5-Stage Bardenpho), membrane reactor systems, a more detailed primary settling tank model, and sludge thickening models, can be incorporated. In the future, with these additions, the program will allow for increased flexibility in design options for the designer. The only limitation is the program developer's time and creativity.

A case study of the design and upgrade of an MLE system is provided in Appendix D. Where relevant, this case study was used as a basis for the design windows and examples presented in this chapter, *viz*. SST, Xt Optimisation, AxAeD WAS, Aeration, Cost and Modularisation, and Flux and Specifications Design Summary.

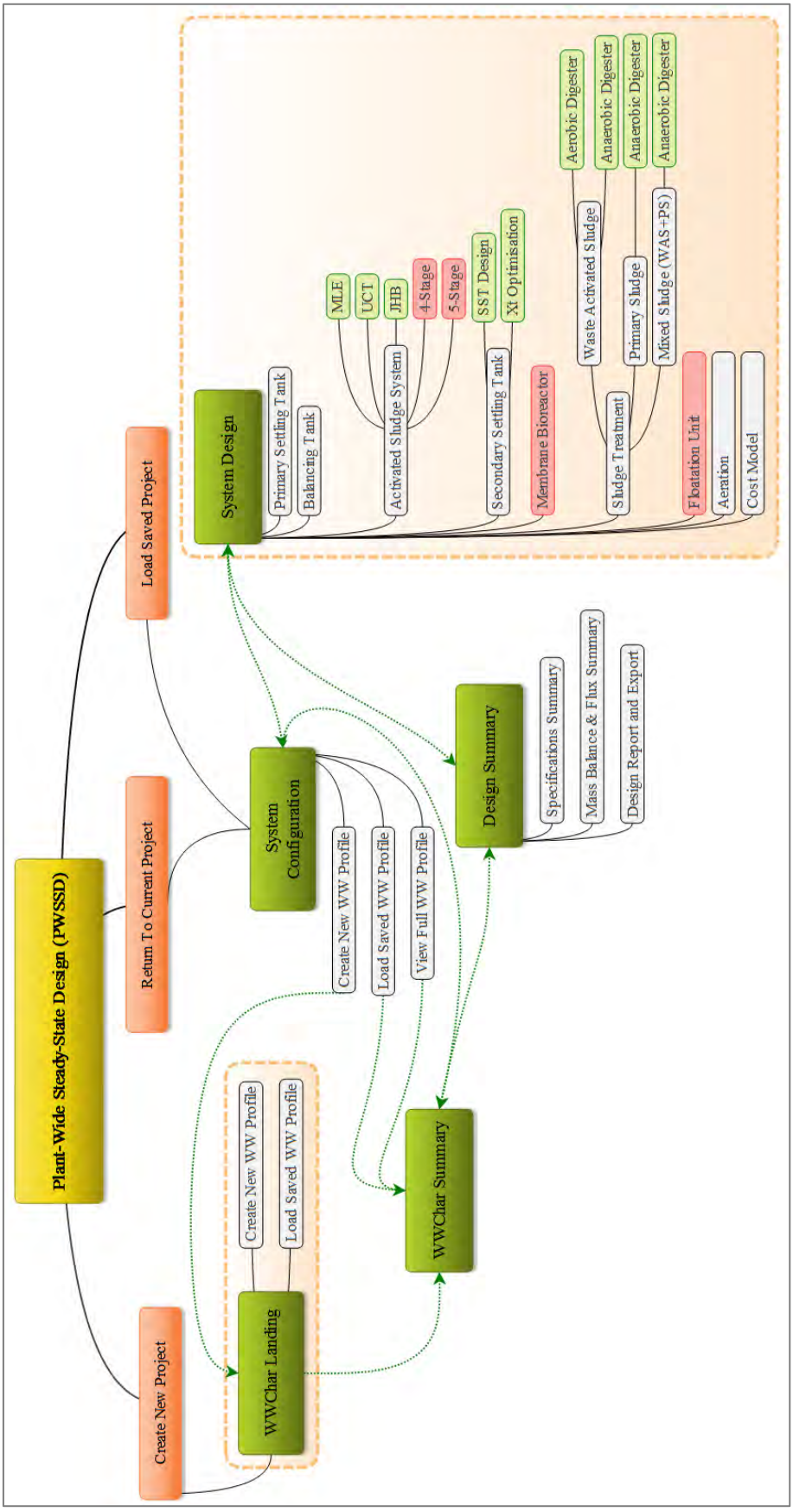



**Figure 6.65: Flow chart for PWSSD**

# 7. Program Design Part E: Capacity Estimation

A capacity estimation (CapEst) component was developed for the program. CapEst uses the steady-state AS models in the PWSSD component; estimations can be run for all the system configurations provided in the PWSSD component (MLE, UCT, and JHB). This powerful tool processes the steady-state models in reverse to find the maximum influent ADWF that the system can accommodate for a defined and sized configuration. Knowing this theoretical ADWF capacity, the actual system's performance can be evaluated and compared to CapEst's of alternative AS systems. The CapEst process is a quicker process compared with the plant-wide design process. After creating a wastewater profile with the WWChar component, one simply enters a few important inputs and then clicks the "Estimate Capacity" button to run the evaluation. The CapEst solver determines the maximum ADWF in an incremental trial and error approach. It is theoretically possible to derive a series of equations that can solve for the maximum ADWF; however because the PWSSD models were already developed and written into a spreadsheet and code, it was a lot simpler to write a VBA procedure that increases the influent ADWF until a specific condition is met. For example starting with a flow of 0 ML/d and increasing it until the maximum overflow rate of the SSTs at PWWF is obtained. Alternative bottlenecks can also be evaluated, for example aeration capacity; this is simply done by changing the end condition that the CapEst solver looks for.

CapEst can be accessed from the main program window, the CapEst window consists of five frames: *System Configuration* (**A**); *System Inputs* (**B**); *CapEst Selection and Results* (**C**); *Wastewater profile* (**D**); and *Design Guidance* (**E**). A screen capture of the CapEst window is shown in Figure 7.1; enlargements of **B** and **C** are available in later Figures (7.2, 7.3, and 7.5).

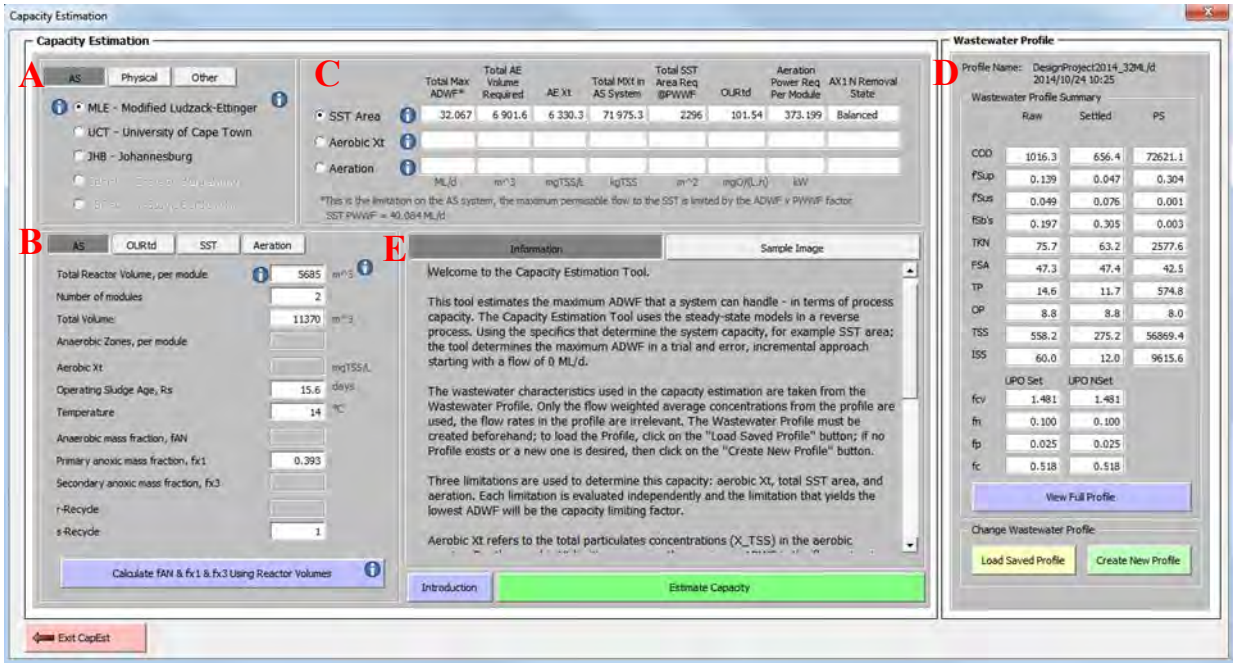



**Figure 7.1: Capacity Estimation**

The *System Configuration* frame (**A**) allows for the selection of the type of AS system (MLE, UCT or JHB), and as well as the physical treatment schemes (flow balancing and PST). The selection of these options changes the type of AS model used, and as well as the inputs to that are required for the CapEst.

The inputs are contained in the *System Inputs* frame (**B**). This frame contains four inputs pages: 1) *AS*; 2) $OUR_{td}$; 3) *SST* and 4) *Aeration*. The AS inputs page allows for entering AS system specific parameters such as the operating sludge age, reactor volume, mass fractions, temperature etc. The $OUR_{td}$ input page is also related to the AS model, however this page focuses on the inputs that determine the nitrification and denitrification capacity of the system, which along with COD removal, dictate the oxygen and aeration requirements. The *SST* input page is for the SST specifications and settling parameters; the PDWF and PWWF flow factors can also be specified on this page. The last page, *Aeration*, is for the aeration model inputs.

The *CapEst Selection and Results* frame (**C**) shows the results from the estimation and allows for the selection of the CapEst scenario to be evaluated. The CapEst scenario specifies the end condition of the CapEst solver and the bottle neck of the system. There are three CapEst scenarios available: SST area, aerobic $X_t$, and aeration. The SST area scenario makes the SSTs the bottleneck and hence finds the maximum ADWF (scaled up to the PWWF) that the SSTs can handle. The aerobic $X_t$ scenario makes the total particulates concentration ($X_t$) in the aerobic reactor the end condition, and finds the maximum ADWF to obtain the entered aerobic $X_t$. The aeration scenario finds the maximum ADWF that the aeration system can handle. The three scenarios and some important points regarding them are discussed further in the next section.

The wastewater characteristics used for CapEst is taken from the wastewater profile linked to the CapEst. It is important to note that the CapEst results are highly dependent on the wastewater profile, this determines the FWA concentrations, and hence the organic load on the system. The different WWChar methods in the WWChar component should be used to characterise the wastewater before the capacity estimation can be done. The *Wastewater Profile* frame (**D**) allows a previously created profile to be loaded in to the CapEst, or a new one to be created and used. Only the flow-weighted average concentrations (COD, TKN, TP, particulates) from the profile are used - the flow rates in the profile are irrelevant because the goal of CapEst is to determine the maximum ADWF, for a defined PWWF/ADWF ratio.

The *Design Guidance* frame (**E**) contains information regarding the CapEst process. Information can be displayed by clicking on the *Blue Info* buttons.

## 7.1 Capacity Estimation Scenarios

Three CapEst scenarios can be selected. The scenario selected changes the end condition of the CapEst solver. They can be selected by using the option buttons in the *CapEst Selection and Results* frame. An overview of each scenario is provided in this section.

### 7.1.1 SST Area

In terms of process capacity, the SSTs are usually the bottlenecks of the WWTP. This is because the SSTs are sensitive to the hydraulic loads of the system; for a specified total SST area, the greater the diurnal variation and PWWF factor the lower the capacity of the system. This scenario assumes the bottleneck is the SSTs and for a given sludge age and sludge settleability, and finds the influent flow rate of the system, which sets the reactor TSS concentration so that the SSTs operate at its limiting, overflow rate. It is important to note that this influent flow rate is the PWWF and not the ADWF. The ADWF determines the feed concentration to the SST, but this ADWF is then scaled up to the PWWF that will then determine the SST area required. Hence, a PWWF flow factor w.r.t to ADWF flow is required.

A quick summary of the CapEst process for this scenario is as follows: CapEst starts with an ADWF of 0 ML/d, the entered mass fractions determine the volume fractions of the different reactors; and then with the entered total AS reactor volume, the aerobic volume is calculated using the aerobic volume fraction. The ADWF determines the sludge mass in the system; the aerobic reactor $X_t$ concentration can then be calculated because the aerobic mass fraction and aerobic volume is known. The aerobic $X_t$ concentration is the feed concentration to the SST. The PWWF is calculated by taking the ADWF and multiplying it by the PWWF:ADWF flow factor. The $X_t$ and the sludge settling parameters (n and $V_0$) dictate the SST maximum overflow rate. The required SST area is then calculated by dividing the PWWF by the maximum overflow rate and adjusting for the SST flux rating. This required SST area is compared with the entered, available, SST area. The CapEst procedure then reiterates the ADWF until the required SST area equals the available SST area.

It is recommended to use flow factors for the estimation; however, if desired, the PWWF:ADWF factor can be set to 1:1. The result would be that the ADWF equals the PWWF and hence the maximum ADWF of the AS system will be the same as the maximum flow rate for the SSTs. The PWWF:ADWF factor can be specified in two ways, it can be entered directly, or it can be obtained from the wastewater profile. If it is obtained from the wastewater profile, i.e. it is not a custom value, the factor will be 1.25:1 if a balancing tank is included in system configuration.

### 7.1.2 Aerobic Xt

Aerobic $X_t$ refers to the total particulates concentrations (X_TSS) in the aerobic reactor. For the aerobic $X_t$ scenario, CapEst determines the required ADWF to obtain a specific aerobic reactor $X_t$. Knowing this ADWF can be useful in the sense that it can be compared with the actual ADWF on the system. This comparison can then be used to judge the accuracy of the wastewater profile and characteristics. For example, if the actual WWTP has an ADWF of 32 ML/d and an aerobic $X_t$ of 6300 mg/L, but the CapEst gives an ADWF less than 32 ML/d (e.g. 30 ML/d) to achieve an aerobic $X_t$ of 6300 mgTSS/L, then it can be accepted that the wastewater has not been characterized correctly. There of course can be many reasons for this difference. However it is most likely that one or more of the flow rate, the influent total COD concentration, the influent unbiodegradable particulate organics (UPO) COD concentration (or fraction, fS'up) or the influent ISS concentration ($X_{IOi}$) in the wastewater profile used for the CapEst are higher than the actual concentrations at the WWTP. For EBPR plants, the biological P removal also influences the TSS concentration in the aerobic reactor - the higher the P removal, the higher the $X_t$ for the same organic load and wastewater characteristics. Hence for the UCT and JHB systems, the measured P removal has to be correctly predicted to make a correct comparison between measured and calculated reactor TSS concentration.

The procedure for this scenario is largely the same as for the SST scenario the only difference is the end conditions of the CapEst procedure. CapEst starts with an ADWF, this ADWF determines the organic load on the AS system. The organic load, along with the AS system inputs, determine the sludge mass produced ($MX_t$). The total reactor volume is specified by the designer, using this total volume and the entered mass fractions, the aerobic reactor $X_t$ is calculated. The aerobic $X_t$ and the PWWF determines the required total SST area. CapEst increases or decreases ADWF until the calculated aerobic $X_t$ concentration equals the entered aerobic $X_t$ concentration, ignoring the loading (over of under) conditions on the SST.

The reason for using the term aerobic $X_t$, and not just $X_t$, is because for certain systems the $X_t$ is not the same in every reactor. The $X_t$ that feeds the SST is required; in all systems (MLE, UCT, JHB, 4-Stage and 5-Stage Bardenpho) the SST's feed concentration is the aerobic reactor's $X_t$. Therefore the term aerobic $X_t$ is used to identify specifically the $X_t$ that is required. The aerobic $X_t$ has some further importance in the system design and capacity estimation. The aerobic $X_t$ is usually the design $X_t$ and for hydraulic control of sludge age, sludge is harvested from the aerobic reactor. The mass of sludge ($MX_t$) is determined by the organic load, a fixed mass of sludge is required to be wasted in order to provide the desired sludge age. This waste mass, divided by the WAS $X_t$, determines the WAS flow rate from the reactor for all configurations. The WAS $X_t$, like the SST feed concentration, is the $X_t$ of the aerobic reactor. Technically, the $MX_t$ (kgTSS) can be used instead of $X_t$ because CapEst estimates the ADWF to produce a certain $MX_t$ for the system. However, asking the designer for the $MX_t$ (kgTSS) is unreasonable because it is not a measured parameter. Asking for the

aerobic $X_t$ concentration is more sensible as a 1L sample can be easily collected from the aerobic reactor, and have the TSS concentration measured, if this is not routinely done.

### 7.1.3 Aeration

The aeration scenario is the last available scenario in CapEst. In this scenario, an ADWF to utilise fully the aeration equipment is determined. Like the SST area scenario, the aeration requirements are determined from the peak flows, in this case, it is the peak TOD load. The factor for this is obtained from the wastewater profile used in the CapEst. Note in the aeration model, a division of the total peak power between four AS compartments is used (typically 33%, 25%, 21% and 21% of total peak power in compartments 1 to 4 respectively). However, for CapEst, this is disregarded as the calculated total peak power required per module (i.e. 100%) is compared to the total aeration power available per module (100%). Thus if one compartment's total aeration power supply is entered in the CapEst window, the ADWF capacity of the entire system will be underestimated. The CapEst procedure is again the same as for the SST area and aerobic $X_t$ scenarios, the ADWF starts at 0 ML/d and increases until the end condition is reached, which is when the total calculated peak power demand per module equals the available (entered) total power supply

## 7.2 Capacity Estimation Input Requirements

The input requirements for CapEst are straightforward; in fact, the most complicated process is the WWChar process to generate a wastewater profile to be used for CapEst. This characterisation process, which is done beforehand, does not affect the CapEst procedure; it only affects the CapEst results. There are four pages for the inputs: 1) *AS*; 2) $OUR_{td}$; 3) *SST* and 4) *Aeration*. Each page focuses on different aspects of the system; all four pages have to be completed.

The *AS* and $OUR_{td}$ inputs page is shown in Figure 7.2. The inputs on the *AS* inputs pages will vary depending on the AS system configuration selected (MLE, UCT, JHB etc.), the *SST*, $OUR_{td}$ and *Aeration* input pages are independent of the AS system configuration. The *AS* inputs page contains the following inputs: reactor volume, anaerobic zones, sludge age (SRT), temperature, mass fractions, and r- and s-recycles. When the aerobic $X_t$ CapEst scenario is selected, the aerobic $X_t$ input is made available. The inputs on the *AS* page determine the sludge mass production in the AS reactor and hence the feed concentration to the SST.

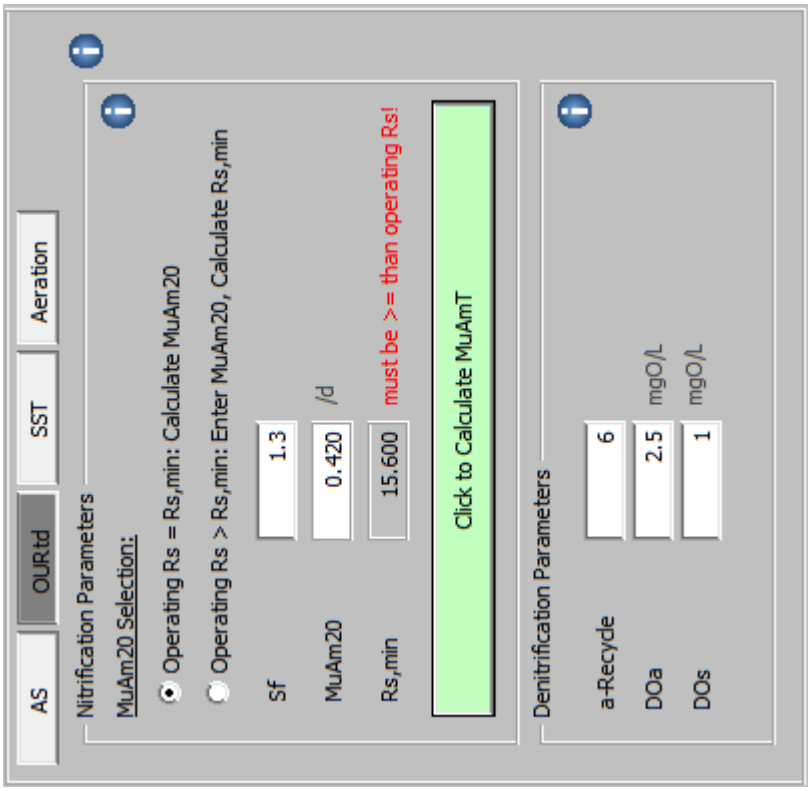
The $OUR_{td}$ inputs page allows for the selection of the nitrifier growth rate ($\mu_{Am20}$), the safety factor in nitrification ($S_f$), the a-recycle, and the dissolved oxygen concentrations in the a- and s-recycles. These inputs determine the nitrification and denitrification capacity of the AS system and hence the oxygen demand – which is needed to estimate the aeration requirements. The input of $\mu_{Am20}$ can be done in two ways. The first assumes that the operating SRT is at the

minimum SRT to ensure nitrification; the entered $S_f$, temperature, and mass fractions allow for the calculation of $\mu_{Am20}$. Alternatively, the second method assumes that the operating SRT is greater than the minimum SRT; here $\mu_{Am20}$ cannot be calculated and thus must be entered directly. The minimum SRT is then calculated from the entered $\mu_{Am20}$, $S_f$, temperature and mass fractions, the operating SRT entered on the *AS* input page must be greater than this calculated minimum SRT.

The *SST* input page, Figure 7.3, contains the inputs relevant for computing the SST model. The inputs required for the SST are SST area per SST, Number of SSTs, Settling measurement of SVI, DSVI, or SSVI, and the PDWF and PWWF factors w.r.t to ADWF. The SST model uses the idealized 1-dimensional flux theory (1DFT) for which the initial settling velocity ($V_0$) and hindered settling parameter (n) are required. These two parameters are calculated using the empirical equations that link them to SVI, DSVI, and SSVI. Like in the SST design window, a message regarding the weakness of SVI is displayed to the designer if the SVI measurement is chosen. An input for the 1D Flux Theory's flux rating is also provided.

The PDWF and PWWF factors w.r.t ADWF can be chosen by the designer or it can be loaded from the wastewater profile. The *Use the factors associated with the wastewater Profile* checkbox is used for this selection. If no factors are to be applied, then this checkbox should be deselected and a PDWF and PWWF factor of 1:1 must be entered into the respective textboxes. If the flow factors are not chosen, then if a balancing tank is included in the system configuration, the PDWF and PWWF factor will be set to 1:1 and 1.25:1.

The *Aeration* inputs page is also shown in Figure 7.3. These inputs are exactly the same inputs as for the Aeration Design window in the PWSSD component. The inputs required are site altitude, impurities correction factors (alpha and beta), dissolved oxygen concentration, standard oxygen transfer rate and the mechanical efficiency of the aerators. If the aeration scenario is selected, the total power supply of the aerators per AS module must also be entered because this is the end condition that is required for the CapEst procedure.



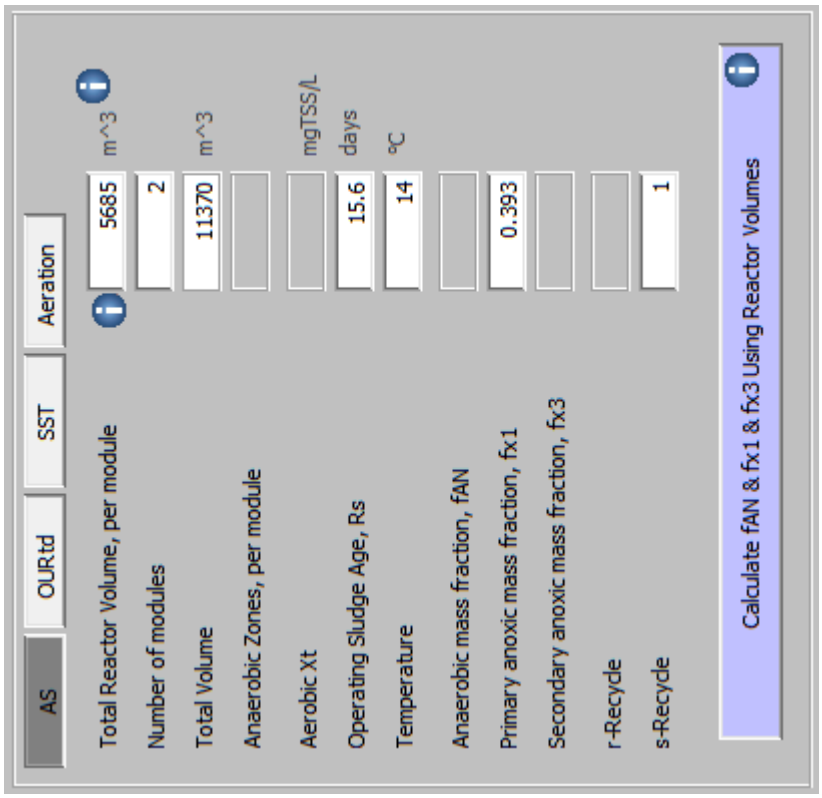




**Figure 7.2: Capacity Estimation – AS system and $OUR_{td}$ input pages**

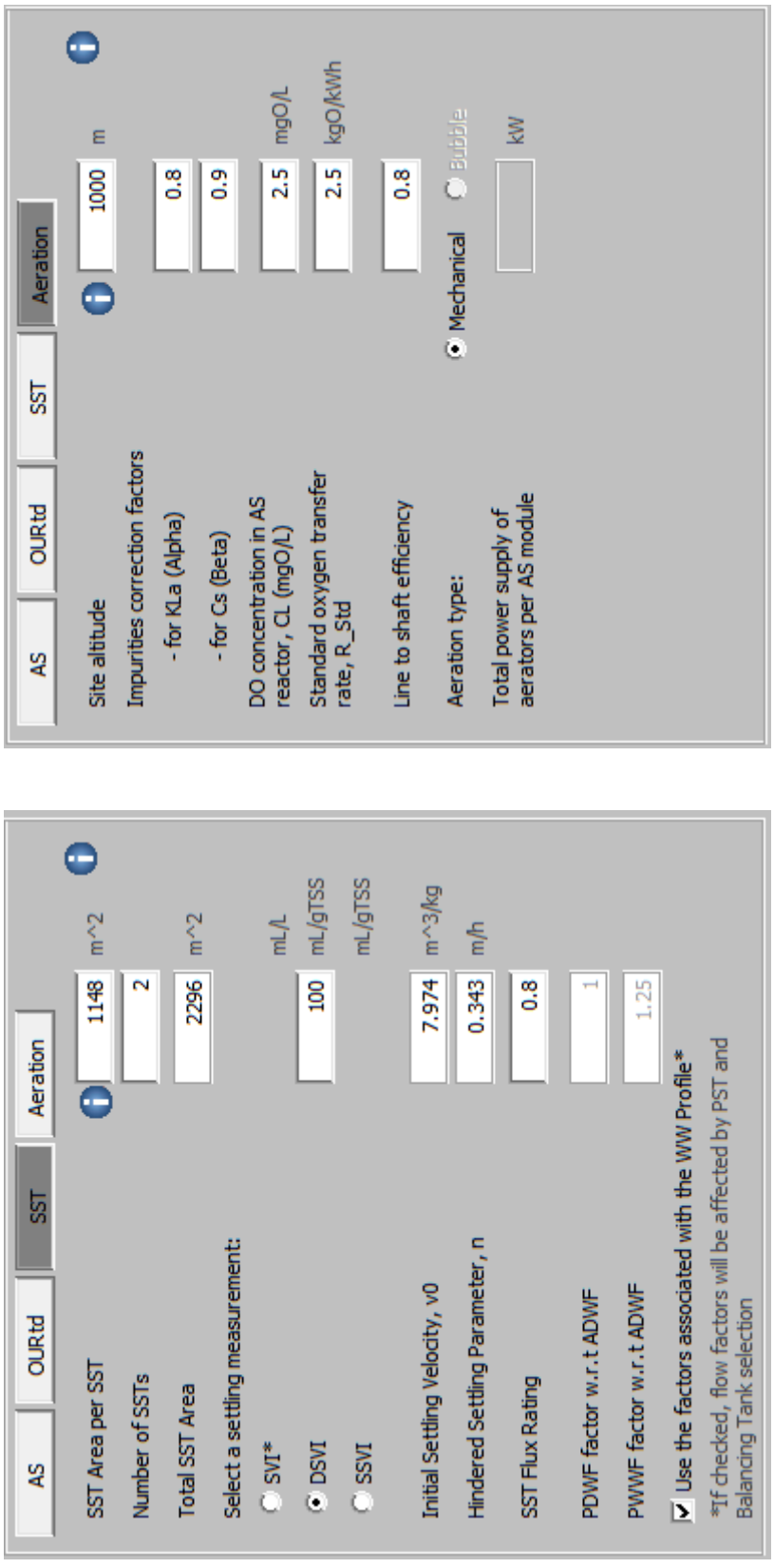



**Figure 7.3: Capacity Estimation – SST and Aeration input pages**

Due to the uneven distribution of sludge mass in certain system configurations resulting in different anaerobic, anoxic, and aerobic reactor TSS concentrations, the mass fractions are not necessarily equal to the volume fractions. If these mass fractions are not known, and the volume fractions are entered in place of the mass fractions, then CapEst will overestimate (for UCT system) or underestimate (for JHB system) the ADWF depending on the system selected. A CapEst was performed on the flow-balanced UCT system example using the same wastewater characteristics in the PWSSD chapters (summarised in Appendix C). This system is operated at 16 days SRT, has 2 in-series anaerobic zones, r and s-recycles of 1:1 respectively, total SST area of 3000 $m^2$, DSVI of 100 mL/gTSS and the volume and mass fractions shown in the Table 7.1. If the volume fractions were entered as the mass fractions, the CapEst gives the maximum ADWF, for the SST scenario, as 36.5 ML/d. If the mass fractions were correctly used, the CapEst gives the maximum ADWF as 38.8 ML/d. This is only a 6% difference, which is not large, but it can be deciding factor for upgrading or not upgrading a WWTP.

**Table 7.1: Volume, volume fraction, and mass fractions for a UCT system example and the CapEst result if the volume fraction or mass fraction is entered**

| Zone | Volume ($m^3$) | Volume Fractions and ADWF if this is entered for CapEst | Mass Fractions and ADWF if this is entered for CapEst |
|---|---|---|---|
| Anaerobic | 3775 | 0.182 | 0.100 |
| Anoxic | 7380 | 0.355 | 0.391 |
| Aerobic | 9607 | 0.462 | 0.509 |
| CapEst ADWF (ML/d) | | 36.5 | 38.8 |

To avoid entering the volume fractions as the mass fractions, a tool to calculate the mass fractions using the reactor volumes and recycle ratios has been created and included. This can be accessed by clicking the *Calculate $f_{AN}$ & $f_{xt}$ Using Reactor Volumes* button. The AS system configuration is selected and the reactor volumes are entered on this window. The mass fractions are calculated from these inputs and then transferred to the CapEst *AS* inputs page. The *Mass Fractions Calculator* is show in Figure 7.4.

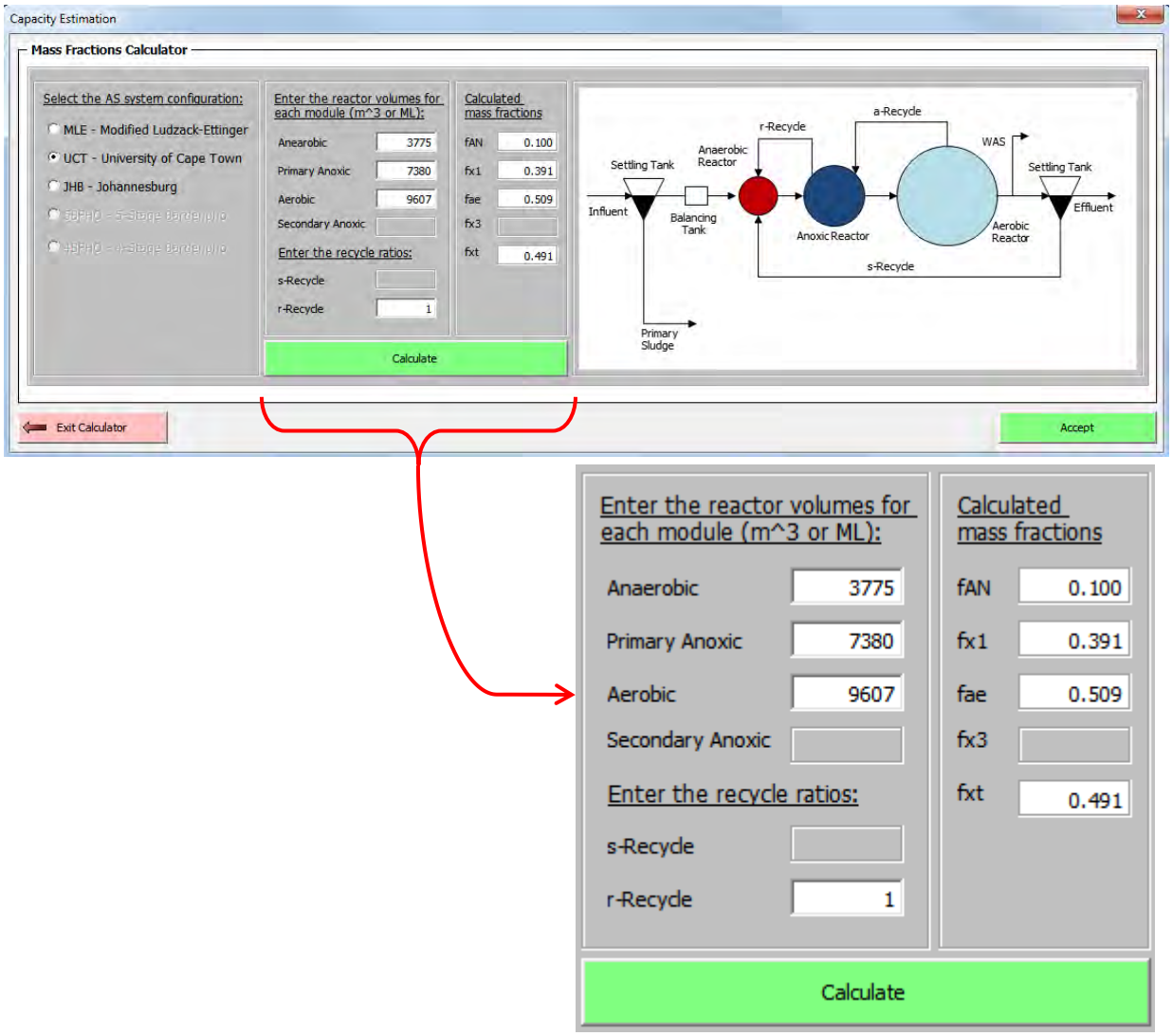






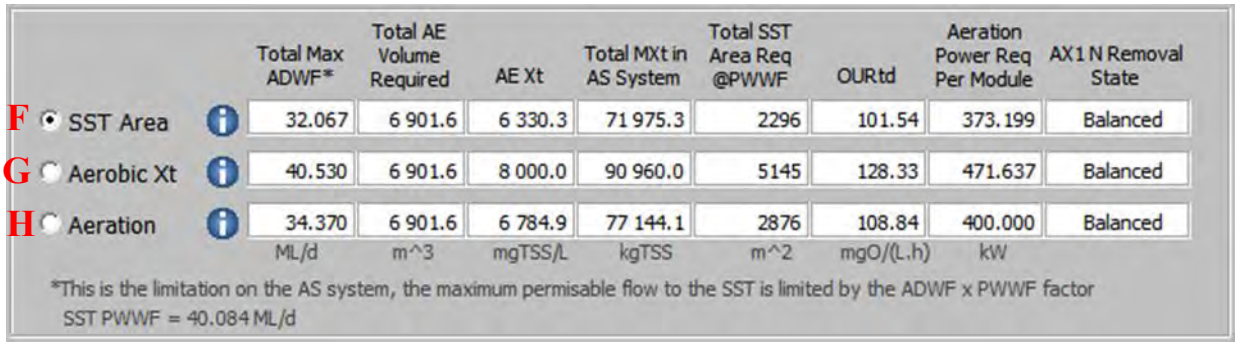
**Figure 7.4: Capacity Estimation – Mass Fractions Calculator**

## 7.3 Capacity Estimation Results and Example

The *CapEst Selection and Results* frame displays the results for the CapEst solver. The following results are displayed: maximum total ADWF, total aerobic volume aerobic $X_t$, total $MX_t$, SST area required, $OUR_{td}$, aeration power required per module, and AX1 removal state. The maximum total ADWF is the influent flow rate for the entire system, the maximum ADWF per module must be divided by the number of modules in the system, the same goes for the total aerobic volume and the total particulates mass in the AS reactor ($MX_t$). The other results are for individual modules.

Figure 7.5 shows an SST scenario (**F**) CapEst on the flow-balanced, settled WW MLE system discussed in Section 6.1.1. The inputs for this estimation are shown in Figure 7.2 and Figure 7.3. For this scenario, the maximum ADWF determined by CapEst is 32.067 ML/d,

which is almost identical to the actual ADWF, 32.08 ML/d, used in the Section 6.1.1 MLE design example. This is of course expected because the inputs and system sizing are the same; the slight difference is due to number rounding of the inputs.



| | | Total Max ADWF* | Total AE Volume Required | AE Xt | Total MXt in AS System | Total SST Area Req @PWWF | OURtd | Aeration Power Req Per Module | AX1 N Removal State |
|---|---|---|---|---|---|---|---|---|---|
| F | SST Area | 32.067 | 6 901.6 | 6 330.3 | 71 975.3 | 2296 | 101.54 | 373.199 | Balanced |
| G | Aerobic Xt | 40.530 | 6 901.6 | 8 000.0 | 90 960.0 | 5145 | 128.33 | 471.637 | Balanced |
| H | Aeration | 34.370 | 6 901.6 | 6 784.9 | 77 144.1 | 2876 | 108.84 | 400.000 | Balanced |
| | | ML/d | m^3 | mgTSS/L | kgTSS | m^2 | mgO/(L.h) | kW | |

*This is the limitation on the AS system, the maximum permisable flow to the SST is limited by the ADWF x PWWF factor
SST PWWF = 40.084 ML/d

**Figure 7.5: Capacity Estimation – Results for the three different scenarios**

A number of further analysis options can be performed and compared to the original 32.067 ML/d system. Keeping all inputs the same but:

1) Build 1 additional 5685 $m^3$ AS module (total of 3 modules) – hypothetical cost 2889*
2) Build 2 additional 1148 $m^2$ SSTs (total of 4 SSTs) – hypothetical cost 3307
3) Build 1 AS module and 1 SST (total of 3 modules and 3 SSTs) – hypothetical cost 4543
4) Build 2 additional 5685 $m^3$ AS module (total of 4 modules) – hypothetical cost 5779

The ADWF capacities for these options will be 42.08 ML/d, 39.30 ML/d, 48.10 ML/d, and 50.639 ML/d, constituting to a 31%, 22%, 50% and 58% increase in capacity. At a quick glance at these results, the second choice is not the best decision as it offers a lower increase in capacity compared to option one and is hypothetically more expensive. Option 4 offers the greatest increase but is the most expensive option. Option 3 appears as the best option, as its hypothetical costs lie between option one and four, and its percentage increase in capacity is closer to option four. By dividing the hypothetical cost by the percentage increase, these judgements can be backed up. The total costs per percentage increase for the four options are: 93.20, 150.32, 90.86, and 99.64, which shows that option 3 > option 2 > option 4 > option 1. The analysis of the four options are summarised in Table 7.2. This outcome is of course entirely dependent on the parameters in the AS and SST cost functions. The values used in this analysis are entirely hypothetical. The consultants and contractors that design and build WWTPs need to enter/provide realistic values, which they know best from their experience.

**Table 7.2: Total cost per % increase in capacity for the various expansion options**

* Cost in R1000's, with cost function inputs of 20(θ)^1.212 and 770(V)^0.761, see Section 6.4.4

| Expansion Option | ADWF Capacity (ML/d) | AS Cost (R1000's) | SST Cost (R1000's) | Total Cost | Capacity Increase from original 32 ML/d MLE (%) | Cost per %Increase (Lower = Better) |
|---|---|---|---|---|---|---|
| +1 AS Module | 42.08 | 2889 | 0 | 2889 | 31 | 93.20 |
| +2 SSTs | 39.30 | 0 | 3307 | 3307 | 22 | 150.32 |
| +1 AS Module & +1 SST | 48.10 | 2889 | 1653 | 4543 | 50 | 90.86 |
| +2 AS Module | 50.64 | 5779 | 0 | 5779 | 58 | 99.64 |

An aerobic $X_t$ (**G**) and aeration scenario (**H**) can also be performed on this system. For the aerobic $X_t$ scenario, using the same inputs as for the SST scenario but for an aerobic $X_t$ of 8000 mgTSS/L (entered in to the *Aerobic Xt* input box), the maximum ADWF flow to achieve this concentration in the aerobic reactor is 40.53 ML/d. With this flow rate and aerobic $X_t$, the total SST area required is 5415 $m^2$ at PWWF and an aeration power supply of 471.6 kW is required per module. The AX1 N removal state is still balanced because the state is dictated by the SRT, $f_{xt}$, and the influent TKN and COD concentrations - not the influent ADWF. For the aeration scenario, 400 kW is entered into the *Total power supply of aerators per AS module* input box. The maximum ADWF that can be sustained by the 400 kW aerators is 34.37 ML/d. Note that this ADWF is the total influent flow to the system, in this example, there are 2 AS modules, and thus the ADWF per module is 34.37 ML/d divided by 2, giving 17.185 ML/d.

If the flow-balanced, settled WW MLE system is changed to a UCT system by adding a 1200 $m^3$ anaerobic reactor and having an r-recycle of 1:1, the new total volume per module is 6885 $m^3$ (UCT Opt1). The anaerobic and anoxic mass fractions as determined by the Mass Fractions Calculator are 0.095 and 0.355. This gives a total unaerated mass fraction ($f_{xt}$) of 0.450, and an aerobic mass fraction (fae) of 0.550. The change in the $f_{xt}$ changes the minimum SRT allowed. The system is no longer a balanced system and the original operating SRT of 15.60 days might not be sufficient to ensure nitrification. If there is no change to the $\mu_{Am20}$ and temperature and $S_f$ parameters, the minimum SRT calculated from the *OUR$_{td}$* inputs page is 18.216 days. A new operating SRT that is higher than the minimum must be entered – 19 days is used. Then if there are no changes to the SSTs and aeration inputs, the capacity of this new UCT system is 24.555 ML/d. This lower capacity (than the original MLE system) is expected because there is a greater sludge production due to the BEPR process. However, a problem occurs in that the primary anoxic reactor (AX1) is overloaded, this is because the AX1 is not large enough to denitrify fully its nitrate load or the a-recycle is too high. Keeping the 1200 $m^3$ anaerobic reactor expansion, but converting 200 $m^3$ of the aerobic reactor to an anoxic zone, thus giving a new primary anoxic volume and aerobic volume of 2434 $m^3$ and 3251 $m^3$ (UCT Opt2), the new mass fractions are 0.095 ($f_{AN}$), 0.387 ($f_{x1}$), 0.518 (fae) and 0.482 ($f_{xt}$), and the new minimum sludge age is 20.104 days. Setting the operating SRT to 22 days gives an ADWF capacity of 22.135 ML/d and a balanced AX1 exactly loaded with nitrate at an a-recycle of 6:1.

Alternatively, for conversion to a JHB system, constructing a new 800 $m^3$ anaerobic reactor and a 400 $m^3$ secondary anoxic reactor per module will give a total volume per module of 6885 $m^3$. For this expansion, again the AX1 state would be overloaded; to address this issue, 200 $m^3$ of the existing aerobic reactor is converted to an anoxic zone thus increasing the primary anoxic reactor by 200 $m^3$. The new reactor volumes per module is 800 $m^3$ anaerobic, 2434 $m^3$ primary anoxic, 3251 $m^3$ aerobic and 200 $m^3$ secondary anoxic. Giving new mass fractions of 0.110 ($f_{AN}$), 0.334 ($f_{x1}$), 0.110 ($f_{x3}$), 0.446 (fae), and $f_{xt}$ is 0.554. For the same $\mu_{Am20}$, $S_f$, and temperature, the minimum SRT is 26.216 days. Setting the operating SRT to 27 days, the capacity of this new JHB system is 22.321 ML/d. The UCT and JHB expansion options are summarised in Table 7.3.

**Table 7.3: UCT and JHB expansion options for the SST scenario**

| Parameter | MLE Original | | UCT New Opt1 | | UCT New Opt2 | | JHB New | |
|---|---|---|---|---|---|---|---|---|
| Anaerobic ($m^3$, $f_{AN}$) | - | - | 1200 | 0.095 | 1200, | 0.095 | 800 | 0.110 |
| Primary Anoxic ($m^3$, $f_{x1}$) | 2234 | 0.393 | 2234 | 0.355 | 2434 | 0.387 | 2434 | 0.334 |
| Aerobic ($m^3$, fae) | 3451 | 0.607 | 3451 | 0.550 | 3251 | 0.517 | 3251 | 0.446 |
| Secondary Anoxic ($m^3$, $f_{x3}$) | - | - | - | - | - | | 400 | 0.110 |
| ADWF Capacity (ML/d) | 32.067 | | 24.555 | | 22.607 | | 22.321 | |
| SRT,min | 15.60 | | 18.216 | | 20.104 | | 26.216 | |
| Operating SRT | 15.60 | | 19 | | 22 | | 27 | |
| AX1 N Removal State | Balanced | | Overloaded | | Balanced | | Underloaded | |

## 7.4 Capacity Estimation Conclusion

CapEst is a useful tool for analysis of the AS system. Once a PWSSD design is generated from the PWSSD component, the CapEst component can be used to analyse the PWSSD design, to investigate its possible expansions and in a limited sense, sensitivity analysis on certain parameters. The CapEst component is highly flexible in that it can be expanded to include any type scenario analysis, the SST, aerobic $X_t$, and aeration scenarios are a small fraction of its capability. Furthermore, any model output from the steady-state models can be displayed in the results frame, thus allowing for custom tailoring of the CapEst window.

# 8. Program Design Part F: Program Flow

This short section covers the general navigation windows and the overall flow of the program.

## 8.1 Program Landing

The Program Landing window, as shown in Figure 4.1, is the title page of the program. On this window, the three program components (PWSSD, WWChar, and CapEst) can be accessed. A tutorial button displays this document (Chapters 3 to 8: Program Design), but in a *.chm* (help file) format. The *Exit Program* button exits the program, and the *Close This Window* button closes the Program Landing window. When this window is closed, the user has access to the spreadsheets and models, changes to them (although not recommended) can be made.

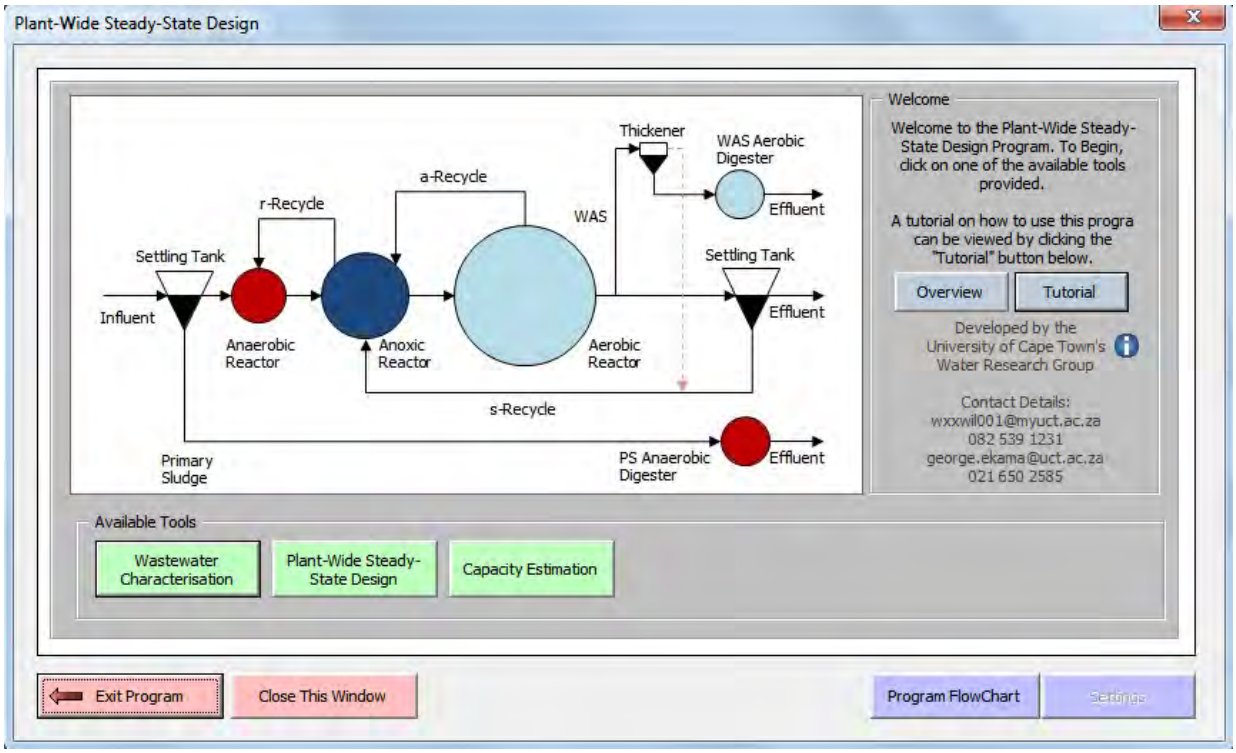



**Figure 8.1: Program Landing**

## 8.2 Program Flow Chart

A flow chart detailing the navigation of the entire PWSSD program is provided on the next page (Figure 8.2). This flow chart shows the link between the PWSSD and WWChar components. When in the PWSSD component, the designer can seamlessly navigate to the WWChar component where a summary of the characteristics can be viewed, or a new wastewater profile can be created or loaded into the plant-wide design.

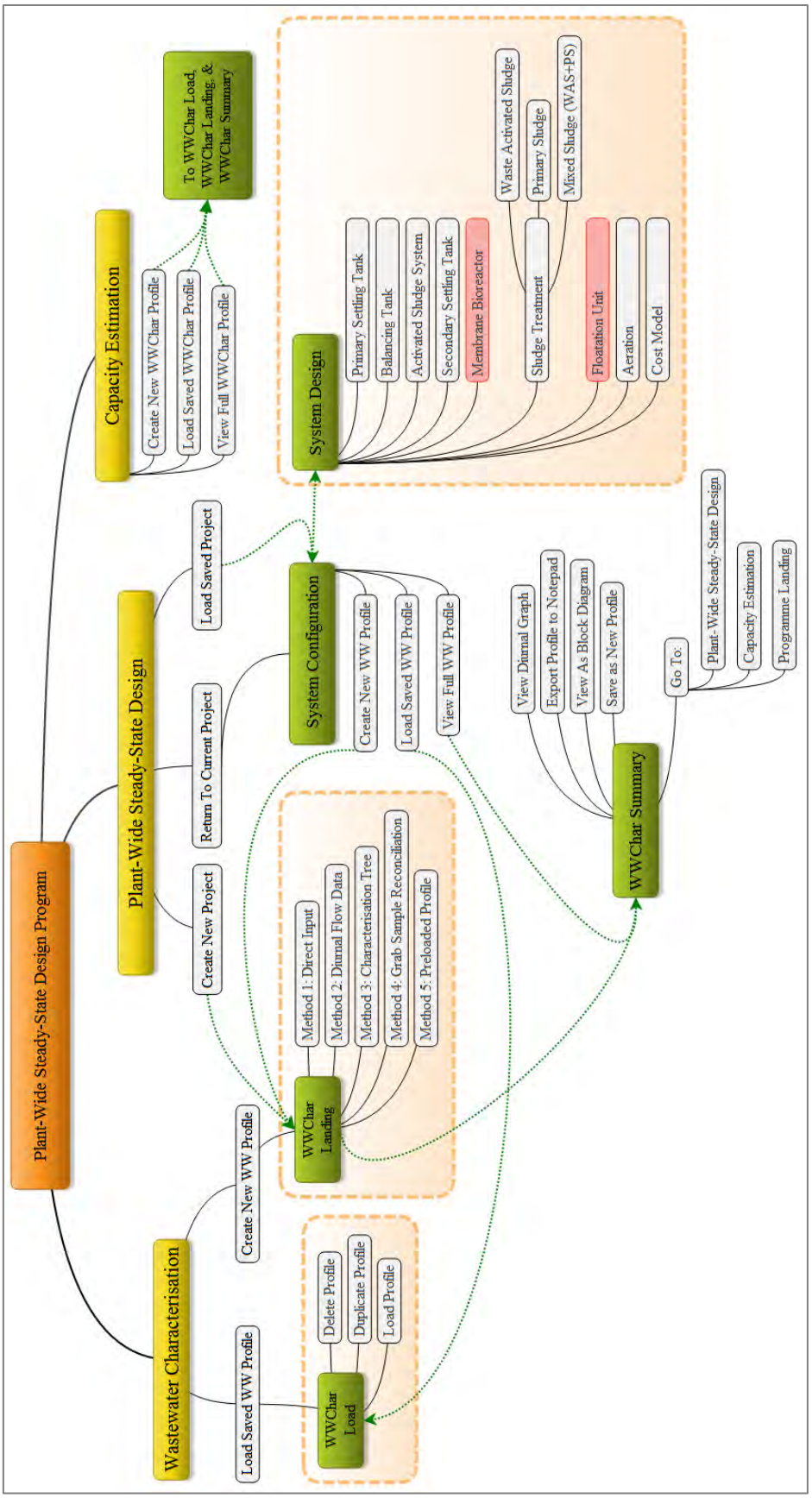



**Figure 8.2: Flow chart for all three components (WWChar, PWSSD, CapEst)**

# 9. Discussion

With the PWSSD program, a complete steady-state design can be completed within a relative short amount of time. Much useful information is generated from the steady-state models. This information generally relates to the overall design and sizing of the treatment system, which is useful as it provides the initial conditions for a dynamic simulation. In dynamic simulation, the finer details of the system can be analysed and the system can be tested in its response to varying loads and flow rates. Doing WWTP design in this manner is effective and efficient as the steady-state and dynamic models are used correctly for their intended purposes.

## 9.1 Program Structure

For the development of any program, the choice of programming language is critical as it defines the limitations and tools available to the programmer. For the development of the PWSSD program, the Excel/VBA environment was selected as it best suited the project and provided the tools available to develop an integrated, user-interface focused, and flexible platform for plant-wide WWTP design. Although, the PWSSD program is limited to the Excel/VBA environment and it cannot run as a standalone program. Furthermore, with all programs, issues arise in the development of the program. Unfortunately, it is inevitable that coding errors and program bugs will occur; in general, from experience, the more complicated procedures and program features are more prone to coding bugs. The debugging of the user-interfaces and models is an ongoing process. However, the object orientated nature and easy syntax of VBA allows for debugging to be a relatively easy process, although it can be time consuming. Considering its simple structure (but not necessarily weak), the VBA language can be learnt with relative ease and this is one of the advantages of the VB (and the subset VBA) language. In addition to this, VBA can be linked to external applications, via export files. Most dynamic WWTP simulation software can read delineated .txt (Notepad) files. These simple files types are easily generated with Excel/VBA.

## 9.2 Wastewater Characterisation

Before any design procedure can begin, the influent wastewater characteristics need to be determined. With the PWSSD program, a comprehensive and flexible WWChar component is available; most WWTP software packages do not offer this. The WWChar component is a collection of different WWChar methods that cater for WWChar in different data scenarios. In poor data scenarios, where the available data is limited or of unusable quality, the WWChar method focuses on the fundamental characteristics of the wastewater. These fundamental characteristics, such as the flow rate, $f_{S',up}$, and peak factors, determine the overall size of the WWTP. With richer data scenarios, the data available is better in that it is more readily usable and better in quality. Data such as diurnal flow concentrations, filtered concentrations,

percentage removals, mass fractions etc. provide more tailored characteristics. Combined with preloaded program defaults, missing data is substituted and thus a flexible characterisation procedure is developed. This is a novel way of approaching WWChar, doing WWChar in this manner allows for a variety of data scenarios to be catered for. However, it is important to stress that a certain inputs are mandatory in order to start the characterisation; furthermore, the preloaded defaults are based on historically measured values and are not necessarily applicable for the WWTP in consideration. The designer should always keep in mind that the better the inputs, the better the outputs, thus one should not depend entirely on the preloaded defaults.

The WWChar methods are not limited to its current state and various improvements can be made in the feature. The underlying principle in all methods is that only settleable particulates are removed in the PST, at a 100% removal rate, thus only non-settleable particulates are present in the settled WW. With this assumption, the non-settleable particulate concentrations (for UPO and BPO) are used to determine the settleable particulate concentration in the raw WW. This assumption does not completely reflect reality; however, without stronger research on the behaviour of the particulates in the PST, it is the only viable manner for the characterisation of the raw WW, settled WW and PS. Further research is required to determine correctly the split of settleable and non-settleable particulates.

## 9.3 Plant-Wide Steady-State Design

With a wastewater profile generated from the WWChar component, the PWSSD component can be used to complete the steady-state design. The AS system is intricately linked with downstream and upstream unit processes such as PST, flow balancing, WAS digestion, SST, and an aeration system. These connected systems are available for the designer to be included in the WWTP configuration, the configuration process is simple and contained in one window.

The conceptual design and coding of the design windows are kept consistent (as possibly allowed); in general, they contain three sections, from left to right: *Model Inputs*, *Design Summary*, and *Design Guidance*. The *Model Inputs* section allows all the necessary inputs to be entered. For most design windows, the *Model Inputs* must be completed fully. This requirement is to ensure model integrity, missing inputs results in arithmetic errors such as dividing by zero or unsolvable equations. Default inputs can be used; this is applicable if the designer does not have the required inputs for the model. However, as with the default inputs in the WWChar component, these default inputs are not applicable for all WWTP designs. These default inputs (summarised in 1.Appendix E) are contained in a spreadsheet and can be adjusted if necessary.. Research into the default inputs is a possibility; a useful feature for the program would be to have customised default model inputs for specific regions or design scenarios. The user can select a locality, such as South Africa or Europe, and the default inputs would reflect the commonly used values in those regions. The same concept can also be applied to the WWChar component for the default mass ratios, peak factors, USO COD fraction etc.

With the *Design Summary*, all the important design outputs are summarised. The items displayed can be adjusted in the future if required. At the end of the design procedure, the Specifications Summary and Flux Summary tools can be used. These tools summarise the steady-state model outputs on an image of the WWTP. This is a useful feature as it can be printed and included in design reports. A useful feature that could be included in future editions of the program would be a function to turn on or turn off selected unit processes on the summary tools.

The *Design Guidance* provides for meaningful commentary and information on the design process and the models. Currently, it is primarily text based, but the flexibility of VBA allows images to be displayed. In future, the text-based information can be supplemented by graphs or images. This visual media is stored in the file directory of the PWSSD program and is simply loaded into an image control when required. The *Design Guidance* is a means to strengthen the foundations of the design by addressing the knowledge gaps in using the models. Dynamic simulation software are immensely powerful and useful, however, they require a complete knowhow of the dynamic models (ASM1, ASM2 etc.). If the model user does not have this knowledge, then the use of dynamic simulation software is problematic because inputs are guessed and model parameters are tweaked until the simulation runs satisfactorily. This is further compounded by the easy-to-use nature of the user-interfaces, i.e. navigation around the program is not difficult. The development of WWTP design and simulation software should therefore not only focus on the models, how accurate and powerful they are, and how easy it is to use the program, but it should also provide means to show the program user on the correct way of using the program. The *Design Guidance* aims to address this shortfall; with the contextual, expert-guided information, the WWTP design can be executed correctly and more efficiently.

## 9.4 Capacity Estimation

The Capacity Estimation (CapEst) component works in unison with the WWChar and PWSSD components in that the steady-state models contained in the PWSSD component are processed in reverse, with the wastewater profile created in the WWChar component, to find the maximum ADWF capacity of the WWTP. With the link the toe steady-state models, the CapEst component is therefore highly flexible as it can be expanded to include any type scenario analysis and use any steady-state model outputs as the goal for CapEst, i.e. find the ADWF that results in a specific value for a selected model output. The SST, aerobic $X_t$, and aeration scenarios are a small fraction of its capability. Furthermore, any model output from the steady-state models can be displayed in the CapEst results frame, thus allowing for custom tailoring of the CapEst window. Considering these strengths, and that not much knowledge concerning the steady-state models is required to run an estimation, CapEst is useful for the evaluation of an existing WWTP as it is an easy-to-use feature that can provide meaningful results.

# 10. Conclusion

Plant-wide wastewater treatment plant (WWTP) design is a design philosophy that focuses on a holistic and integrated WWTP design. In a plant-wide design, the model outputs are utilised in an integrated manner, where the outputs from one unit process are the inputs to a downstream unit process. In doing so, the unit processes are linked together and the WWTP is evaluated as a whole treatment system.

Three components were developed for the PWSSD program. Each component fulfils a specific role in the plant-wide design. The first component is the WWChar component that serves as a pre-processor for the all the steady-state models. Without the WWChar component, these models cannot be processed. The WWChar component is a collection of WWChar methods that are tailored for specific data scenarios. There are two important concepts (or principles) used in the WWChar component. The first, and most impactful, is that the relative proportions of the seven organic groups do not change throughout the day, and thus their $f_{cv}$, $f_n$, $f_p$ and $f_c$ mass ratios are also fixed. It is important to note that this does not reflect reality; however, this is necessary, for the development of the WWChar procedures. Secondly, seven organic groups were used in the WWChar component (and as well as the rest of the program). The BPO and UPO groups were each split into two physical groups, settleable and non-settleable, with the assumption that all settleable particulates are removed in the PST. These two groups can have the same or different compositions. Further research is required to quantify correctly the split between the settleable and non-settleable particulates, and if their compositions are the same or not; hence, this split was included as foresight for future work.

Once a wastewater profile is generated from the WWChar component, the PWSSD or CapEst components can be used. Both of these components utilise the various steady-state models in an integrated manner to achieve a specific goal. In the PWSSD component, a complete plant-wide design can be performed, and the designer has different choices for the plant configuration. Currently, the design has the choice of three AS system configuration, AD and AxAeD digestion, SST, PST and GravThk, flow balancing, mechanical aeration, and cost estimation. Additional options are planned for the future, and if applicable, these additions can be included for the CapEst component. Options being developed or are considered include a dynamic balancing tank model, dissolved air flotation model for WAS thickening, bubble aeration model for aeration, better modelling of P and mineral precipitation in the digestion systems, and as well as UCTOLD and UCTPHO dynamic simulation models..

At the end of the plant-wide design, summaries of the design can be viewed. The information presented here can be used externally for dynamic simulation. The link between steady-state models and dynamic simulation is important, and with the PWSSD program, this link can be strengthened. Doing so improves the efficiency in WWTP design and simulation. The PWSSD component includes a useful *Design Guidance* component, in which the model user is provided contextual information on the design, the use, and the principle theories of the various steady-state models. In terms of the CapEst component, this can be used to analyse an

existing WWTP or PWSSD design. Investigations into the sensitivity of the parameters and bottleneck areas are possible with the CapEst component.

The holistic nature of this program allows for a complete plant-wide WWTP design to be completed within a few minutes, and for the generation of meaningful information that aid decision making. In interacting with the PWSSD program, it can be seen that it is not only a design and analysis tool but also an educational tool that can be used to demonstrate the strength of the steady-state models. Thus, by using this program, designers can have a better foundation in WWTP modelling and the basics of the treatment processes will be strengthened, modelling foundations can be strengthened allowing designers to approach and use the dynamic models more efficiently, and correctly.

With the PWSSD program's simplicity and strength in generating high-level information, it is envisioned that the program can be incorporated alongside dynamic simulation software as a pre-processor for the use of dynamic models. By clicking a button, the outputs from the steady-state models, such as flow rate, reactor sizes, and mass fractions, can be transferred to the dynamic models where the systems' performance under dynamic loading can be evaluated.

# References

Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T.M., Siegrist, H., *et al*. 2002. The IWA Anaerobic Digestion Model No 1 (ADM1). *Water science and technology: a journal of the International Association on Water Pollution Research*. 45(10):65–73. Available: http://www.ncbi.nlm.nih.gov/pubmed/12188579.

Bratby, J. 1978. Aspects of Sludge Thickening by Dissolved-Air Flotation. *Water Pollution Control*. 77(3):421–432.

Bratby, J. n.d. *Aeration in the activated sludge process (unpublished)*. Cape Town.

Bratby, J. & Marais, G. v. R. 1976. A Guide for the Design of Dissolved-air (Pressure) Flotation Systems for Activated Sludge Process. *Water S.A.* 2(2):87–97.

Bratby, J., Walker, S., Barnes, C. & Jones, G. 2008. Float On and On. Taking flotation thickeners to the limits of performance. *Water Environment and Technology*. 56–89.

Catunda, P.F.. & van Haandel, A.C. 1992. Activated sludge settling Part I: Experimental determination of activated sludge settleability. *Water S.A.* 18(3):165–172.

Copp, J. Ed. 2001. *The COST Simulation Benchmark: Description and Simulator Manual*. ISBN 92-894-1658-0.

Corominas, L., Rieger, L., Takács, I., Ekama, G.A., Hauduc, H., Vanrolleghem, P.A., Oehmen, A., Gernaey, K.V., *et al*. 2010. New framework for standardized notation in wastewater treatment modelling. *Water Science & Technology*. 61(4):841–857.

Daigger, G.T. & Roper, R.E.J. 1985. The relationship between SVI and activated sludge settling characteristics. *Water Pollution Control Federation*. 57(8):859–866.

Dold, P.L., Ekama, G.A. & Marais, G.V.R. 1980. A general model for the activated sludge process. *Progressive Water Technology*. 12(6):44–77.

Dold, P.L., Buhr, H.O. & Marais, G. v. R. 1982. Design and Control of Equalization Tanks. *WRC Research Report W 42 February 1982*.

Dold, P.L., Buhr, H.O. & Marais, G. v. R. 1984. A Computer-Based Strategy for the Control of Equalization Tanks. *Water Science & Technology*. 13:349–354.

Dold, P.L., Bagg, W.K. & Marais, G. v. R. 1986. *Measurement of Readily Biodegradable COD Fraction in Municipal Wastewater by Ultrafiltration.* UCT Report No. W57, Dept. Civil Eng., Univ. of Cape Town, Rondebosch 7701, South Africa.

Eckenfelder, W.W. (Jr). 1980. *Principles of Water Quality Management*. CBI Publishing Inc., Boston, Massachusetts, USA.

Ekama, G.A. 2009. Using bioprocess stoichiometry to build a plant-wide mass balance based steady-state WWTP model. *Water research*. 43(8):2101–2120. DOI: 10.1016/j.watres.2009.01.036.

Ekama, G.A. 2010. The role and control of sludge age in biological nutrient removal activated sludge systems. *Water Science & Technology*. 61(7):1645–1652.

Ekama, G.A. & Marais, G. v. R. 1986. Sludge settleability and secondary settling tank design procedures. *Water Pollution Control*. 5(1):101–113.

Ekama, G.A. & Wentzel, M.C. 2004. A predictive model for the reactor inorganic suspended solids concentration in activated sludge systems. *Water Research*. 38(19):4093–4106.

Ekama, G.A. & Wentzel, M.C. 2008a. Chapter 4: Organic Removal. In *Biological Wastewater Treatment: Principles, Modelling and Design*. 1st ed. M. Henze, M.C.M. van Loosdrecht, G.A. Ekama, & D. Brdjanovic, Eds. IWA Publishing. 53–86.

Ekama, G.A. & Wentzel, M.C. 2008b. Chapter 5: Nitrogen Removal. In *Biological Wastewater Treatment: Principles, Modelling and Design*. 1st ed. M. Henze, M.C.M. van Loosdrecht, G.A. Ekama, & D. Brdjanovic, Eds. London: IWA Publishing. 87–138.

Ekama, G.A., Barnard, J.L., Gunthert, F.W., Krebs, P., McCorquodale, J.A., Parker, D.S. & Wahlberg, E.J. 1997. *Secondary Settling Tanks Theory, Modelling, Design and Operation. Scientific and Technical Report No.6*. IWAQ.

Ekama, G.A., Sötemann, S.W. & Wentzel, M.C. 2006. Mass balance-based plant-wide wastewater treatment plant models – Part 3 Biodegradability of activated sludge organics under anaerobic conditions. *Water SA*. 32(3):287–296.

Ekama, G.A., Wentzel, M.C. & Sötemann, S.W. 2006. Mass balance-based plant-wide wastewater treatment plant models – Part 2: Tracking the influent inorganic suspended solids. *Water SA*. 32(3):277–285. DOI: 10.4314/wsa.v32i3.5272.

Garrard, C. 2014. Computer Modelling of a Balancing Tank. Undergraduate Thesis (unpublished). University of Cape Town, Rondebosch, South Africa.

Gernaey, K.V., van Loosdrecht, M.C.M., Henze, M., Lind, M. & Jørgensen, S.B. 2004. Activated sludge wastewater treatment plant modelling and simulation: State of the art. *Environmental Modelling & Software*. 19(9):763–783. DOI: 10.1016/j.envsoft.2003.03.005.

Grau, P., Vanrolleghem, P.A. & Ayesa, E. 2007. BSM2 plant-wide Model construction and comparative analysis with other methodologies for integrated modelling. In *Procs. The Seventh International IWA Symposium on Systems Analysis and Integrated Assessment in Water Management. Washington, DC, USA, 7–9 May 2007*.

Van Haandel, A.C. & van der Lubbe, J.G.M. 2007. *Handbook Biological Waste Water Treatment*. 1st ed. Leidschendam, Netherlands: Quist Publishing.

Harding, T.H. 2009. A Steady State Stoichiometric Model Describing The Anaerobic Digestion of Biological Excess Phosphorus Removal Waste Activated Sludge. MSc Thesis. University of Cape Town, South Africa.

Henze, M., van Loosdrecht, M.C.M., Ekama, G.A. & Brdjanovic, D. Eds. 2008. *Biological Wastewater Treatment: Principles, Modelling and Design*. 1st ed. London: IWA Publishing.

Henze, M., Grady, C.P.L.J., Gujer, W., Marais, G. v. R. & Matsuo, T. 1987. Activated Sludge Model No. 1. *IAWQ Scientific and Technical Report No. 1.*

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C. & Marais, G. v. R. 1995. Activated Sludge Model No. 2 (ASM2). *IWA Scientific and Technical Report No.3*.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, C., Marais, G.V.R. & van Loosdrecht, M.C.M. 1999. Activated Sludge Model No.2D, ASM2D. *Water Science and Technology*. 39(1):165–182.

Hug, T., Benedetti, L., Hall, E.R., Johnson, B.R., Morgenroth, E., Nopens, I., Rieger, L., Shaw, A., *et al*. 2009. Wastewater treatment models in teaching and training: the mismatch between education and requirements for jobs. *Water Science and Technology*. 59(4):745–753. DOI: 10.2166/wst.2009.595.

Ikumi, D.S., Harding, T.H., Brouckaert, C.J. & Ekama, G.A. 2014. Plant wide integrated biological, chemical and physical processes modelling of wastewater treatment plants in three phases (aqueous-gas-solid). Research Report W138, Department of Civil Engineering, University of Cape Town, Rondebosch, 7700, Western Cape, South Africa, South Africa.

Ikumi, D.S., Harding, T.H. & Ekama, G.A. 2014. Biodegradability of wastewater and activated sludge organics in anaerobic digestion. *Water research*. 56(1):267–79. DOI: 10.1016/j.watres.2014.02.008.

Ikumi, D.S., Harding, T.H., Brouckaert, C.J. & Ekama, G.A. 2015. *Mass balances modelling over wastewater treatment plants III - Final Report to WRC on Contract K5/1822*. Research Report, Water Research Commission, Pretoria. Available: (www.wrc.org.za).

Izzet, H.B., Wentzel, M.C. & Ekama, G.A. 1992. *The Effect of Thermophilic Heat Treatment on the Anaerobic Digestibility of Primary Sludge.* Research Report W76, Univ. of Cape Town, Dept. of Civil Eng. Rondebosch 7701, Cape, South Africa. JANUS.

Jones, R.M. & Takács, I. 2004. Importance of anaerobic digestion modelling on predicting the overall performance of wastewater treatment plants. In *Procs. The Anaerobic Digestion Tenth World Congress, Montreal, Canada, 29 Aug.–2 Sept. 2004*. 1371–1375.

Van Loosdrecht, M.C.M., Ekama, G.A., Wentzel, M.C., Brdjanovic, D. & Hooijmans, C.M. 2008. Chapter 14: Modelling Activated Sludge Processes. In *Biological Wastewater Treatment: Principles, Modelling and Design*. 1st ed. M. Henze, M.C.M. van Loosdrecht, G.A. Ekama, & D. Brdjanovic, Eds. London: IWA Publishing. 361–392.

Makinia, J. 2010. *Mathematical Modelling and Computer Simulation of Activated Sludge Systems*. IWA Publishing.

Marais, G. v. R. & Ekama, G.A. 1976. The activated sludge process part 1 - Steady state behaviour. *Water S.A.* 2(4):163–200.

Marais, P.M. & Ekama, G.A. 2004. Comparison of the 1D flux theory with a 2D hydrodynamic secondary settling tank model. *Water Science & Technology*. 50(7):195–2004.

Marais, P.M., Ekama, G.A. & de Haas, D.W. 2000. Comparison of the 1D idealized flux theory and a 2D hydrodynamic model with full scale secondary settling tank performance data. In *WISA 2000 Biennial Conference*. V. 2. Sun City, South Africa. 1–8.

Mebrahtu, M.K. 2007. Aerobic Digestion of Waste Activated Sludge From Biological Nutrient Removal Activated Sludge Systems. MSc Thesis. University of Cape Town, South Africa.

Messenger, J.R., de Villiers, H.A. & Ekama, G.A. 1993. Evaluation of dual digestion system: Part 2: Operation and performance of pure oxygen aerobic reactor. *Water Science and Technology*. 19:193–200.

MIKE by DHI. n.d. *WEST – modelling wastewater treatment plants*. Available: http://www.mikebydhi.com/products/west [2013, April 18].

Musvoto, E.V., Wentzel, M.C., Loewenthal, R.W. & Ekama, G.A. 2000. Extension and application of the three phase weak acid/base kinetic model to the aeration treatment of anaerobic digester liquors. *Water S.A.* 26(4):417–437.

Musvoto, E.V., Samson, K., Taljard, M., Fawcett, K. & Alexander, W.V. 2002. Calculation of Peak Oxygen Demand in the of Full Scale Nitrogen Removal Activated Sludge Plants. *Water S.A.* Special Ed(May):56–60.

O'Rourke, J.T. 1968. Kinetics of Anaerobic Treatment at Reduced Temperatures. Phd dissertation. Department of Civil Engeering, Stanford.

Ozinsky, A.E. & Ekama, G.A. 1995. Secondary settling tank model- ling and design Part 2: Linking sludge settleability measures. *Water S.A.* 21(4):333–349.

Pitman, A.R. 1984. Settling of nutrient removal activated sludges. *Water Science & Technology*. 17:493–504.

Plósz, B.G., De Clercq, J., Nopens, I., Benedetti, L. & Vanrolleghem, P. a. 2011. Shall we upgrade one-dimensional secondary settler models used in WWTP simulators? – An

assessment of model structure uncertainty and its propagation. *Water Science & Technology*. 63(8):1726. DOI: 10.2166/wst.2011.412.

Ramphao, M., Wentzel, M.C., Merritt, R., Ekama, G.A., Young, T. & Buckley, C.A. 2005. Impact of Membrane Solid-Liquid Seperation on Design of Biological Nutrient Removal Activated Sludge Systems. *Biotechnology and Bioengineering*. 89(6):630–646.

Renko, E.K. 1998. Modelling hindered batch settling Part I : A model for linking zone settling velocity and stirred sludge volume index. *Water S.A.* 24(4):325–330.

Ristow, N.E., Sötemann, S.W., Loewenthal, R.W., Wentzel, M.C. & Ekama, G.A. 2005. *Hydrolysis of Primary Sludge under Methanogenic, Acidogenic and Sulfate Reducing Conditions.* WRC Report No. 1216/1/05, Water Research Commission, Private Bag X03, Gezina, 0031, RSA. ISBN 1-77005-290-5.

Rössle, W.H. & Pretorius, W.A. 2001. A review of characterisation requirements for in-line prefermenters Paper 1 : Wastewater characterisation. *Water S.A.* 27(3):405–412.

Sötemann, S.W., Ristow, N.E., Wentzel, M.C. & Ekama, G.A. 2005. A steady state model for anaerobic digestion of sewage sludges. *Water SA*. 31(4):511–528.

Sötemann, S.W., van Rensburg, P., Ristow, N.E., Wentzel, M.C., Loewenthal, R.W. & Ekama, G.A. 2005. Integrated chemical/physical and biological processes modelling Part 2 - Anaerobic digestion of sewage sludges. *Water SA*. 31(4):545–550.

Sötemann, S.W., Ekama, G.A. & Wentzel, M.C. 2006. Mass balance-based plant-wide wastewater treatment plant models – Part 4: Aerobic digestion of primary and waste activated sludges. *Water SA*. 32(3):297–306.

Von Sperling, M. & Fróes, C.M.V. 1999. Determination of the required surface area for activated sludge final clarifiers based on a unified database. *Water Research*. 33(8):1884–1894. DOI: http://dx.doi.org/10.1016/S0043-1354(98)00401-1.

Takács, I. & Ekama, G.A. 2008. Chapter 12: Final Settling. In *Biological Wastewater Treatment: Principles, Modelling and Design*. 1st ed. M. Henze, M.C.M. van Loosdrecht, G.A. Ekama, & D. Brdjanovic, Eds. London: IWA Publishing. 309–334.

Takács, I., Dudley, J. & Snowling, S. 2007. A closer look at the dangers of uncalibrated simulators. In *Proceedings WEFTEC 2007, Water Environment Federation 80th Annual Conference. October 13–17, 2007.* San Diego, USA.

Vanhooren, H., Meirlaen, J., Amerlinck, Y., Claeys, F., Vangheluwe, H. & Vanrolleghem, P.A. 2003. WEST: Modelling biological wastewater treatment. *Journal of Hydroinformatics*. 5(1):27–50.

Vogts, M. & Ekama, G.A. 2012. Anoxic-aerobic digestion of waste activated sludge from biological nitrogen and phosphorus removal systems. In *Procs. 12th biennial WISA conference and exhibition*. Cape Town, 7-10 May. 1154–164.

Vogts, M. & Ekama, G.A. 2015. *The removal of nitrogen and phosphorus in anoxic-aerobic digestion of waste activated sludge from biological nutrient removal systems*. Research Report W139, Department of Civil Engineering, University of Cape Town, Rondebosch, 7700, Western Cape, South Africa.

Volcke, E.I.P., van Loosdrecht, M.C.M. & Vanrolleghem, P.A. 2006. Continuity based model interfacing for plant-wide simulation: A general approach. *Water Research*. 40:2817–282.

Wahlberg, E.J., H.Z., G., Gharagozian, A. & Stenstrom, M.K. 1998. Secondary clarifier analysis using data from the Clarifier Research Technical Committee protocol. *Water Environment Research*. 70(2):249–253.

Warner, A.P.C., Ekama, G.A. & Marais, G. v. R. 1986. The activated sludge process Part 4 - Application of the general kinetic model to anoxic-aerobic digestion of waste activated sludge. *Water Research*. 20(8):943–958.

Water Environment Foundation. 2005. Chapter 5: Solids Thickening and Dewatering Systems. In *National Manual of Good Practice for Biosolids*. Available: http://www.wef.org/Biosolids/page.aspx?id=7767.

Water Pollution Control Federation (WEF). 1987. *Operation and Maintenance of Sludge Dewatering Systems: Manual of Practice No. OM-8.*

Wentzel, M.C., Loewenthal, R.W., Ekama, G.A., Dold, P.L. & Marais, G. v. R. 1988. Enhanced polyphosphate organism cultures in activated sludge systems. Part I: Enhanced culture development. *Water S.A.* 14(2):81–92.

Wentzel, M.C., Ekama, G.A., Loewenthal, R.W., Dold, P.L. & Marais, G. v. R. 1989. Enhanced polyphosphate organism cultures in activated sludge systems. Part II: Expirmental behaviour. *Water S.A.* 15(2):71–88.

Wentzel, M.C., Dold, P.L., Ekama, G.A. & Marais, G. v. R. 1989. Enhanced polyphosphate organism cultures in activated sludge systems. Part III: Kinetic model. *Water SA*. 15(2):89–102.

Wentzel, M.C., Ekama, G.A., Dold, P.L. & Marais, G. v. R. 1990. Biological excess phosporuous removal - Steady State Design. *Water SA*. 16(1):29–48.

Wentzel, M.C., Mbewe, A., Lakay, M.T. & Ekama, G.A. 1999. Batch test for characterisation of the carbonaceous materials in municipal wastewaters. *Water S.A.* 25(3):327–336.

Wentzel, M.C., Ekama, G.A. & Sötemann, S.W. 2006. Mass balance-based plant-wide wastewater treatment plant models - Part 1: Biodegradability of wastewater organics under anaerobic conditions. *Water SA*. 32(3):269–275. DOI: 10.4314/wsa.v32i3.5261.

Wentzel, M.C., Comeau, Y., Ekama, G.A., van Loosdrecht, M.C.M. & Brdjanovic, D. 2008. Chapter 7: Phosphorus Removal. In *Biological Wastewater Treatment: Principles, Modelling and Design*. 1st ed. M. Henze, M.C.M. van Loosdrecht, G.A. Ekama, & D. Brdjanovic, Eds. London: IWA Publishing. 155–220.

WRC. 1984. *Theory, design and operation of nutrient removal activated sludge processes. WRC Report TT 16/84*. Water Research Commission (WRC), Private Bad X03, Gezina, 0031, South Africa.

# Appendices

Appendix A: Comparison of DFData and WWChar Tree DFPs

Appendix B: Characterisation Tables and Methods for WWChar Tree

Appendix C: Wastewater Characteristics for Program Design Section

Appendix D: MLE Design and Upgrade Case Study

Appendix E: Model Defaults

Appendix F: Steady-State JHB ND Equations

Appendix G: Overview of Design Guidance Content

# Appendix A. Comparison of DFData and WWChar Tree DFPs

A comparison of the actual DFP used in the DFData section (blue) and the randomly generated DFP for the WWChar Tree section (red) is provided in the graphs below. From the characterisation results comparison (see Table 5.14: Comparison DFData and WWChar Tree of FWA characterisation results) it can be seen that the characterisation results are similar. However, visibly all DFPs (except for the DFP for flow rate) are quite different. Conversely, on a close inspection, it can be seen that the areas (fluxes) under the curves are similar, i.e. the red line is higher at certain points but at other points it is lower. The net result is that the FWA concentrations are relatively close.

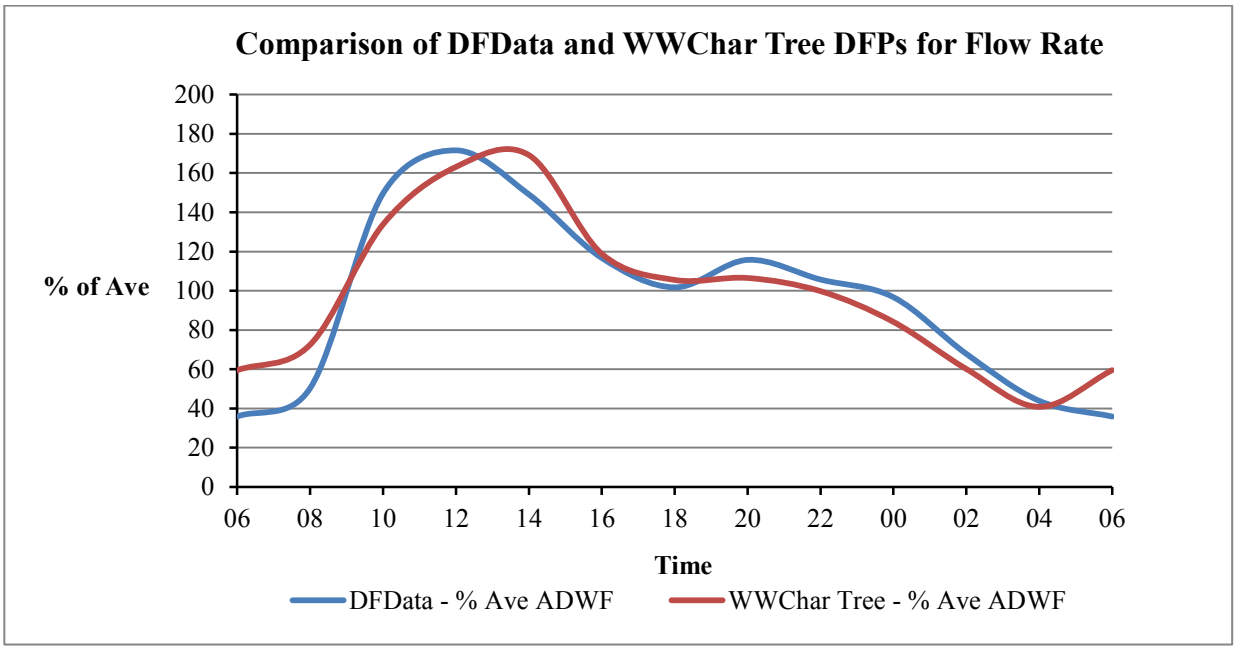



**Figure A.1: Flow rate DFP comparison for DFData and WWChar Tree**

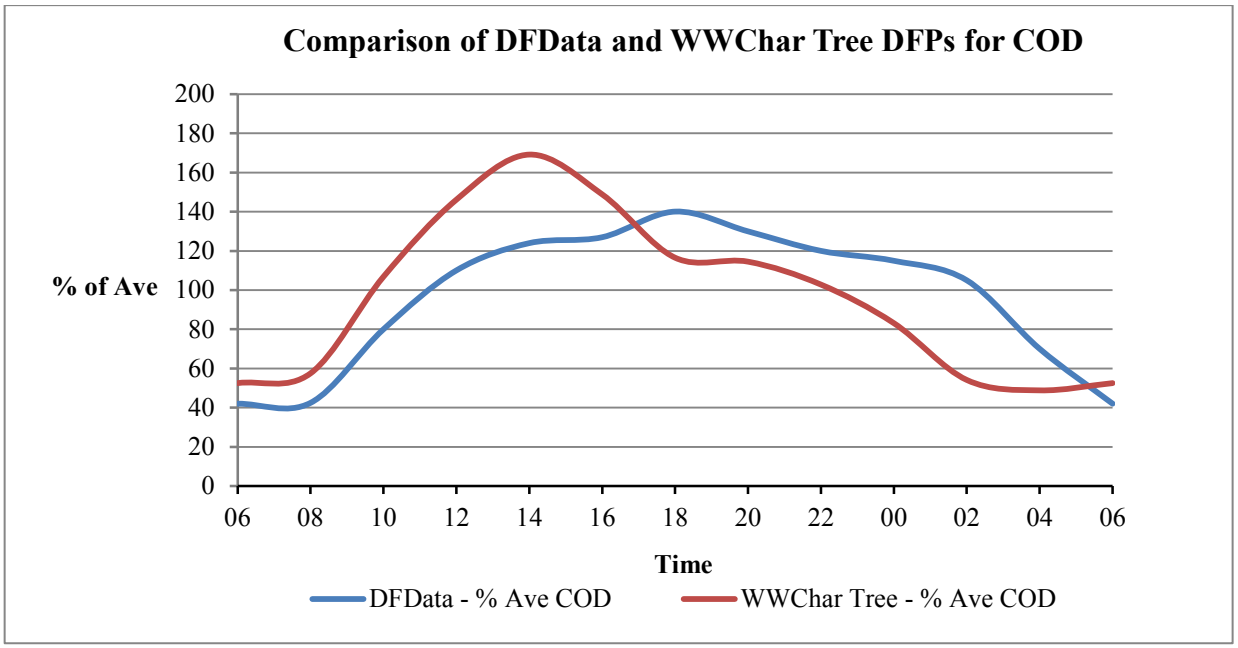



**Figure A.2: COD DFP comparison for DFData and WWChar Tree**

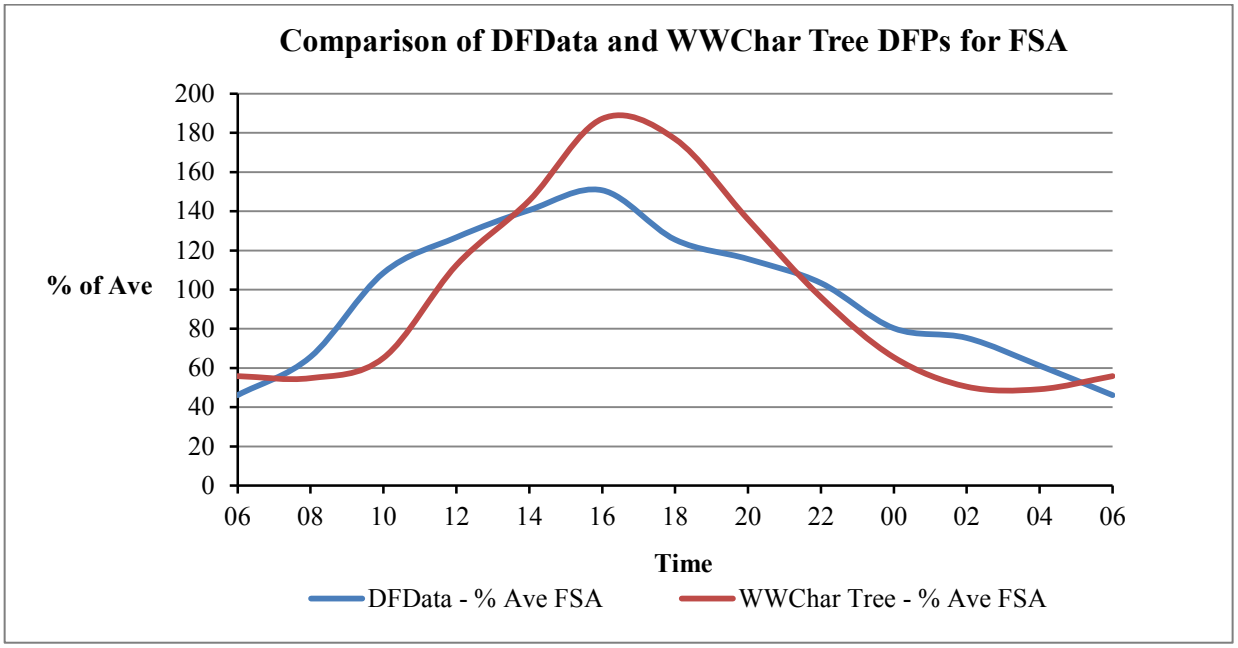



**Figure A.3: FSA DFP comparison for DFData and WWChar Tree**

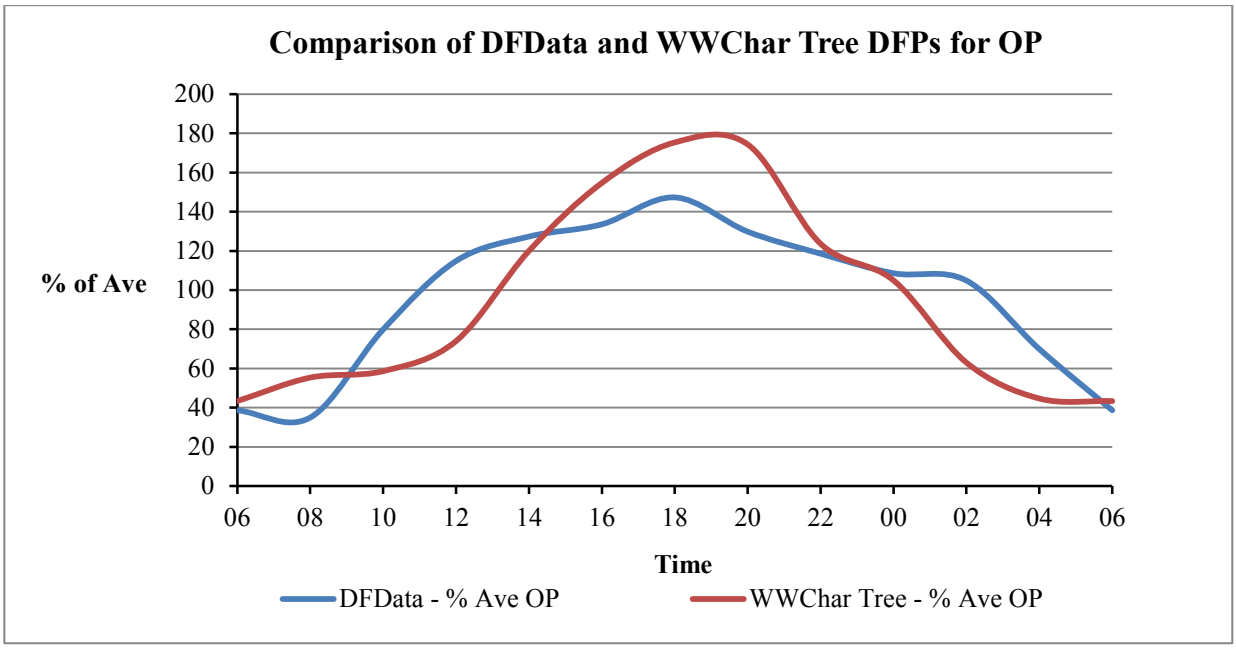



**Figure A.4: OP DFP comparison for DFData and WWChar Tree**

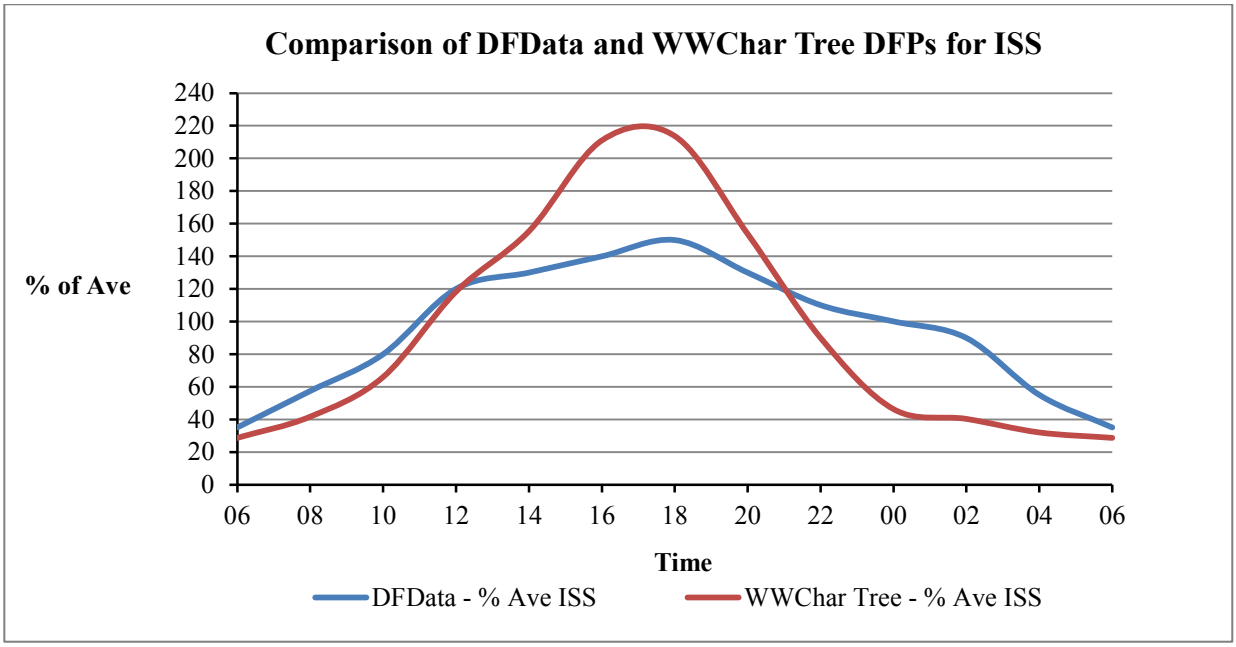



**Figure A.5: ISS DFP comparison for DFData and WWChar Tree**

# Appendix B. Characterisation Tables and Methods for WWChar Tree

## B1. COD

- Compulsory data: Raw COD (Raw $S_{ti}$) and Filtered COD ($S_{si}$)
- Settled COD options:
  - Entered directly (Settled $S_{ti}$) or
  - Calculated with %COD removal in PST (Equation B.1)

**Equation B.1: Settled COD from Raw COD and %COD removal in PST**

$$\text{Settled } S_{ti} = \text{Raw } S_{ti} \times \left(1 - \frac{\%\text{COD Removal}}{100}\right)$$

- UPO fraction ($f_{S'up}$) options:

| | UPO Fraction Input Options | | |
|---|---|---|---|
| $f_{S'up}$ (Raw) | Yes | Yes | No |
| $f_{S'up}$ (Settled) | Yes | No | Yes |
| $f_{PS'up}$ (PS) | No | Yes | Yes |
| $f_{S'up}$ (Raw) | ENT | ENT | Equation B.4 |
| $f_{S'up}$ (Settled) | ENT | Equation B.3 | ENT |
| $f_{PS'up}$ (PS) | Equation B.2 | ENT | ENT |

Where:
- MR = calculated from $f_{cv}$ mass ratio and COD concentration
- ENT = entered

**Equation B.2: PS UPO fraction ($f_{PS'up}$) from UPO mass balance**

$$f_{PS'up} = \frac{\left[\text{Raw } f_{S'up} \times \text{Raw } S_{ti}\right] - \left[\text{Settled } f_{S'up} \times \text{Settled } S_{ti} \times \sigma\right]}{\left[\text{Raw } S_{ti} - (\text{Settled } S_{ti} \times \sigma)\right]}$$

**Equation B.3: Settled wastewater UPO fraction (Settled $f_{S'up}$) from UPO mass balance**

$$\text{Set } f_{S'up} = \frac{\left[f_{PS'up} \times (\text{Raw } S_{ti} - \text{Settled } S_{ti} \times \sigma)\right] - \left[\text{Raw } f_{S'up} \times \text{Raw } S_{ti}\right]}{-\left[\text{Settled } S_{ti} \times \sigma\right]}$$

**Equation B.4: Raw wastewater UPO fraction (Raw $f_{S'up}$) from UPO mass balance**

$$\text{Raw } f_{S'up} = \frac{\left[f_{PS'up} \times (\text{Raw } S_{ti} - \text{Settled } S_{ti} \times \sigma)\right] + \left[\text{Settled } f_{S'up} \times \text{Settled } S_{ti} \times \sigma\right]}{\text{Raw } S_{ti}}$$

Where: $\sigma = \left(1 - \frac{\%\text{PST Underflow}}{100}\right)$

- USO fraction $f_{S'us}$ options:
  - Entered $S_{use}$ directly or
  - Enter $f_{S'us}$
  - Default $f_{S'us}$ of 0.0500 if no data entered
- VFA options:
  - Entered $S_{bsai}$ in mgCOD/L
  - Entered $S_{bsai}$ in mgHAc/L
  - Default $f_{S'bsai}$ of 0.045 if no data entered

COD characteristics can be calculated with raw COD, settled COD, raw $f_{S'up}$, settled $f_{S'up}$, VFA, and USO information. This is done with the procedure in the Table B.1 below.

**Table B.1: WWChar Tree – Raw WW and settled WW COD characterisation table**

| COD Characteristics | Code | Raw wastewater | Settled wastewater |
|---|---|---|---|
| Total influent | A | ENT | ENT |
| Influent BPO | B | A – E – H – K | A – E – H – K |
| Influent BPO (Settleable) | C | B – D | 0 |
| Influent BPO (Non-Settleable) | D | From Settled wastewater | A – E – H – K |
| Influent BSO | E | O – K | O – K |
| Influent VFA | F | ENT | ENT |
| Influent FBSO | G | E – G | E – G |
| Influent UPO | H | $f_{S'up}$× Raw $S_{ti}$ | $f_{S'up}$× Set $S_{ti}$ |
| Influent UPO (Settleable) | I | H – J | H – J |
| Influent UPO (Non-Settleable) | J | $f_{S'up}$× Set $S_{ti}$ | $f_{S'up}$× Set $S_{ti}$ |
| Influent USO | K | ENT | ENT |
| Total biodegradable | L | B + E | B + E |
| Total unbiodegradable | M | H + K | H + K |
| Total particulate | N | B + H | B + H |
| Total soluble | O | ENT | ENT |

Where:
- ENT = entered

## B2. Particulates

Table B.2 and Table B.3 below are the same tables presented the Section 5.3.3.6 Particulates Inputs - 5. Part.

**Table B.2: WWChar Tree – Raw wastewater particulates characterisation table**

| | Raw wastewater Particulates Input Options | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Raw TSS | Yes | No | No | No | Yes | Yes | Yes | No | |
| Raw ISS | No | Yes | No | Yes | Yes | No | Yes | No | |
| Raw VSS | No | No | Yes | Yes | No | Yes | Yes | No | |
| Raw $f_{ii}$ | No | No | Yes | No | No | No | No | Yes | |
| Raw TSS | ENT | DIF | FII | SUM | ENT | ENT | ENT | FII | **(6)** |
| Raw ISS | DIF | ENT | DIF | ENT | ENT | DIF | ENT | DIF | **(7)** |
| Raw VSS | SUM | SUM | ENT | ENT | DIF | ENT | ENT | SUM | **(5)** |
| BPO VSS | | | | | | | | | |
| Settleable | MR | MR | MR | MR | MR | MR | MR | MR | **(3)** |
| Non-Settleable | MR | MR | DIF | DIF | DIF | DIF | DIF | MR | **(4)** |
| UPO VSS | | | | | | | | | |
| Settleable | MR | MR | MR | MR | MR | MR | MR | MR | **(1)** |
| Non-Settleable | MR | MR | MR | MR | MR | MR | MR | MR | **(2r)** |

Where:
- MR = calculated from $f_{cv}$ mass ratio and COD concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation
- FII = calculated with fii (VSS/TSS) ratio

**Table B.3: WWChar Tree – Settled wastewater particulates characterisation table**

| | Settled wastewater Particulates Input Options | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Set WW TSS | Yes | No | No | No | Yes | Yes | Yes | No | No | |
| Set WW ISS | No | Yes | No | Yes | Yes | No | Yes | No | No | |
| Set WW VSS | No | No | Yes | Yes | No | Yes | Yes | No | No | |
| Set WW $f_{ii}$ | No | No | Yes | No | No | No | No | Yes | No | |
| Imhoff Cone | No | No | No | No | No | No | No | No | Yes | |
| Set WW TSS | ENT | DIF | FII | SUM | ENT | ENT | ENT | FII | DIF | **(8)** |
| Set WW ISS | DIF | ENT | DIF | ENT | ENT | DIF | ENT | DIF | DIF | **(9)** |
| Set WW VSS | SUM | SUM | ENT | ENT | DIF | ENT | ENT | SUM | DIF | **(10)** |
| BPO VSS | | | | | | | | | | |
| Settleable | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Non-Settleable | MR | MR | DIF | DIF | DIF | DIF | DIF | MR | DIF | **(4s)** |
| UPO VSS | | | | | | | | | | |
| Settleable | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Non-Settleable | MR | MR | MR | MR | MR | MR | MR | MR | MR | **(2s)** |

Note:
- If the non-settleable BPO VSS is calculated here, then the settleable and non-settleable BPO VSS in the raw WW calculation is revised with the non-settleable BPO VSS calculate here.

## B3. Nitrogen

In the N procedures, the same concept as for the particulates characterisation is followed. The procedure will always use the mass ratios to calculate the settleable and non-settleable particulate OrgN concentrations. Then with the entered data, the particulates and soluble OrgN concentrations are calculated; mass ratios ($f_n$, $f_{cv}$) and the COD or VSS concentrations are used as substitutes if data is missing. Compared to the particulates characterisation procedure, there is an added complexity due to the soluble concentrations. In general, if the entered data leaves only one soluble concentration unknown (FBSO, USO, or FSA), then the unknown is calculated via differences, i.e. mass balance. If there are two or more unknowns, then the USO is calculated using mass ratios, and the last unknown is calculated using differences. However, if the USO is entered, then the FBSO is the soluble calculated using mass ratios. The FSA is always the last soluble concentration to be calculated, so if FSA is not entered, then it is always calculated via differences. This is because FSA has no mass ratios associated with it.

For the settled WW N characteristics, if the settled WW TKN concentration is entered or if it is calculated from the entered a %TKN removal in the PST, then the non-settleable BPO OrgN concentration is calculated using the entered data. This concentration is then transferred back to the raw WW N characteristics where the settleable and non-settleable BPO OrgN concentrations are recalculated.

The above also applies to the P characteristics. The N and P characterisation tables are presented in the next few pages, Table B.4 to Table B.7.

**Table B.4: WWChar Tree – Raw wastewater N characterisation table**

| | Raw wastewater N Input Options | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw TKN | Yes | No | No | No | Yes | Yes | Yes | No | No | Yes | Yes | Yes | No | Yes | No | | | | | | | |
| Raw FSA | No | Yes | No | No | Yes | No | No | Yes | Yes | No | Yes | No | Yes | Yes | No | | | | | | | |
| Raw filt TKN | No | No | Yes | No | No | Yes | No | Yes | No | Yes | Yes | No | Yes | Yes | Yes | | | | | | | |
| Raw filt eff OrgN | No | No | No | Yes | No | No | Yes | No | Yes | Yes | No | Yes | Yes | Yes | Yes | | | | | | | |
| Raw TKN/COD | No | No | No | Yes | No | No | No | No | No | No | No | No | No | No | Yes | | | | | | | |
| Raw TKN | ENT | SUM | SUM | N/C | ENT | ENT | ENT | SUM | SUM | SUM | ENT | ENT | SUM | ENT | N/C | | | | | | | |
| Raw FSA | DIF | ENT | DIF | DIF | ENT | DIF | DIF | ENT | ENT | ENT | DIF | DIF | ENT | ENT | DIF | | | | | | | |
| Raw OrgN | SUM | SUM | ENT | SUM | DIF | SUM | SUM | SUM | SUM | SUM | DIF | DIF | SUM | SUM | SUM | | | | | | | |
| Inf BPO | | | | | | | | | | | | | | | | | | | | | | |
| Inf BPO (Set) | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | | | | | | | |
| Inf BPO (Non-Set) | MR | MR | MR | MR | DIF | DIF | MR | MR | MR | MR | DIF | DIF | MR | DIF | MR | | | | | | | |
| Inf BSO | | | | | | | | | | | | | | | | | | | | | | |
| Inf VFA | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | | | | | | |
| Inf FBSO | MR | MR | MR | MR | MR | MR | MR | DIF | DIF | MR | DIF | DIF | MR | DIF | MR | | | | | | | |
| Inf UPO | | | | | | | | | | | | | | | | | | | | | | |
| Inf UPO (Set) | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | | | | | | | |
| Inf UPO (Non-Set) | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | | | | | | | |
| Inf USO | MR | MR | MR | ENT | MR | MR | ENT | MR | ENT | MR | MR | MR | ENT | ENT | MR | | | | | | | |
| Filt TKN (FBSO + USO +FSA) | SUM | SUM | ENT | SUM | SUM | ENT | SUM | ENT | SUM | ENT | ENT | SUM | ENT | ENT | SUM | | | | | | | |

Where:

- MR = calculated from $f_n$ mass ratio and VSS concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation
- N/C = calculated with TKN/COD ratio

**Table B.5: WWChar Tree – Settled wastewater N characterisation table**

| | Settled wastewater N Input Options | |
|---|---|---|
| Settled TKN entered? | Yes | No |
| Settled TKN | ENT | From Raw |
| Settled FSA | From Raw | From Raw |
| Settled OrgN | DIF | From Raw |
| Inf BPO | | |
| Inf BPO (Set) | 0 | 0 |
| Inf BPO (Non-Set) | DIF | From Raw |
| Inf BSO | | |
| Inf VFA | - | - |
| Inf FBSO | From Raw | From Raw |
| Inf UPO | | |
| Inf UPO (Set) | 0 | 0 |
| Inf UPO (Non-Set) | From Raw | From Raw |
| Inf USO | From Raw | From Raw |
| Filt TKN (FBSO + USO +FSA) | From Raw | From Raw |

Where:
- MR = calculated from $f_n$ mass ratio and VSS concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation
- N/C = calculated with TKN/COD ratio

## B4. Phosphorous

The P characterisation procedure is identical as for the N (Appendix B.3).

**Table B.6: WWChar Tree – Raw wastewater P characterisation table**

| | Raw wastewater N Input Options | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw TP | Yes | No | No | No | Yes | Yes | Yes | No | No | No | Yes | Yes | Yes | No | Yes | No | Yes | Yes | No | Yes | No | Yes | No | No |
| Raw OP | No | Yes | No | No | Yes | No | No | Yes | Yes | No | Yes | Yes | No | Yes | No | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes | No |
| Raw filt TP | No | No | Yes | No | No | Yes | No | Yes | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| Raw filt eff OrgP | No | No | No | Yes | No | No | Yes | No | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| Raw TP/COD | No | No | No | Yes | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | Yes |
| Raw TP | ENT | SUM | SUM | P/C | ENT | ENT | ENT | SUM | SUM | SUM | ENT | ENT | ENT | SUM | ENT | ENT | ENT | ENT | SUM | ENT | ENT | ENT | ENT | P/C |
| Raw OP | DIF | ENT | DIF | DIF | ENT | DIF | DIF | ENT | ENT | DIF | ENT | ENT | DIF | ENT | ENT | DIF | ENT | DIF | ENT | DIF | ENT | ENT | ENT | DIF |
| Raw OrgP | SUM | SUM | ENT | SUM | DIF | SUM | SUM | SUM | SUM | SUM | DIF | SUM | SUM | SUM | DIF | DIF | DIF | DIF | SUM | DIF | SUM | SUM | SUM | SUM |
| Inf BPO | | | | | | | | | | | | | | | | | | | | | | | | |
| Inf BPO (Set) | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR |
| Inf BPO (Non-Set) | MR | MR | MR | MR | DIF | DIF | MR | MR | MR | MR | DIF | MR | MR | MR | DIF | DIF | DIF | DIF | MR | DIF | MR | DIF | DIF | MR |
| Inf BSO | | | | | | | | | | | | | | | | | | | | | | | | |
| Inf VFA | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Inf FBSO | MR | MR | MR | MR | MR | MR | MR | DIF | DIF | MR | DIF | DIF | MR | DIF | DIF | DIF | DIF | DIF | DIF | MR | DIF | DIF | DIF | MR |
| Inf UPO | | | | | | | | | | | | | | | | | | | | | | | | |
| Inf UPO (Set) | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR |
| Inf UPO (Non-Set) | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR | MR |
| Inf USO | MR | MR | MR | ENT | MR | MR | ENT | MR | ENT | MR | MR | ENT | MR | MR | MR | MR | ENT | MR | ENT | MR | ENT | ENT | ENT | MR |
| Filt TP (FBSO + USO +FSA) | SUM | SUM | ENT | SUM | SUM | ENT | SUM | ENT | SUM | ENT | ENT | SUM | ENT | ENT | ENT | SUM | ENT | ENT | ENT | ENT | ENT | ENT | ENT | SUM |

Where:
- MR = calculated from fcn mass ratio and VSS concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation
- P/C = calculated with TP/COD ratio

**Table B.7: WWChar Tree – Settled wastewater P characterisation table**

| | Settled wastewater P Input Options | |
|---|---|---|
| Settled TP entered? | Yes | No |
| Settled TP | ENT | From Raw |
| Settled OP | From Raw | From Raw |
| Settled OrgP | DIF | From Raw |
| Inf BPO | | |
| Inf BPO (Set) | 0 | 0 |
| Inf BPO (Non-Set) | DIF | From Raw |
| Inf BSO | | |
| Inf VFA | - | - |
| Inf FBSO | From Raw | From Raw |
| Inf UPO | | |
| Inf UPO (Set) | 0 | 0 |
| Inf UPO (Non-Set) | From Raw | From Raw |
| Inf USO | From Raw | From Raw |
| Filt TP (FBSO + USO + OP) | From Raw | From Raw |

Where:
- MR = calculated from $f_n$ mass ratio and VSS concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation
- P/C = calculated with TP/COD ratio

## B5. Carbon

Table B.8 summarises the characterisation procedure for the raw WW carbon (C) characteristics. For the C, the VFA is always calculated from mass ratios ($f_{cv}$ and $f_c$) and the COD concentration; this is because the $f_c$ mass ratio is known. With this information, if the filtered TOC is supplied, then there are only two unknown soluble concentrations: FBSO and USO. If the USO is supplied then the FBSO is calculated via differences (i.e. mass balance); else, if no data is supplied, then the USO is calculated using mass ratios. The FBSO is then calculating via differences. For the settleable and non-settleable UPO, they are always calculated using their respective $f_c$ mass ratios and the VSS concentrations. The BPO settleable is also calculated in the same way. Lastly, if the supplied data does not allow the last unknown concentration, non-settleable BPO, to be calculated by differences then mass ratios are again used. For the settled WW C characteristics, the soluble and non-settleable particulate concentrations are the same. If the settled WW TOC concentration is entered, then the non-settleable BPO concentration is calculated. With this concentration, the BPO split in the raw WW is recalculated. Table B.9 summarises the settled WW C characterising procedure.

**Table B.8: WWChar Tree – Raw wastewater C characterisation table**

| | Raw wastewater C Input Options | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Raw TOC | Yes | No | No | Yes | Yes | No | Yes | No |
| Filtered TOC | No | Yes | No | Yes | No | Yes | Yes | No |
| Filtered effluent TOC | No | No | Yes | No | Yes | Yes | Yes | No |
| Total influent raw TOC | ENT | SUM | SUM | ENT | ENT | SUM | ENT | SUM |
| Influent BPO | | | | | | | | |
| Influent BPO (Settleable) | MR | MR | MR | MR | MR | MR | MR | MR |
| Influent BPO (Non-Settleable) | DIF | MR | MR | DIF | DIF | MR | DIF | MR |
| Influent BSO | | | | | | | | |
| Influent VFA | MR | MR | MR | MR | MR | MR | MR | MR |
| Influent FBSO | MR | DIF | MR | DIF | MR | DIF | DIF | MR |
| Influent UPO | | | | | | | | |
| Influent UPO (Settleable) | MR | MR | MR | MR | MR | MR | MR | MR |
| Influent UPO (Non-Settleable) | MR | MR | MR | MR | MR | MR | MR | MR |
| Influent USO | MR | MR | ENT | MR | ENT | ENT | ENT | MR |
| Total biodegradable | SUM | SUM | SUM | SUM | SUM | SUM | SUM | SUM |
| Total unbiodegradable | SUM | SUM | SUM | SUM | SUM | SUM | SUM | SUM |
| Total particulate | SUM | SUM | SUM | SUM | SUM | SUM | SUM | SUM |
| Total soluble | SUM | ENT | SUM | ENT | SUM | ENT | ENT | SUM |

Where:

- MR = calculated from $f_n$ mass ratio and VSS concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation

**Table B.9: WWChar Tree – Settled wastewater C characterisation table**

| | Settled wastewater P Input Options | |
|---|---|---|
| Settled TOC entered? | Yes | No |
| Settled TOC | ENT | From Raw |
| Inf BPO | | |
| Inf BPO (Set) | 0 | 0 |
| Inf BPO (Non-Set) | DIF | From Raw |
| Inf BSO | | |
| Inf VFA | From Raw | From Raw |
| Inf FBSO | From Raw | From Raw |
| Inf UPO | | |
| Inf UPO (Set) | 0 | 0 |
| Inf UPO (Non-Set) | From Raw | From Raw |
| Inf USO | From Raw | From Raw |

Where:

- MR = calculated from $f_n$ mass ratio and VSS concentration
- ENT = entered
- DIF = calculated from difference
- SUM = calculated from summation

# Appendix C. Wastewater Characteristics for Program Design Section

The FWA concentrations for the characteristics shown in the tables below were generated using the DFData method, with the DFData data set, as discussed in the DFData section. Note that for the UCT notation, a comma is used before the subscript i, for example $N_{obp,i}$. This is not in the original notation, but it is used for here and for the PWSSD program. It was deemed necessary have the subscript, for the source of the characteristic, separate from the rest of the subscripts. This was done to make the source subscript more visible, particularly when the source is PS, WAS. For PS the source subscript is PS, for example $N_{obp,PS}$. For the WAS, the source subscript is w, for example $N_{obp,w}$. For the WAS and PS blend, the source subscript is m, for example $N_{obp,m}$. Raw and settled WW both use the i subscript, this is shown for the tables below.

**Table C.1: Wastewater characteristics for program design section - COD**

| Chemical Oxygen Demand | | | Raw | Settled | PS |
|---|---|---|---|---|---|
| Characteristic | Symbol (UCT) | Symbol (IWA) | mg/L | mg/L | mg/L |
| Total influent COD | $S_{t,i}$ | $COD_{TOT,Inf}$ | 1016.27 | 656.45 | 72621.07 |
| Inorganic COD | $S_{a,i}$ | $COD_{InOrg,Inf}$ | 0.00 | 0.00 | 0.00 |
| Organic influent COD | $S_{o,i}$ | $COD_{Org,Inf}$ | 1016.27 | 656.45 | 72621.07 |
| Influent BPO | $S_{bp,i}$ | $XC_{B,Inf}$ | 624.94 | 375.42 | 50279.10 |
| Influent BPO (Settleable) | $S_{bp,i,Set}$ | $XC_{B,Inf,Set}$ | 249.67 | 0.00 | 49934.79 |
| Influent BPO (Non-Settleable) | $S_{bp,i,NSet}$ | $XC_{B,Inf,NSet}$ | 375.27 | 375.42 | 344.31 |
| Influent BSO | $S_{bs,i}$ | $S_{B,Inf}$ | 200.05 | 200.14 | 183.55 |
| Influent VFA | $S_{bsa,i}$ | $S_{VFA,Inf}$ | 60.02 | 60.04 | 55.07 |
| Influent FBSO | $S_{bsf,i}$ | $S_{F,Inf}$ | 140.04 | 140.10 | 128.49 |
| Influent UPO | $S_{up,i}$ | $X_{U,Inf}$ | 141.26 | 30.85 | 22112.53 |
| Influent UPO (Settleable) | $S_{up,i,Set}$ | $X_{U,Inf,Set}$ | 110.42 | 0.00 | 22084.23 |
| Influent UPO (Non-Settleable) | $S_{up,i,NSet}$ | $X_{U,Inf,NSet}$ | 30.84 | 30.85 | 28.30 |
| Influent USO | $S_{us,i}$ | $S_{U,Inf}$ | 50.01 | 50.03 | 45.89 |
| Total biodegradable | $S_{b,i}$ | $COD_{B,Inf}$ | 824.99 | 575.56 | 50462.66 |
| Total unbiodegradable | $S_{u,i}$ | $COD_{U,Inf}$ | 191.27 | 80.89 | 22158.42 |
| Total particulate | $S_{p,i}$ | $COD_{X,Inf}$ | 766.20 | 406.28 | 72391.63 |
| Total soluble | $S_{s,i}$ | $COD_{S,Inf}$ | 250.07 | 250.17 | 229.44 |

**Table C.2: Wastewater characteristics for program design section - Nitrogen**

| Nitrogen | | | Raw | Settled | PS |
|---|---|---|---|---|---|
| Characteristic | Symbol (UCT) | Symbol (IWA) | mg/L | mg/L | mg/L |
| Total influent TKN | $N_{t,i}$ | $N_{TKN,Inf}$ | 75.74 | 63.17 | 2577.63 |
| Total influent FSA | $N_{a,i}$ | $S_{FSA,Inf}$ | 47.33 | 47.35 | 42.47 |
| Total influent organic N | $N_{o,i}$ | $N_{Org,Inf}$ | 28.41 | 15.81 | 2535.17 |
| Influent BPO | $N_{obp,i}$ | $XC_{B,N,Inf}$ | 12.87 | 7.72 | 1036.58 |
| Influent BPO (Settleable) | $N_{obp,i,Set}$ | $XC_{B,N,Inf,Set}$ | 5.15 | 0.00 | 1029.50 |
| Influent BPO (Non-Settleable) | $N_{obp,i,NSet}$ | $XC_{B,N,Inf,NSet}$ | 7.72 | 7.72 | 7.08 |
| Influent BSO | $N_{obs,i}$ | $S_{B,N,Inf}$ | 4.84 | 4.84 | 4.44 |
| Influent VFA | $N_{obsa,i}$ | $S_{VFA,N,Inf}$ | 0.00 | 0.00 | 0.00 |
| Influent FBSO | $N_{obsf,i}$ | $S_{F,N,Inf}$ | 4.84 | 4.84 | 4.44 |
| Influent UPO | $N_{oup,i}$ | $X_{U,N,Inf}$ | 9.54 | 2.08 | 1493.08 |
| Influent UPO (Settleable) | $N_{oup,i,Set}$ | $X_{U,Inf,Set}$ | 7.46 | 0.00 | 1491.17 |
| Influent UPO (Non-Settleable) | $N_{oup,i,NSet}$ | $X_{U,Inf,NSet}$ | 2.08 | 2.08 | 1.91 |
| Influent USO | $N_{ous,i}$ | $S_{U,N,Inf}$ | 1.16 | 1.16 | 1.06 |
| Total biodegradable | $N_{ob,i}$ | $N_{B,Inf}$ | 17.71 | 12.57 | 1041.02 |
| Total unbiodegradable | $N_{ou,i}$ | $N_{U,Inf}$ | 10.70 | 3.24 | 1494.15 |
| Total particulate | $N_{op,i}$ | $X_{N,Inf}$ | 22.41 | 9.81 | 2529.66 |
| Total organic soluble | $N_{os,i}$ | $S_{N,Org,Inf}$ | 6.00 | 6.00 | 5.51 |
| Nitrates | $N_{t,i}$ | $S_{NOx,Inf}$ | 0.00 | 0.00 | 0.00 |

**Table C.3: Wastewater characteristics for program design section - Phosphorus**

| Phosphorous | | | Raw | Settled | PS |
|---|---|---|---|---|---|
| Characteristic | Symbol (UCT) | Symbol (IWA) | mg/L | mg/L | mg/L |
| Total influent P | $P_{t,i}$ | $P_{TOT,Inf}$ | 14.56 | 11.74 | 574.83 |
| Total influent orthophosphates | $P_{a,i}$ | $S_{PO4,Inf}$ | 8.82 | 8.83 | 8.01 |
| Total influent organic P | $P_{o,i}$ | $P_{Org,Inf}$ | 5.73 | 2.91 | 566.82 |
| Influent BPO | $P_{obp,i}$ | $XC_{B,P,Inf}$ | 2.42 | 1.46 | 192.70 |
| Influent BPO (Settleable) | $P_{obp,i,Set}$ | $XC_{B,P,Inf,Set}$ | 0.96 | 0.00 | 191.36 |
| Influent BPO (Non-Settleable) | $P_{obp,i,NSet}$ | $XC_{B,P,Inf,NSet}$ | 1.46 | 1.46 | 1.34 |
| Influent BSO | $P_{obs,i}$ | $S_{B,P,Inf}$ | 0.93 | 0.93 | 0.85 |
| Influent VFA | $P_{obsa,i}$ | $S_{VFA,P,Inf}$ | 0.00 | 0.00 | 0.00 |
| Influent FBSO | $P_{obsf,i}$ | $S_{F,P,Inf}$ | 0.93 | 0.93 | 0.85 |
| Influent UPO | $P_{oup,i}$ | $X_{U,P,Inf}$ | 2.38 | 0.52 | 373.27 |
| Influent UPO (Settleable) | $P_{oup,i,Set}$ | $X_{U,Inf,Set}$ | 1.86 | 0.00 | 372.79 |
| Influent UPO (Non-Settleable) | $P_{oup,i,NSet}$ | $X_{U,Inf,NSet}$ | 0.52 | 0.52 | 0.48 |
| Influent USO | $P_{ous,i}$ | $S_{U,P,Inf}$ | 0.00 | 0.00 | 0.00 |
| Total biodegradable | $P_{ob,i}$ | $P_{B,Inf}$ | 3.35 | 2.39 | 193.55 |
| Total unbiodegradable | $P_{ou,i}$ | $P_{U,Inf}$ | 2.38 | 0.52 | 373.27 |
| Total particulate | $P_{op,i}$ | $X_{P,Inf}$ | 4.80 | 1.98 | 565.97 |
| Total organic soluble | $P_{os,i}$ | $S_{P,Org,Inf}$ | 0.93 | 0.93 | 0.85 |

**Table C.4: Wastewater characteristics for program design section - Carbon**

| Carbon | | | Raw | Settled | PS |
|---|---|---|---|---|---|
| Characteristic | Symbol (UCT) | Symbol (IWA) | mg/L | mg/L | mg/L |
| Total influent C | $C_{t,i}$ | $TOC_{TOT,Inf}$ | 336.89 | 217.85 | 24026.09 |
| InOrg C | $C_{a,i}$ | $C_{InOrg,Inf}$ | 0.00 | 0.00 | 0.00 |
| Organic C | $C_{o,i}$ | $TOC_{Org,Inf}$ | 336.89 | 217.85 | 24026.09 |
| Influent BPO | $C_{bp,i}$ | $XC_{B,C,Inf}$ | 201.66 | 121.20 | 16213.19 |
| Influent BPO (Settleable) | $C_{bp,i,Set}$ | $XC_{B,C,Inf,Set}$ | 80.51 | 0.00 | 16102.03 |
| Influent BPO (Non-Settleable) | $C_{bp,i,NSet}$ | $XC_{B,C,Inf,NSet}$ | 121.15 | 121.20 | 111.16 |
| Influent BSO | $C_{bs,i}$ | $S_{B,C,Inf}$ | 68.82 | 68.85 | 63.14 |
| Influent VFA | $C_{bsa,i}$ | $S_{VFA,C,Inf}$ | 22.50 | 22.51 | 20.64 |
| Influent FBSO | $C_{bfs,i}$ | $S_{F,C,Inf}$ | 46.32 | 46.34 | 42.50 |
| Influent UPO | $C_{up,i}$ | $X_{U,C,Inf}$ | 49.41 | 10.79 | 7734.16 |
| Influent UPO (Settleable) | $C_{up,i,Set}$ | $X_{U,C,Inf,Set}$ | 38.62 | 0.00 | 7724.26 |
| Influent UPO (Non-Settleable) | $C_{up,i,NSet}$ | $X_{U,C,Inf,NSet}$ | 10.79 | 10.79 | 9.90 |
| Influent USO | $C_{us,i}$ | $S_{U,C,Inf}$ | 17.00 | 17.01 | 15.60 |
| Total biodegradable TOC | $C_{b,i}$ | $TOC_{B,Inf}$ | 270.48 | 190.04 | 16276.33 |
| Total unbiodegradable TOC | $C_{u,i}$ | $TOC_{U,Inf}$ | 66.41 | 27.80 | 7749.76 |
| Total particulate TOC | $C_{p,i}$ | $X_{C,Inf}$ | 251.07 | 131.99 | 23947.35 |
| Total soluble TOC | $C_{s,i}$ | $S_{C,Org,Inf}$ | 85.82 | 85.86 | 78.74 |

**Table C.5: Wastewater characteristics for program design section – Particulates (TSS, VSS, ISS)**

| Particulates | | | Raw | Settled | PS |
|---|---|---|---|---|---|
| Characteristic | Symbol (UCT) | Symbol (IWA) | mg/L | mg/L | mg/L |
| TSS | $X_{t,i}$ | $X_{TSS,Inf}$ | 558.16 | 275.19 | 56869.38 |
| ISS | $X_{io,i}$ | $X_{FSS,Inf}$ | 60.03 | 12.01 | 9615.59 |
| VSS | $X_{v,i}$ | $X_{VSS,Inf}$ | 498.13 | 263.18 | 47253.79 |
| Influent BPO | $X_{b,i}$ | $X_{VSS,B,Inf}$ | 402.75 | 242.35 | 32322.98 |
| Influent BPO (Settleable) | $X_{b,i,Set}$ | $X_{VSS,B,Inf,Set}$ | 160.50 | 0.00 | 32100.71 |
| Influent BPO (Non-Settleable) | $X_{b,i,NSet}$ | $X_{VSS,B,Inf,NSet}$ | 242.25 | 242.35 | 222.26 |
| Influent UPO | $X_{u,i}$ | $X_{VSS,U,Inf}$ | 95.38 | 20.83 | 14930.81 |
| Influent UPO (Settleable) | $X_{u,i,Set}$ | $X_{VSS,U,Inf,Set}$ | 74.56 | 0.00 | 14911.70 |
| Influent UPO (Non-Settleable) | $X_{u,i,NSet}$ | $X_{VSS,U,Inf,NSet}$ | 20.82 | 20.83 | 19.11 |

**Table C.6: Wastewater characteristics for program design section – Flow, Alk, pH**

| Flow & Other | | | Raw | Settled | PS |
|---|---|---|---|---|---|
| Characteristic | Symbol (UCT) | Symbol (IWA) | mg/L | mg/L | mg/L |
| ADWF | ADWF | ADWF | 32.08 | 31.92 | 0.16 |
| PDWF | PDWF | $Q_{Raw,PDWF}$ | 55.03 | 54.87 | 0.16 |
| PWWF | PWWF | $Q_{Raw,PWWF}$ | 48.12 | 47.88 | 0.24 |
| Alk | Alk | $S_{ALK,inf}$ | 300.00 | 300.00 | 300 |
| pH | pH | pH | 6.80 | 6.80 | 6.8 |
| Peak OUR Factor | D,Peak | D,Peak | 0.77 | 0.59 | |

**Table C.7: Wastewater characteristics for program design section – Mass ratios**

| Mass Ratios | | | | | | | |
|---|---|---|---|---|---|---|---|
| Symbol | VFA | FBSO | USO | SetBPO | NonSetBPO | SetUPO | NonSetUPO |
| $f_{cv}$ | 1.067 | 1.450 | 1.500 | 1.550 | 1.550 | 1.481 | 1.481 |
| $f_n$ | 0.000 | 0.051 | 0.035 | 0.032 | 0.032 | 0.100 | 0.100 |
| $f_p$ | 0.000 | 0.010 | 0.000 | 0.006 | 0.006 | 0.025 | 0.025 |
| $f_c$ | 0.400 | 0.471 | 0.498 | 0.498 | 0.498 | 0.518 | 0.518 |

# Appendix D. MLE Design and Upgrade Case Study

A case study for the design and upgrade of a WWTP is presented. This case study shows the ability of the steady-state model and the information that it can generate. In this case study, the client requires a MLE wastewater treatment plant to treat 32 ML/d of municipal wastewater with the wastewater characteristics presented in Appendix C.

## D1. Overview

The construction of this WWTP is split into two phases. The first phase involves treating half of the final flow, i.e. 16 ML/d, with a raw WW MLE system with AxAeD WAS. This phase (P1) is shown in Figure D.1. In the second phase of the WWTP project, the 32 ML/d flow rate (~194 000 population) must be accounted for. Two options are available for this phase and a cost estimate (using the cost inputs shown in Figure 6.54) must be performed to determine the most cost-effective option. The first option of phase two (P2O1) involves the expansion of the P1 system to a flow-balanced, settled WW MLE system, with AxAeD WAS, and AD PS. This option is shown in Figure D.2. The second option of phase two (P2O2) is the construction of an identical P1 system that will function parallel to the original system, i.e. 2 × 16 ML/d raw WW MLE system with AxAeD WAS (Figure D.1).

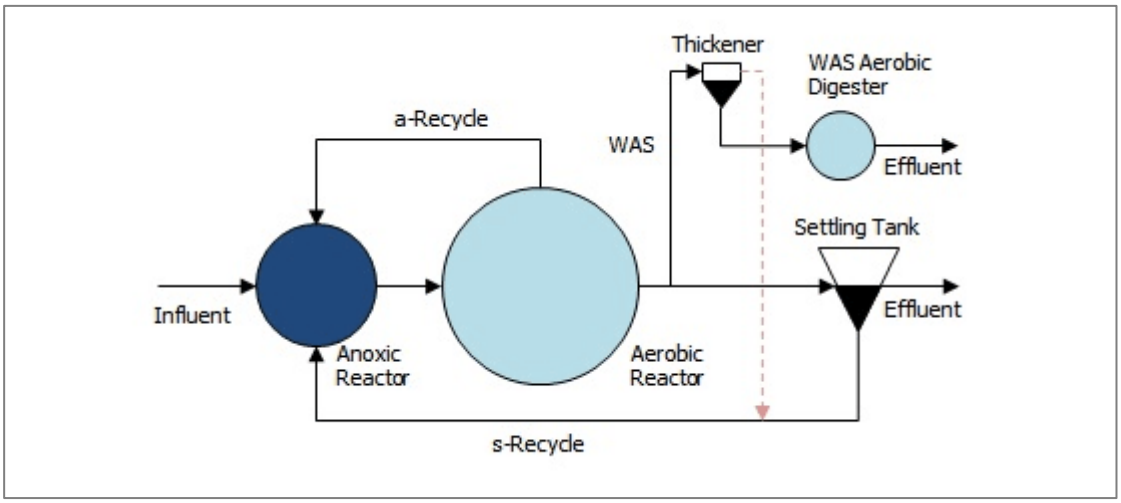



**Figure D.1: P1 – 16ML/d Raw wastewater MLE system with AxAeD WAS**

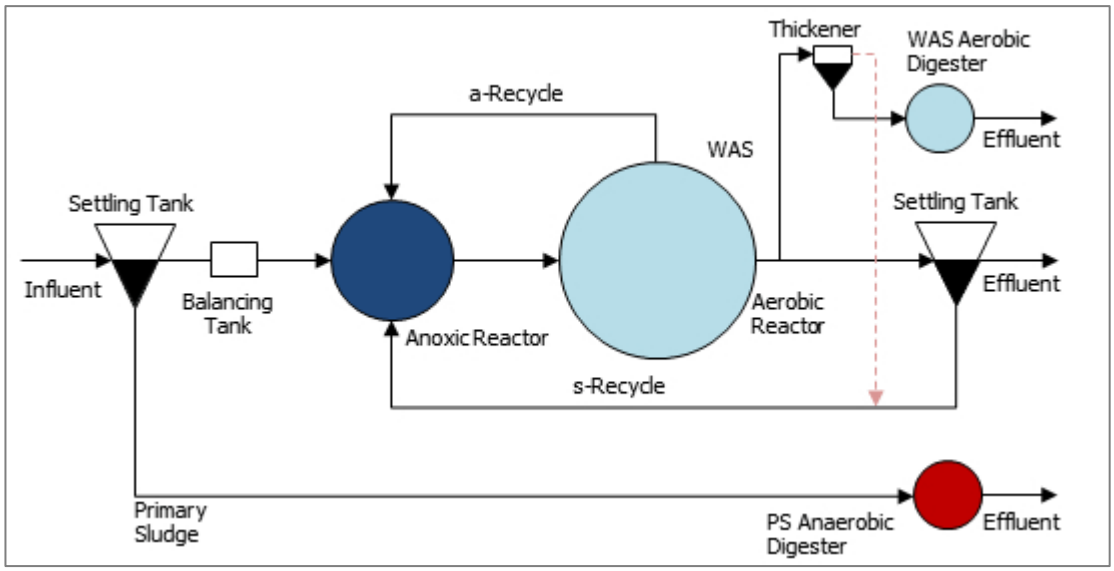



**Figure D.2: P2O1 – 32ML/d flow-balanced settled WW MLE system with AxAeD WAS and AD PS**

## D2. Design Summary

A complete technical analysis using the PWSSD component of the program was completed for all three options. The results from this analysis are presented in Table D.3 to Table D.13. From the technical evaluation, the P2O1 settled WW system's AS reactor and WAS AxAeD volumes were determined to be slightly larger than the required volumes for the P1 raw WW system. Therefore, if the settled WW is the option selected, then the settled WW system's activated sludge reactor and aerobic digester must be built in the first phase.

P2O1 is the recommended option as it was determined to be cheaper (in terms of capital costs) and because the system was calculated as being more spatially efficient. The P2O2 raw WW system requires larger reactors and more extensive aeration equipment. The larger reactor volume is due to the lack of PST, and hence a higher UPO fraction of the influent wastewater and a lower VSS/TSS ratio (more ISS in the system). For the aeration system, because flow balancing is not provided, the AS system experiences the full diurnal flow variations. This results in a larger aeration system as the peak TOD needs to be managed. The larger AS reactor and aeration system resulted in the final costs of the P2O2 raw WW system being 35.7% more expensive than the final cost of the P2O1 settled WW system. This cost analysis is presented in the Table D.1 and Table D.2. A cost estimate for a gravity WAS thickener is also included in these tables. A design component for WAS thickening is not currently available in the PWSSD program hence this was done externally.

In terms of performance, both systems (P2O1 and P2O2) have similar effluent COD, N and P effluent concentrations. However, in relation to the influent, the P2O2 raw WW system has significantly higher %P removal. This is attributed to the higher sludge mass production

and hence a higher P uptake to sludge mass. Nevertheless, both systems have similar effluent OP concentrations. Concerning the %N removal, both systems also have similar %N removal.

**Table D.1: P1 ➔ P2O1 cost estimation**

| Unit Process | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Total Cost after complete upgrade | Sizes & Quantity Per Phase | |
|---|---|---|---|---|---|
| | | | | Phase 1 | Phase 2 |
| Balancing Tank | - | + R 1 998 000 | R 1 998 000 | - | 1 × 6928 $m^3$ |
| PST | - | + R 2 498 000 | R 2 498 000 | - | 2 × 30.3 m |
| Gravity Thickener | - | + R 411 000 | R 411 000 | - | 1 × 12.1 m |
| AS Reactor | R 5 779 000 | (Built in P1) | R 5 779 000 | 2 × 5685 $m^3$ | (Built in P1) |
| SST | R 3 282 000 | (Built in P1) | R 3 282 000 | 2 × 38 m | (Built in P1) |
| Aeration AS | R 5 799 000 | + R 795 000 | R 6 593 000 | 364 kW* | 453 kW* |
| Aeration AeroD | R 1 800 000 | + R 305 000 | R 2 105 000 | 204 kW** | 253 kW** |
| AD | - | + R 2 241 000 | R 2 241 000 | - | 1 × 1604 $m^3$ |
| AeroD | R 1 279 000 | (Built in P1) | R 1 279 000 | 2 × 1336 $m^3$ (in-series) | (Built in P1) |
| WAS Thick | R 946 000 | (Built in P1) | R 946 000 | 1 × 24.1 m | (Built in P1) |
| Total Cost | R 18 885 000 | + R 8 248 000 | R 27 132 000 | | |

* Total power required per AS module, 2 modules required

**Total power required per digester series, 1 module required with 2 digesters in-series

**Table D.2: P1 ➔ P2O2 cost estimation**

| Unit Process | Phase 1: 16ML/d Raw | Phase 1: 32ML/d Raw | Total Cost after complete upgrade | Sizes & Quantity Per Phase | |
|---|---|---|---|---|---|
| | | | | Phase 1 | Phase 2 |
| Balancing Tank | - | - | - | - | - |
| PST | - | - | - | - | - |
| Gravity Thickener | - | - | - | - | - |
| AS Reactor | R 5 443 000 | + R 5 779 000 | R 5 779 000 | 2 × 5254 $m^3$ | 4 × 5685 $m^3$ |
| SST | R 3 282 000 | + R 3 282 000 | R 3 282 000 | 2 × 38 m | 4 × 38 m |
| Aeration AS | R 5 799 000 | + R 5 799 000 | R 5 799 000 | 364 kW* | 364 kW* |
| Aeration AeroD | R 1 800 000 | + R 1 800 000 | R 1 800 000 | 204 kW** | 204 kW** |
| AD | - | - | - | | |
| AeroD | R 1 279 000 | + R 1 279 000 | R 1 279 000 | 2 × 1183 $m^3$ (in-series) | 2 × 1336 $m^3$ (in-series) |
| WAS Thickener | R 946 000 | + R 946 000 | R 946 000 | 1 × 24.1 m | 2 × 24.1 m |
| Total Cost | R 18 422 000 | + R 18 422 000 | R 36 844 000 | | |

* Total power required per AS module, 2 modules required in P1, 4 modules required in P2

**Total power required per digester series, 1 module required with 2 digesters in-series, 2 modules for P2

## D3. Technical Design Summary for Each Unit Process

### D3.1 PST

The PST area required to accommodate the maximum peak wet weather flow (PWWF) was determined to be 1442.1 $m^2$. To supply this area, 2 × 30.3 m diameter PST's are required. In terms of flow rate, the underflow rate is set at 5% of the raw 32 ML/d ADWF; thus, the PS flow rate is 160 $m^3$/d, equalling 6.67 $m^3$/h. The influent settled WW flow is then 31.83 ML/d, equalling 1330 $m^3$/h.

The PST removes settleable particulates from the influent raw WW. These particulates change the characteristics of the wastewater and hence the design of the activated sludge system. Assuming that all settleable particulates are removed in the PST, and that the only particulates in the settled WW are non-settleable particulates, the wastewater characteristics indicate that an average 35.4% COD removal in the PST can be achieved. For the %N and %P removal, this is 16.6% and 19.3% respectively. These lower percentage removals are attributed to the larger soluble fraction of the N and P characteristics, 0.70 and 0.67 respectively, compared to the soluble fraction of the COD characteristics, 0.24. Thus, the different percentage removals change the TKN:COD, and TP:COD ratios, which in turn has an impact on the activated sludge system design.

For the MLE system, the higher TKN:COD ratio in the settled WW results in longer balanced SRT for the P2O1 system (SRT = 15.6 days). For the P2O2 (and P1) system, SRT = 12.3 days. However, for the influent flow of 32 ML/d, even though the balanced sludge for P2O1 is longer than P2O2, the AS reactor is smaller for the P2O1 MLE system. This is due to the high percentage ISS removal (80%) in the PST and the lower unbiodegradable particulate COD fraction in the settled WW (0.047 compared to the raw WW's 0.139). This means that, for the same influent flow rate and reactor size as a raw WW system, a settled WW system has a higher influent ADWF capacity.

**Table D.3: PST design summary**

| Parameter | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| PST Area | $m^2$ | N/A | 2262 | N/A |
| Diameter | m | | 38.0 | |
| Quantity | | | 2 | |
| qA ADWF | m/h | | 0.918 | |
| qA PWWF | m/h | | 0.918 | |

## D3.2 Flow Equalisation

Flow equalisation is beneficial in that it lowers the PWWF:ADWF ratio from 2.57 to 1.25. This significantly improves the performance and capacity of the AS system. Furthermore, smaller aeration equipment and SSTs can be used. In terms of capacity, for the P2O2 system with a total SST area of 2262 $m^2$ and total reactor volume of 11370 $m^3$, a flow-balanced system has 28.5% more ADWF capacity than a non-balanced system, quantitatively this is 32.0 ML/d compared to 24.9 ML/d. In terms of capital costs, upgrading the P1 system to a flow-balanced settled WW system (P2O1) is cheaper than upgrading the P1 system to a non-balanced flow settled WW system. This capacity estimate and cost analysis is presented in the Tables below.

**Table D.4: Capacity Estimate for flow-balanced and non-flow-balanced settled MLE**

| Type | Max ADWF (ML/d) | PWWF:ADWF | Xt (mgTSS/L) | MXt (kgTSS) | Required SST Area ($m^2$) |
|---|---|---|---|---|---|
| Flow-Balanced | 32.0 | 1.25:1 | 6300 | 71 632 | 2262 |
| Non-Balanced | 25.2 | 2.57:1 | 4 918 | 55 915 | 2262 |

**Table D.5: Aerator comparison of flow-balanced and non-balanced settled MLE**

| Aerobic Reactor Compartment | Phase 1 Raw | Phase 2 - No Balancing | Phase 2 - Flow Balancing |
|---|---|---|---|
| 1 | 2 × 65 kW | **2 × 40 kW** and 2 × 65 kW | **1 × 40 kW** and 2 × 65 kW |
| 2 | 1 × 40 kW and 1 × 65 kW | 1 × 40 kW and **2 × 65 kW** | **2 × 65 kW** |
| 3 | 1 × 40 kW and 1 × 65 kW | **2 × 40 kW** and 1 × 65 kW | 1 × 40 kW and 1 × 65 kW |
| 4 | 1 × 40 kW and 1 × 65 kW | **2 × 40 kW** and 1 × 65 kW | 1 × 40 kW and 1 × 65 kW |
| **Total Change per module (2 modules required)** | - | **+ 4 × 40 kW (Total of 8) + 1 × 65 kW (Total of 2)** | **+ 1 × 65 kW (Total of 2) Move 1 × 40 kW at Comp2 to Comp1 1** |
| Balancing Tank Cost | - | - | + R 1 998 000 |
| Additional AS Aeration Cost | - | + R 3 228 000 | + R 795 000 |
| Total AS Aeration Cost | R 5 799 000 | R 9 027 000 | R 6 593 000 |
| Existing SST area okay? | - | No, extra 250 $m^2$ required! Opt Xt = 4.5 gTSS/L. AS $V_t$ = 15 918 $m^3$ | Yes |
| Net Additional Cost | - | + R 3 228 000 | + R 2 793 000 |

NB! Net additional costs only considered balancing tank and aeration system, the additional SSTs and reactors to supply the required SST area and reactor volume are not considered.

### D3.3 AS System

- Phase 1 – 16 ML/d raw WW balanced MLE AS system

The balanced raw MLE system is designed to operate at 12.27 days SRT with an $f_{x1}$ of 0.285. This is for operation at 14°C, which is the average winter temperature experienced at the location of the treatment plant.

In terms of system volume, the balanced raw MLE system requires a total reactor size of 10508 $m^3$; this is split into anoxic and aerobic volumes of 2995 $m^3$ and 7513 $m^3$. The total volume slightly exceeds the maximum volume that can be constructed (10 000 $m^3$). Therefore, the MLE system has to be split into two modules of 5254 $m^3$ each, with anoxic and aerobic volumes of 1497 $m^3$ and 3757 $m^3$ respectively. This volume is optimised, in terms of the reactor TSS concentration, to the required SST area. It was optimised with the condition that the number of reactors equals the number of SSTs and that there must be an even number of reactors and SSTs. This is so that identical modules can be built and so that the flow rate can be simply split into two flows, instead of a more default split of three. The result is that, at 14°C, the expected (optimised) TSS concentration in the reactor is 6200 mgTSS/L. Note that the AS system volume is designed for the winter temperature of 14°C. At the winter TSS concentration, to establish the required 12.27 day SRT a WAS flow rate of 856.2 $m^3$/h is required giving a WAS flux of 5308.5 kgTSS/d.

A 6:1 a-recycle is used, which provides up to 88.4% nitrogen removal and 665.5 kmol/d of $N_2$ gas production. The effluent nitrate, TKN, and FSA concentrations are 5.9 mg$NO_3$-N/L, 2.8 mgTKN-N/L and 1.7 mg$NH_x$/L. The effluent nitrate and FSA concentrations are far below the Green Drop effluent nitrogen limits (6 mg$NH_x$/L and 15 mg$NO_3$-N/L). The %N removal can be increased if a higher a-recycle is used; at 8:1, 90% N removal can be achieved. However, the pumping costs will be significantly high; the benefit of removing the extra 1.6% N will not be worthwhile. Therefore, for economical reasons, the a-recycle is limited to 6:1.

For the phosphorous, the effluent OP is 8.8 mgOP-P/L (Green Drop effluent limit 10 mgOP-P/L). This translates to 43.8% phosphorous removal. The effluent OP is close to the Green Drop effluent limits; however, because the requirement for nitrification fixes the SRT of the system, the effluent OP cannot be lowered. If this effluent OP is unsatisfactory then the system should be changed to a biologically enhanced phosphorous removal (BEPR) activated sludge system, e.g. a UCT NDBEPR system. Once the MLE system is constructed, conversion to a UCT NDBEPR system will not be difficult. An anaerobic reactor will be required; adjustments to the anoxic and aerobic reactor volumes will also be required so that the appropriate anaerobic and anoxic sludge masses are provided. Due to the increase in sludge production of BEPR systems, additional SSTs will be also be required if the same influent raw WW flow rate is maintained.

The balanced raw WW MLE system will have an effluent COD concentration of 50 mgCOD/L. This is fixed by the influent wastewater characteristics.

- Phase 2 Option 1 – 32 ML/d settled balanced wastewater MLE AS system

For the settled WW system, the SRT is balanced 15.60 days, and requires an $f_{x1}$ of 0.393. The optimised $X_t$ concentrations is 6300 mgTSS/L, giving a total volume is at 11370 $m^3$, with total anoxic and aerobic volumes of 2993 $m^3$ and 7513 $m^3$ respectively. The total volume is split into two modules of 5685 $m^3$ each, with 2233 $m^3$ anoxic and 3452 $m^3$ aerobic zones. In terms of volume per person, the settled WW requires 58.60 L of reactor volume per person. The P1 raw WW system, which treats 16 ML/d or half the target population of 194 000 (i.e. 97 000), has a ratio of 108.3 L of reactor volume per person. From these ratios, it is quite evident that the size of the settled WW system is much smaller. Note that is P1, the total reactor volume is 10508 $m^3$. Therefore, if P2O2 is selected, then the settled WW system's 11370 $m^3$ activated sludge reactor, with a 0.393 anoxic fraction, must be built in P1!

The required SST areas for P1 and P2O1 are the same; thus, the consequence of having a slightly larger reactor in P1 is that an increase in ADWF capacity is possible. This ADWF capacity for P1 will be 18.34 ML/d, as oppose to the original 16 ML/d. In addition to this, note that the P2O1 reactor fixes the anoxic fraction for P1. Therefore, the minimum (operating SRT) in P1 will not be 12.27 days. For a 0.393 anoxic fraction, 15.60 days is required. Therefore, in P1, with the 11370 $m^3$ reactor, 0.393 anoxic fraction and 15.60 day SRT, the system will not be a balanced MLE system in that it will have 17% extra N removal capacity. As a result of the increased SRT but relatively small increase in reactor volume, the reactor TSS concentration will be higher, 6950 mgTSS/L. However, the total SST area is still 2262 $m^3$; hence, this concentration is not an optimised concentration. These inefficiencies cannot be avoided, nevertheless the P2O1 reactor has to be built in P1 otherwise the future 32 ML/d capacity cannot be achieved.

The settled WW system's a-recycle ratio is 6:1. At this ratio, the effluent nitrate is 6.0 mg$NO_3$-N/L, FSA and TKN is 1.7 mgFSA-N/L and 2.8 mgTKN-N/L, $N_2$ gas production is 1343.1 kmol/d, and 86% N removal is obtained. P removal is at 26.1%, this is lower than in the raw WW system (43.8%) because of the lower sludge production. However, the percentage removal does not translate to a higher effluent OP because the PST removes a portion of the influent TP; therefore, the effluent OP for the settled WW system, 8.7 mgOP-P/L, is almost the same as for the raw WW system.

- Phase 2 Option 2 – 32 ML/d balanced raw WW MLE AS system

For this option, the P1 raw WW system is simply duplicated to provide a 32 ML/d raw W system. A comparison of the all three AS system is presented in Table D.6.

**Table D.6: AS system design summary**

| Parameter | Units | Phase 1: 16ML/d Raw | | Phase 2 Option 1: 32 ML/d Settled | | Phase 2 Option 2: 32 ML/d Raw | |
|---|---|---|---|---|---|---|---|
| SRT | days | 12.27 | | 15.60 | | 12.27 | |
| $f_{x1}$ | - | 0.285 | | 0.393 | | 0.285 | |
| V total | $m^3$ | 10 509 | | 11 370 | | 21 017.0 | |
| V per mod | $m^3$ | 5 254 | | 5685 | | 5 254.2 | |
| $V_{AX}$ per mod | $m^3$ | 1 497 | | 2233 | | 1 497.3 | |
| $V_{AE}$ per mod | $m^3$ | 3 757 | | 3452 | | 3 757.0 | |
| Modules | - | 2 | | 2 | | 4 | |
| $MX_{BH}$ Total | kgVSS/d | 20 992.7 | | 31 045.2 | | 41 985.3 | |
| $MX_{EH}$ Total | kgVSS/d | 10 417.8 | | 19 578.9 | | 20 835.5 | |
| $MX_U$ Total | kgVSS/d | 18 776.4 | | 10 371.1 | | 37 552.7 | |
| $MX_{Io}$ Total | kgVSS/d | 14 966.0 | | 10 636.7 | | 29 931.9 | |
| $MX_V$ Total | kgVSS/d | 50 186.8 | | 60 995.2 | | 100 373.5 | |
| $MX_T$ Total | kgTSS/d | 65 152.8 | | 71 631.9 | | 130 305.4 | |
| $X_v$ per mod | mgVSS/L | 4 775.8 | | 5364 | | 4 775.8 | |
| $X_t$ per mod | mgTSS/L | 6 200.0 | | 6300 | | 6 200.0 | |
| $FX_v$ Total | kgVSS/d | 4 089.1 | | 3910 | | 8 178.3 | |
| $FX_t$ Total | kgTSS/d | 5 308.5 | | 4593 | | 10 617.1 | |
| $Q_w$ Total | $m^3$/d | 856 | | 729 | | 1712 | |
| $f_{av}$ per mod | gAVSS/gVSS | 0.418 | | 0.509 | | 0.418 | |
| $f_{at}$ per mod | gAVSS/gTSS | 0.322 | | 0.433 | | 0.322 | |
| $f_{ii}$ per mod | gVSS/gTSS | 0.770 | | 0.852 | | 0.770 | |
| $S_{use}$ | mgCOD/L | 50 | | 50 | | 50 | |
| $N_{te}$ | mgN/L | 2.822 | | 2.823 | | 2.822 | |
| $N_{ae}$ | mgN/L | 1.662 | | 1.662 | | 1.662 | |
| $N_{ne}$ | mgN/L | 5.928 | | 6.0 | | 5.928 | |
| $P_{te}$ | mgP/L | 8.10 | | 8.7 | | 8.10 | |
| %NRem | % | 88.45 | | 86.0 | | 88.45 | |
| %PRem | % | 43.79 | | 26.1 | | 43.79 | |
| | | (14°C) | (22°C) | 14°C) | (22°C) | (14°C) | (22°C) |
| $OUR_{td}$ | mgO/(L.h) | 61.1 | 63.4 | 101.0 | 104.32 | 61.1 | 63.4 |
| $OUR_{td}$ Peak | mgO/(L.h) | 77.1 | 77.1 | 101.0 | 104.32 | 77.1 | 77.1 |
| $FO_c$ Total | kgO/d | 9442.1 | 9783.21 | 13 563.9 | 13 982.2 | 18884.1 | 19566.4 |
| $FO_n$ Total | kgO/d | 3476.0 | 3658.12 | 7 014.8 | 7 295.2 | 6952.0 | 7316.2 |
| $FO_d$ Total | kgO/d | 1901.5 | 2001.16 | 3 837.3 | 3 990.8 | 3803.0 | 4002.3 |
| $FO_{td}$ Total | kgO/d | 11016.5 | 11440.17 | 16 41.2 | 17 286.6 | 22033.0 | 22880.3 |

### D3.4 SST

Two SSTs of 1130.8 $m^2$ each (37.9 m in diameter) are required for P1. This gives a total SST area of 2261.6 $m^2$. At the winter temperature, with a DSVI of 100 mL/gTSS, the maximum capacity of this system is the designed 16ML/d. However once constructed, if the DSVI improves to 80 mL/gTSS the maximum ADWF capacity will improve to 17.9 ML/d; conversely if it weakens to 120 mL/gTSS, the maximum ADWF capacity will drop to 14.4 ML/d. These capacity estimates assume that the configuration does not change and the diurnal flow rate patterns, with a PWWF:ADWF ratio of 2.57, stay the same. With the same assumptions, at the summer temperature, a DSVI of 100 mL/gTSS provides a maximum ADWF of 16.63 ML/d. This slight increase is due to the lower particulates concentration in the activated sludge reactor

For the P2O1, the SST requirements are very similar to the P1. A total SST area of 2262 $m^2$ is required. This can be met by 2 × 38.0 m diameter SSTs. The SST area is almost the same as P1 because the PWWF and optimised Xt concentrations are almost identical. In P1 the optimised $X_t$ is 6200 mgTSS/L; in P2O2 it is 6300 mgTSS/L. For the PWWF in P1, the PWWF:ADWF ratio is 2.57, giving a PWWF of 16 ML/d × 2.57 = 41.12 ML/d. In P2O2, due to the balancing tank, the PWWF:ADWF factor is 1.25. Thus, the PWWF for this option is 32 ML/d × 1.25 = 40 ML/d. The net result of these PWWF and $X_t$ concentrations gives similar SST areas. Therefore, when upgrading to the settled WW system, no additional SSTs are required provided the 2 × 38.0 m diameter SSTs are constructed in P1.

A summary of the SST design is provided in Table D.7, which continues onto the next page.

**Table D.7: SST design summary**

| Parameter | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| SST Area | $m^2$ | 2262 | 2262 | 4523 |
| Diameter | m | 37.9 | 38.0 | 37.9 |
| Quantity | | 2 | 2 | 4 |
| qA PWWF | m/h | 0.951 | 0.918 | 0.951 |
| PWWF | $m^3/h$ | 1 719.8 | 1666.7 | 3 439.50 |
| $X_R$ ADWF | gTSS/L | 11.8 | 14.2 | 11.806 |
| $X_R$ PDWF | gTSS/L | 15.8 | 14.6 | 15.818 |
| $X_R$ PWWF | gTSS/L | 11.8 | 11.6 | 11.814 |
| sRec ADWF | | 1.106 | 0.760 | 1.106 |
| sRec PDWF | | 0.645 | 0.760 | 0.645 |
| sRec PWWF | | 1.104 | 1.135 | 1.104 |

| Parameter | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| Crit sRec ADWF | | 0.491 | 0.760 | 0.491 |
| Crit sRec PDWF | | 0.645 | 0.760 | 0.645 |
| Crit sRec PWWF | | 1.104 | 1.135 | 1.104 |
| Underflow Q ADWF | $m^3/h$ | 739.100 | 1010.491 | 1478.200 |
| Underflow Q PDWF | $m^3/h$ | 739.100 | 1010.491 | 1478.200 |
| Underflow Q PWWF | $m^3/h$ | 1899.114 | 1886.522 | 3798.227 |

### D3.5 AxAeD WAS

The AxAeD WAS retention time (HRT) and digester volume is determined from the thickened WAS flow rate, which in turn is determined by the thickening concentration. For the P1 and P2O1 systems, a maximum OUR in the first digester was selected to be 125 mgO/(L.h). To obtain the maximum 125 mgO/(L.h) in the first digester, the influent WAS concentration must be 5.2 %TSS; however, this concentration cannot be achieved by a gravity WAS thickener. The maximum applied flux to achieve a 5.2 %TSS underflow concentration is extremely low; thus, an impractical WAS thickener area is required. A more reasonable 2.73 %TSS is therefore used, giving a 24.1 m diameter thickener (576.8 $m^2$). A WAS thickener design is currently not available in the PWSSD program, and hence it was done externally.

- **Phase 1 – 16 ML/d raw WW balanced MLE AS system**

The active fraction of the WAS is 0.418 $f_{av}$ (AVSS/VSS) and $f_{at}$ 0.322 (AVSS/VTSS). These active fractions are too high to be directly discharged to sludge drying beds, an $f_{av}$ of 0.115 giving a specific oxygen utilisation rate (SOURe) of 1.50 mgO/(gVSS.h) is required for direct discharge. Therefore, a sludge treatment is required to stabilise it to the $f_{av}$ requirements. Two in-series aerobic digesters are used, the total HRT is 12.2 days, and the total volume is 2365.4 $m^3$. Per digester, this is 6.1 days each and 1182.7 $m^3$. In terms of the effluent particulate fluxes, the aerobic digesters generate 4010.7 kgTSS/d with a $f_{at}$ of 0.086 gAVSS/gTSS ($f_{av}$ of 0.115 AVSS/VSS, 2996.2 kgVSS/d). The digester achieves a %VSS removal of 26.7%. Three in-series digesters can also be used, this will decrease the total volume to 2038.9 $m^3$ (679.65 $m^3$ each). For both options, the capital costs are roughly the same. Thus, it was decided that two in-series is better, as maintenance and construction will be easier.

- **Phase 2 – 32 ML/d settled WW balanced MLE AS system**

The activate fraction of the WAS is 0.509 w.r.t to VSS and 0.433 w.r.t to TSS. To stabilise this to an effluent sludge stability of 1.50 mgO/(gVSS.h), or and $f_{av}$ 0.115, the two in-series digesters need to operate at 7.9 days HRT. This HRT gives digester volumes of 1335.9 $m^3$ each. In P1, the required aerobic digester volumes are 1182.7 $m^3$ each; therefore, like the aerobic reactor, if P2O2 is selected then the settled systems' 2 × 1335.9 $m^3$ digesters need to be built, and not the raw system's 2 × 806.7 $m^3$. Due to the P1 design requiring 2 × 1335.9 $m^3$ digesters (with the 11370 $m^3$ activated sludge reactor, 0.393 anoxic fraction and 15.60 day SRT, giving WAS flow rate of 729 $m^3$/d), the P2 digester's HRT for a 2.73 %TSS WAS is 7.2 days. This HRT provides an effluent SOURe of 1.07 mgO/(gVSS.h) and fav of 0.082, meaning that the excess volume and excess HRT provides a more stable effluent sludge. The AxAeD design is summarised in Table D.8. On the next page, Table D.9 summarises the filtered and unfiltered effluent concentrations from the AxAeD.

**Table D.8: AxAeD design summary**

| Parameter | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| HRT Per Dig | days | 6.1 | 7.9 | 6.1 |
| HRT Total | days | 12.2 | 15.9 | 12.2 |
| Qi Aft Thick | $m^3$/h | 8.102 | 7.01 | 16.204 |
| $X_{ti}$ from AS | | | | |
| $X_{ti}$ Aft Thick | %TSS | 2.73 | 2.73 | 2.73 |
| V digester | $m^3$ | 1182.70 | 1335.85 | 2365.40 |
| V total | $m^3$ | 2365.40 | 2671.71 | 4730.81 |
| Digesters | | 2 in-series | 2 in-series | 2 x 2 in-series |
| $FO_{td}$ | kgO/d | 1806.1 | 2243.4 | 3612.3 |
| $OUR_{td}$ Dig1 | mgO/(L.h) | 65.9 (Extra 50%) | 75.8 (Extra 50%) | 65.9 (Extra 50%) |
| $OUR_{td}$ Dig2 | mgO/(L.h) | 29.6 (Extra 50%) | 29.1 (Extra 50%) | 29.6 (Extra 50%) |
| $X_v$ | mgVSS/L | 15407.6 | 15175.2 | 15407.6 |
| $X_{io}$ | mgISS/L | 5216.9 | 2540.5 | 5216.9 |
| $X_t$ | mgTSS/L | 20624.5 | 17715.7 | 20624.5 |
| $FX_v$ | kgVSS/d | 2996.0 | 2552.9 | 5992.1 |
| $FX_{io}$ | kgISS/d | 1014.4 | 427.4 | 2028.9 |
| $FX_t$ | kgTSS/d | 4010.5 | 2980.3 | 8021.0 |
| SOURe | mgO/gVSS/h | 1.50 | 1.50 | 1.50 |
| $f_{av}$ | gAVSS/gVSS | 0.115 | 0.115 | 0.115 |
| $f_{at}$ | gAVSS/gTSS | 0.086 | 0.098 | 0.086 |
| $f_{ii}$ | gVSS/gTSS | 0.747 | 0.857 | 0.747 |

**Table D.9: AxAeD WAS unfiltered and filtered effluent concentrations**

| | | g/L | | | | mg/L | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase | Type | VSS | TSS | ISS | COD | TKN | FSA | OrgN | $NO_3$ | TP | OP | OrgP |
| P1 | Unfiltered | 15.40 | 20.62 | 52.16 | 22.89 | 1547.5 | 1.7 | 1545.9 | 5.9 | 533.9 | 148.7 | 321.3 |
| P1 | Filtered | 0 | 0 | 0 | 0.050 | 6.8 | 1.7 | 5.1 | 5.9 | 158.4 | 148.7 | 0.0 |
| P2O2 | Unfiltered | 15.17 | 17.71 | 25.40 | 22.52 | 1524.2 | 1.7 | 1522.5 | 6.0 | 589.8 | 210.5 | 301.2 |
| P2O2 | Filtered | 0 | 0 | 0 | 50 | 6.7 | 1.7 | 5.0 | 6.0 | 210.8 | 210.5 | 0.0 |

### D3.6 AD PS

The effluent solids flux from the AD is 4423 kgTSS/d (2881 kgVSS/d), and gas production is 2640 $m^3$/d of $CH_4$ and 1680 $m^3$/d of $CO_2$. These fluxes are equivalent to 7046.2 kgCOD/d ($CH_4$) and 840.2 kgC/d ($CO_2$). The digester pH is expected to be around 6.85. It is imperative to keep this pH stable and above 6.0, otherwise digester failure can occur.

In terms of the performance of the anaerobic digester, a 61.99% VSS removal and 61.94 %COD removal is achieved. These high %Removals are due to the low sludge production in anaerobic digestion process. Its benefits are also visible when a plant-wide mass balanced is computed. The anaerobic digester receives 35.7% of raw WW COD to the WWTP, of this influent COD, 60.5% is transformed to $CH_4$, 39.4% of the COD is found in the effluent solids, and 0.1% in the effluent liquids. Compared to the aerobic digestion system, in which 65.2% of its influent COD is in the effluent solids, meaning that only around 34.8% COD removal is achieved. In terms of the total raw WW COD for the anaerobic digester, of the 100% COD entering the WWTP, 21.6% of this is transformed to $CH_4$ gas and 14.1% lies in the effluent solids of the anaerobic digester. In more visible terms, the anaerobic digester removes $1/5^{th}$ of the influent COD but has capital costs R 2 241 000, which is 8.2% of the total cost of the settled WW system (R 27 132 000). However, one must be careful of reviewing the two systems based only on COD removal efficiency and capital costs as the two systems have significantly different operational complexities and technical requirements (e.g. staff and equipment). Furthermore, issues such as pre-treatment and dewatering must also be taken into account to evaluate which digestion method is more suitable for the project at hand.

A summary of the AD PS design is presented in Table D.10; also, in Table D.11, a summary of the filtered and unfiltered effluent concentrations from the AD is presented.

**Table D.10: PS AD design summary**

| | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| HRT Total | days | N/A | 10 | N/A |
| $Q_i$ | $m^3/h$ | | 6.67 | |
| V digester | $m^3$ | | 1604.0 | |
| $FX_v$ | kgVSS/d | | 2552.9 | |
| $FX_t$ | kgTSS/d | | 2980.3 | |
| Eff COD | gCOD/L | | 22.11 | |
| USO COD | gCOD/L | | 0.05 | |
| UPO COD | gCOD/L | | 22.11 | |
| BPO COD | gCOD/L | | 359.7 | |
| $Z_{AD}$ | gCOD/L | | 3.964 | |
| $Z_{ED}$ | gCOD/L | | 0.325 | |
| $CH_4$ COD | gCOD/L | | 43.876 | |
| $CO_2$ | $m^3$/L influent | | 16.453 | |
| $CH_4$ | $m^3$/L influent | | 10.477 | |
| $pCO_2$ | | | 0.389 | |
| pH | | | 6.821 | |
| E | | | 0.0891 | |

**Table D.11: AD PS unfiltered and filtered effluent concentrations**

| | | g/L | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase | Type | VSS | TSS | ISS | COD | TKN | FSA | OrgN | $NO_3$ | TP | OP | OrgP |
| P2O2 | Unfiltered | 17.960 | 27.576 | 9.616 | 22.11 | 2.578 | 0.660 | 1.917 | 0 | 0.575 | 0.193 | 0.382 |
| P2O2 | Filtered | 0 | 0 | 0 | 0.05 | 0.661 | 0.660 | 0.001 | 0 | 0.193 | 0.193 | 0.000 |

## D3.7 Aeration

The AS aeration system must be designed for the summer temperatures, this is due to the faster endogenous respiration rate resulting in higher oxygen consumption. A more detailed explanation to why this occurs is provided in Section 6.4.2 Aeration

At the summer temperature, for the activated sludge aerobic reactor, the total oxygen demand ($FO_{td}$) is 11440.2 kgO/d. This demand includes an adjustment for denitrification, and it gives an $OUR_{td}$ of 63.44 mgO/(L.h). The benefits of denitrification are evident in the reduction of oxygen demand; without the anoxic reactor, the required carbonaceous and nitrification oxygen demand ($FO_c + FO_n$) is 13396 kgO/d. Therefore, denitrification constitutes to a 14.89% reduction in oxygen demand, i.e. the 14.89% less oxygen can be supplied if denitrification is catered for. For the aeration system, to supply the summer oxygen requirements for P1 scaled up by a peak TOD factor of 1.21, the required output at the aerator shaft is 363.4 kW. The aerobic AS reactor is divided into four compartments. The aerators for each compartment are presented in the list below. Two AS modules are required, thus total aerators is double the quantity in the list below. Additional aerators can be installed when the WWTP is upgraded to a 32ML/d system. The aerators selected for each compartment, per module, are:

- Compartment 1: 2 × 65 kW (total: 130 kW; required: 120 kW)
- Compartment 2: 1 × 40 kW and 1 × 65kW (total: 105 kW; required: 91 kW)
- Compartment 3: 1 × 40 kW and 1 × 65kW (total: 105 kW; required: 76 kW)
- Compartment 4: 1 × 40 kW and 1 × 65kW (total: 105 kW; required: 76 kW)

For the two in-series WAS aerobic digesters, the $FO_{td}$ adjusted for denitrification is 1806.1 kgO/d. This is for the winter temperature (14°C). At the summer temperature of 14°C the $FO_{td}$ decrease to 1597.6 kgO/d. Thus, the aeration system needs to be designed for the winter temperature and not the summer temperature. An explanation to why this occurs is provided in Section 6.4.2 Aeration. At winter the $OUR_{td}$ is 60.83 mgO/(L.h) and 23.94 mgO/(L.h) for digesters 1 and 2 respectively. Denitrification is provided by using a 3h on/off aeration cycle; this will constitute a 14.74% reduction in the $FO_{td}$. In terms of nitrification oxygen demand reduction, this is a 62.52% reduction (summer and winter). The required output at the aerator shaft is 141 kW (digester 1) and 63 kW (digester 2). The selected aerators for the two in-series digester are:

- Aerobic Digester 1: 1 × 40 kW and 2 × 65 kW (total: 170 kW; required: 141 kW)
- Aerobic Digester 2: 1 × 40 kW and 1 × 65 kW (total: 105 kW; required: 63 kW)

A summary of the aeration requirements is presented in Table D.12 and Table D.13.

**Table D.12: AS aeration requirements**

| | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| Peak $O_2$ | kgO/h | 289.494 | 360.137 | 289.494 |
| kW at Shaft | kW | 363.431 | 452.117 | 363.431 |
| Comp1 Req | kW | 119.932 | 149.198 | 119.932 |
| Comp2 Req | kW | 90.858 | 113.029 | 90.858 |
| Comp3 Req | kW | 76.321 | 94.944 | 76.321 |
| Comp4 Req | kW | 76.321 | 94.944 | 76.321 |

**Table D.13: AxAeD aeration requirements**

| | Units | Phase 1: 16ML/d Raw | Phase 2 Option 1: 32 ML/d Settled | Phase 2 Option 2: 32 ML/d Raw |
|---|---|---|---|---|
| Peak $O_2$ Dig1 | kgO/h | 77.931 | 91.085 | 143.899 |
| Peak $O_2$ Dig2 | kgO/h | 34.952 | 30.402 | 56.638 |
| Dig1 Req kW | kW | 140.831 | 164.602 | 260.045 |
| Dig2 Req kW | kW | 63.163 | 54.940 | 102.353 |

# Appendix E. Model Defaults

The tables below summarises the default stoichiometric, kinetic, and input parameters for the various steady-state models and their respective design windows. These defaults are contained in a spreadsheet. The models and design windows reference this spreadsheet, and thus by changing the values on this spreadsheet, the models design windows are automatically updated.

**Table E.1: Default stoichiometric parameters**

| Parameter | Organism | | | | | |
|---|---|---|---|---|---|---|
| | OHOs | | PAOs | | ANOs | |
| Biomass yield | $Y_{OHO}$ | 0.450 | $Y_{PAO}$ | 0.450 | $Y_{ANO}$ | 0.100 |
| Endogenous residue fraction | $f_{XU,OHO}$ | 0.200 | $f_{XU,PAO}$ | 0.250 | $f_{XU,ANO}$ | 0.000 |
| Inorganic fraction | $i_{ISS,OHO}$ | 0.150 | $i_{ISS,PAO}$ | 1.300 | $i_{ISS,ANO}$ | 0.000 |
| Fraction of N in active biomass | $i_{N\_OHO}$ | 0.100 | $i_{N\_PAO}$ | 0.100 | $i_{N\_ANO}$ | 0.100 |
| Fraction of P in active biomass | $i_{P\_OHO}$ | 0.025 | $i_{P\_PAO}$ | 0.025 | $i_{P\_ANO}$ | 0.025 |
| C Fraction of active biomass | $i_{C\_OHO}$ | 0.518 | $i_{C\_PAO}$ | 0.518 | $i_{C\_ANO}$ | 0.518 |
| N Fraction of endogenous biomass | $i_{N\_XUE,OHO}$ | 0.100 | $i_{N\_XUE,PAO}$ | 0.100 | $i_{N\_XUE,ANO}$ | 0.000 |
| P Fraction of endogenous biomass | $i_{P\_XUE,OHO}$ | 0.025 | $i_{P\_XUE,PAO}$ | 0.025 | $i_{P\_XUE,ANO}$ | 0.000 |
| C Fraction of endogenous biomass | $i_{C\_XUE,OHO}$ | 0.518 | $i_{C\_XUE,PAO}$ | 0.518 | $i_{C\_XUE,ANO}$ | 0.000 |
| COD/VSS | $i_{VSS\_OHO}$ | 1.481 | $i_{VSS\_PAO}$ | 1.481 | $i_{VSS\_ANO}$ | 1.481 |
| VSS/TSS ratio for PAO active mass | | | $i_{VT,PAO}$ | 0.460 | | |
| Total P content of PAOs (P + PP) | | | $f_{XBGP}$ | 0.380 | | |
| Ratio of P release/VFA uptake | | | $i_{PO4,Rel}$ | 0.500 | | |

**Table E.2: Default kinetic parameters**

| Parameter | Units | Symbol | Value |
|---|---|---|---|
| First order fermentation rate at 20°C | $m^3$/gVSS/d | $k_{f,20}$ | 0.060 |
| OHO endogenous respiration rate at 20°C | gEVSS/gVSS/d | $b_{OHO,20}$ | 0.240 |
| PAO endogenous respiration rate at 20°C | gEVSS/gVSS/d | $b_{PAO,20}$ | 0.040 |
| Maximum specific growth rate of nitrifiers at 20°C | /d | $\mu_{OHO,Max,20°C}$ | 0.450 |
| Half saturation coefficient for $\mu_{Am20}$ | | $K_{n,20}$ | 1.000 |
| Nitrifiers endogenous respiration rate at 20°C | /d | $b_{A,20}$ | 0.040 |
| Influent RBCOD denitrification rate ($K_1$) | | $K_{1,20}$ | 0.720 |
| Influent SBCOD denitrification rate ($K_2$) | | $K_{2,20}$ | 0.101 |
| Generated SBCOD denitrification rate ($K_3$) | | $K_{3,20}$ | 0.072 |
| WAS denitrification rate ($K_4$) | | $K_{4,20}$ | 0.048 |
| Influent SBCOD denitrification rate ($K'_2$) for BEPR | | $K'_{2,20}$ | 0.230 |
| Generated SBCOD denitrification rate ($K'_3$) for BEPR | | $K'_{3,20}$ | 0.100 |

**Table E.3: Sensitivity coefficients for kinetic parameters**

| Parameter | Symbol | Value |
|---|---|---|
| Coefficient for first order fermentation rate | $\Theta_{Kf}$ | 1.029 |
| Coefficient for OHO endogenous respiration >20°C | $\Theta_{b,OHO,20up}$ | 1.040 |
| Coefficient for OHO endogenous respiration <20°C | $\Theta_{b,OHO,20down}$ | 1.029 |
| Coefficient for PAO endogenous respiration rate | $\Theta_{b,PAO}$ | 1.029 |
| Coefficient for maximum specific growth rate of nitrifiers | $\Theta_{\mu Am}$ | 1.123 |
| Coefficient for half saturation coefficient for $\mu_{Am20}$ | $\Theta_{Kn}$ | 1.123 |
| Coefficient for nitrifiers endogenous respiration rate | $\Theta_{b,ANO}$ | 1.029 |
| Coefficient for influent RBCOD denitrification rate (K1) | $\Theta_{k1}$ | 1.200 |
| Coefficient for influent SBCOD denitrification rate (K2) | $\Theta_{K2}$ | 1.080 |
| Coefficient for generator SBCOD denitrification rate (K3) | $\Theta_{K3}$ | 1.029 |
| Coefficient for WAS denitrification rate (K4) | $\Theta_{K4}$ | 1.029 |

**Table E.4: Default AD model stoichiometric parameters**

| Parameter | Units | Symbol | Value |
|---|---|---|---|
| Acidogens yield coefficient | gCOD biomass/ gCOD organics | $Y_{AD}$ | 0.113 |
| Acidogens endogenous respiration rate | /d | $b_{AD}$ | 0.041 |
| Endogenous residue fraction of Acidogens | gEVSS/gAVSS | $f_{XU,AD}$ | 0.2 |

**Table E.5: Default AD model kinetic parameters**

| Parameter | Units | Symbol | Sludge Type | | | |
|---|---|---|---|---|---|---|
| | | | PS only | OHO only (ND WAS) | PAO only* | NDBEPR WAS |
| Acidogens half saturation concentration | gCOD/L | $K_{s,Zad}$ | 3.76 | 0.408 | 0.408 | 0.607 |
| Acidogens hydrolysis rate | gSbp/gZAD/d | $K_{m,Zad}$ | 3.34 | 2.049 | 2.049 | 2.465 |

*Needs future revision/research

**Table E.6: Aeration model standard values**

| Parameter | Units | Symbol | Value |
|---|---|---|---|
| Saturated Vapour Pressure at Standard Temperature = 20°C | mm Hg | $p_{std}$ | 17.51 |
| Theta Coefficient for pSTD | | $\Theta_{pstd}$ | 1.0639 |
| Standard Pressure at 0m | mm Hg | PSTD | 760 |
| Temperature Coefficient for KLa (Mechanical) | - | $\Theta_{Mech}$ | 1.012 |
| Temperature Coefficient for KLa (Bubble) | - | $\Theta_{Bubble}$ | 1.024 |
| Dissolve Oxygen Correction Factor | mgO/L | $C_{s20}$ | 9.07 |

**Table E.7: Default AS model parameters**

| Parameter | Units | Sym | Default | | | Minimum | | | Maximum | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | MLE | UCT | JHB | MLE | UCT | JHB | MLE | UCT | JHB |
| Temperature | °C | | 14 & 22 | | | 12 | | | 24 | | |
| Nitrifier maximum specific growth rate | /d | $\mu_{Am,20}$ | 0.45 | | | 0.45 | | | 0.75 | | |
| Nitrification safety factor | | $S_f$ | 1.2 | | | 1.2 | | | ∞ | | |
| Sludge Age (Raw) | d | SRT | 12 | 16 | 19 | 3 | | | ∞ | | |
| Sludge Age (Settled) | d | SRT | 16 | 18 | 22 | 3 | | | ∞ | | |
| Maximum unaerated fraction | | $f_{xm}$ | 0.60 | | | 0.60 | | | 0.60 | | |
| Primary Anoxic fraction | | $f_{x1}$ | 0.35 | 0.30 | 0.25 | 0 | | | ∞ | | |
| Secondary Anoxic fraction | | $f_{x3}$ | N/A | N/A | 0.10 | N/A | N/A | 0.0 | N/A | N/A | 0.30 |
| Anaerobic fraction | | $f_{AN}$ | N/A | 0.10 | 0.10 | N/A | 0.05 | 0.05 | N/A | 0.05 | 0.05 |
| Anaerobic reactors | | ANn | N/A | 2 | 2 | N/A | 1 | 1 | N/A | ∞ | ∞ |
| Determine SRT from $f_{xt}$ | | | Yes | | | Yes | | | Yes | | |
| SRT $f_{x1}$ (and $f_{x3}$) Optimisation | | | Yes | | | Yes | | | Yes | | |
| Unaerated fraction set to maximum | | | Yes | No | No | N/A | | | N/A | | |
| Dissolved oxygen in aRec | mgO/L | $DO_a$ | 2.0 | | | 0.1 | | | ∞ | | |
| Dissolved oxygen in sRec | mgO/L | $DO_s$ | 1 | | | 0.1 | | | ∞ | | |
| Dissolved oxygen in rRec | mgO/L | $DO_r$ | N/A | 0 | N/A | N/A | 0 | N/A | N/A | ∞ | N/A |
| a-recycle ratio | | aRec | 5 | | | 0.1 | | | ∞ | | |
| s-recycle ratio | | sRec | 1 | | | 0.1 | | | ∞ | | |
| r-recycle ratio | | rRec | N/A | 1 | N/A | N/A | 0.1 | N/A | N/A | ∞ | N/A |
| Reactor TSS concentration | mgTSS/L | $X_t$ | 4800 | | | 1000 | | | 20 000 | | |
| Max AS reactor volume | $m^3$ | $V_m$ | 10 000 | | | 100 | | | ∞ | | |
| SST Xt Optimisation | | | Yes | | | N/A | | | N/A | | |
| Minimum Alkalinity | mg/L $CaCO_3$ | | 40 | | | N/A | | | N/A | | |
| AX3 optimisation sensitivity, $D_{p3}$ less EqNn limit | | | N/A | N/A | 3 | N/A | | | N/A | | |

Where: N/A = Not applicable; and ∞ = No limit assigned

**Table E.8: Default SST model parameters**

| Parameter | Units | Symbol | Default | Min | Max |
|---|---|---|---|---|---|
| Sludge Volume Index | ml/L | SVI | 95 | 10 | 300 |
| Diluted Sludge Volume Index | ml/gTSS | DSVI | 100 | 10 | 300 |
| Stirred Specific Volume Index | ml/gTSS | SSVI | 80.4 | 10 | 300 |
| Hindered Settling | | n | 0.36 | 0.1 | 1 |
| Initial Settling Velocity | | V0 | 9 | 1 | 20 |
| Flux Rating | | SST_FR | 0.8 | 0.25 | 1 |
| Flow equalisation PWWF:ADWF factor | | | 1.25 | | |
| Optimisation even number of SSTs | | | FALSE | | |
| Optimisation even number of Reactors | | | FALSE | | |
| Equal SSTs and Reactors | | | TRUE | | |

**Table E.9: Default AD and AxAeD model parameters**

| Parameter | Units | Symbol | Default | Min | Max |
|---|---|---|---|---|---|
| AD retention time – PS only | d | HRT | 15 | 1 | ∞ |
| AD retention time – WAS only | d | HRT | 25 | 1 | ∞ |
| AD retention time – WAS + PS | d | HRT | 20 | 1 | ∞ |
| % WAS Flow to PS AD for partial mixing | % | %Mix | 50 | 0 | 100 |
| Thickened $X_{ti}$ concentration (AD WAS only) | mgTSS/L | $X_{ti}$ | 40 000 | 1000 | 80 000 |
| WAS AxAeD retention time per digester | d | $HRT_{\_N}$ | 10 | 4 | |
| WAS AxAeD effluent $SOUR_e$ | mgO/gVSS/h | $SOUR_e$ | 1.5 | 0.1 | 2.5 |
| WAS AxAeD number of digester in series | | N | 1 | 1 | 5 |
| WAS AxAeD Thickened $X_{ti}$ concentration | mgTSS/L | $X_{ti}$ | 40 000 | 1000 | 80 000 |
| WAS AxAeD max OUR in 1st digester | mgO/L/h | $OUR_{t1\_M}$ | 100 | 0 | 100 |

Where: N/A = Not applicable; and ∞ = No limit assigned

**Table E.10: Default mechanical surface aeration model parameters**

| Parameter | Units | Symbol | Default | Min | Max |
|---|---|---|---|---|---|
| Site Altitude | m | Alt | 250 | 0 | 5000 |
| Alpha for $K_{La}$ - AS | d | HRT | 0.8 | 0.2 | 1 |
| Beta for $C_S$ - AS | | HRT | 0.9 | 0.2 | 1 |
| Alpha for $K_{La}$ - WAS | | | 0.5 | | |
| Beta for $C_S$ - WAS | | | 0.7 | | |
| Dissolved Oxygen Concentration in Water | % | %Mix | 2 | 0.1 | 5 |
| Standard Oxygen Transfer Rate | mgTSS/L | $X_{ti}$ | 2.4 | 0.1 | 5 |
| Line to Shaft Efficiency | d | $HRT_{\_N}$ | 0.8 | 0.5 | 1 |
| Aeration Type | | | Mech | | |
| Aeration Compartments | | | 4 | 1 | 8 |
| Compartment 1 % Power Division | % | | 33 | | |
| Compartment 2 % Power Division | % | | 25 | | |
| Compartment 3 % Power Division | % | | 21 | | |
| Compartment 4 % Power Division | % | | 21 | | |
| TOD wave damping factor for BNR | | | 0.28 | | |
| TOD wave damping factor by PST | | | 0.25 | | |

**Table E.11: Default cost and modularisation model parameters**

| Parameter | Units | Cost Function | Max Dimension |
|---|---|---|---|
| Flow balancing tank - sloping sides, no subdivisions | Volume ($m^3$) per 1 000 $m^3$ | $350(V)^{0,90}$ | 10 000 $m^3$ |
| PSTs - 3.5m sidewall, sloping bottom, including pumps. | Diameter (m) per m | $20(Ø)^{1.212}$ | 30 m |
| SSTs - 3.5m sidewall, sloping bottom, including pumps | Diameter (m) per m, | $20(Ø)^{1.212}$ | 30 m |
| Gravity thickeners | Diameter (m) per m | $20(Ø)^{1.212}$ | 30 m |
| Biological reactor | Volume per 1 000 $m^3$ | $770(V)^{0.761}$ | 10 000 $m^3$ |
| Aeration mechanical surface platform | Power (kW) per kW | $40(kW)^{0.55}$ | N/A |
| Aerobic digestion | Volume ($m^3$) per 1 000 $m^3$ | $500(V)^{0.85}$ | 2000 $m^3$ |
| Anaerobic digestion | Volume ($m^3$) per 1 000 $m^3$ | $1500(V)^{0.85}$ | 10 000 $m^3$ |

**Table E.12: Default WWChar mass ratios**

| Symbol | VFA | FBSO | USO | SetBPO | NonSetBPO | SetUPO | NonSetUPO |
|---|---|---|---|---|---|---|---|
| $f_{cv}$ (gCOD/gVSS) | 1.067 | 1.450 | 1.500 | 1.550 | 1.550 | 1.481 | 1.481 |
| $f_n$ (gN/gVSS) | 0.000 | 0.051 | 0.035 | 0.032 | 0.032 | 0.100 | 0.100 |
| $f_p$ (gP/gVSS) | 0.000 | 0.010 | 0.000 | 0.006 | 0.006 | 0.025 | 0.025 |
| $f_c$ (gC/gVSS) | 0.400 | 0.471 | 0.498 | 0.498 | 0.498 | 0.518 | 0.518 |
| Subscript C (x) | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Subscript H (y) | 2.000 | 1.964 | 1.835 | 1.900 | 1.900 | 1.534 | 1.534 |
| Subscript O (z) | 1.000 | 0.672 | 0.602 | 0.576 | 0.576 | 0.421 | 0.421 |
| Subscript N (a) | 0.000 | 0.042 | 0.044 | 0.060 | 0.060 | 0.165 | 0.165 |
| Subscript P (b) | 0.000 | 0.006 | 0.000 | 0.004 | 0.004 | 0.019 | 0.019 |

**Table E.13: Minimum and maximum WWChar mass ratios**

| Symbol | VFA | FBSO | USO | SetBPO | NonSetBPO | SetUPO | NonSetUPO |
|---|---|---|---|---|---|---|---|
| $f_{cv}$ (gCOD/gVSS) | 1.067 | 1.704 | 1.793 | 1.900 | 1.900 | 1.900 | 1.900 |
| $f_n$ (gN/gVSS) | 0.000 | 0.060 | 0.060 | 0.100 | 0.100 | 0.140 | 0.140 |
| $f_p$ (gP/gVSS) | 0.000 | 0.100 | 0.000 | 0.010 | 0.010 | 0.050 | 0.050 |
| $f_c$ (gC/gVSS) | 0.400 | 0.565 | 0.598 | 0.650 | 0.650 | 0.650 | 0.650 |
| $f_{cv}$ (gCOD/gVSS) | 1.067 | 1.100 | 1.100 | 1.100 | 1.100 | 1.100 | 1.100 |
| $f_n$ (gN/gVSS) | 0.000 | 0.010 | 0.010 | 0.010 | 0.010 | 0.080 | 0.080 |
| $f_p$ (gP/gVSS) | 0.000 | 0.006 | 0.000 | 0.001 | 0.001 | 0.001 | 0.010 |
| $f_c$ (gC/gVSS) | 0.400 | 0.377 | 0.399 | 0.400 | 0.400 | 0.380 | 0.380 |

**Table E.14: Default WWChar parameters**

| Parameter | Symbol | Default |
|---|---|---|
| USO COD fraction w.r.t to total COD | $f_{S'us}$ | 0.05 |
| VFA COD fraction w.r.t to total COD | $f_{S'bsai}$ | 0.045 |
| UPO COD fraction w.r.t to total COD for raw WW | $f_{S'up}$ (Raw) | 0.140 |
| UPO COD fraction w.r.t to total COD for settled WW | $f_{S'up}$ (Settled) | 0.050 |
| Percentage ISS removal in PST | %ISS Rem in PST | 80 |
| Percentage COD removal in PST | %COD Rem in PST | 35.4 |
| PST Underflow % w.r.t to influent raw WW ADWF | PST Underflow | 0.5 |
| PDWF to ADWF flow factor | PDWF:ADWF | 2 |
| PWWF to ADWF flow factor | PWWF:PDWF ($f_q$) | 1.5 |
| pH | pH | 7 |
| Influent alkalinity in mgAlk/L as $CaCO_3$ | Alk | 300 |
| Amplitude of TOD wave for raw WW | $TOD_{Amp}$ Raw wastewater | 1.20 |
| Amplitude of TOD wave for settled WW | $TOD_{Amp}$ Settled wastewater | 1.20 |

# Appendix F. Steady-State JHB ND Equations

For the steady-state JHB AS model, the design procedures (equations) as presented in Wentzel *et al*. (2008) must be followed. These equations describe the COD, N and P removal parts of the AS model. However, for the N removal part, only nitrification and N uptake into sludge mass is presented by Wentzel *et al*. (2008). Thus for the denitrification part, to describe the complete nitrification/denitrification process (ND), equations (shown below) were developed specifically for this program. Once the procedure presented in Wentzel *et al*. (2008) is finished, the equations below are calculated in order. A short description, where applicable, is presented below the equations.

**Equation F.1: JHB ND - Alpha for $D_{p1}$**

$$\alpha = \frac{S_{F,ANn} \times (1 + s) \times \left(1 - f_{CV,OHO} \times Y_{OHO}\right)}{2.86}$$

**Equation F.2: JHB ND - Beta for $D_{p1}$and $D_{p3}$**

$$\beta = S_{B,OHO}) \times Y_{OHO} \times \frac{SRT}{(1 + b_{OHO,T} \times SRT)}$$

**Equation F.3: JHB ND - $D_{p1}$**

$$D_{p1} = \alpha + f_{AX1} \times K'_{2T} \times \beta$$

**Equation F.4: JHB ND - $D_{p3}$**

$$D_{p3} = f_{AX3} \times K'_{3T} \times \beta$$

**Equation F.5: JHB ND - Actual $N_c$**

$$N_c = N_{ae} - N_{ouse} - N_s$$

Equation F.5 gives the actual $N_c$ of the system. $N_c$ is the nitrification capacity which is the total influent TKN less the N absorbed to sludge mass (OHOs and PAOs) and less the effluent unbiodegradable OrgN and effluent (residual) FSA that was not nitrified.

**Equation F.6: JHB ND - Theoretical balanced $D_{p1}$ ($D_{p1}$*)**

$$D_{p1}{}^{*} = \left(\frac{N_c}{a + s + 1} + \frac{DO_a}{2.86}\right) \times a$$

$D_{p1}$* is the theoretical $D_{p1}$ that is required if the actual $N_c$ (Equation F.5) gave a balanced AX1, i.e. if the AX1 was balanced for the $N_c$ given in Equation F.5 then $D_{p1} = D_{p1}$* which is given by Equation F.6. Then Equation F.5 is the same as Equation F.8 for the equivalent nitrate load ($EqN_{n1}$) on the AX1 when the AX1 is underloaded or balanced.

If $D_{p1}>D_{p1}$* then AX1 is underloaded, i.e. $D_{p1}$ is greater than what is required for a balanced AX1 ($D_{p1}$*). If $D_{p1}= D_{p1}$* then AX1 is balanced. Else, if $D_{p1}< D_{p1}$* then AX1 is overloaded. Depending on the AX1 state, different equations are used to calculate the equivalent nitrate load on AX1 ($EqN_{n1}$) and the effluent nitrate concentration ($N_{ne}$).

If AX1 is underloaded or balanced then Equation F.7 and Equation F.8 applies. It is assumed that the underflow nitrate is always fully denitrified, by either the AX3 or the subsequent anaerobic reactor (AN). Thus, if AX1 is underloaded or balanced then the flow exiting the AX1 has a zero nitrate concentration, therefore the nitrate generated in the AE ($N_c$) is divided by the zero nitrate flow of the a- and s-recycles, i.e. $N_c$ /(a+s+1). This is the effluent nitrate concentration ($N_{ne}$, Equation F.7). For the $EqN_{n1}$, this is the diluted $N_c$ (Equation F.7) plus the nitrate equivalent of dissolved oxygen in the a-recycle, multiplied by the a-recycle (Equation F.8).

**Equation F.7: JHB ND - AX1 $N_{ne}$ if AX1 is balanced or underloaded**

$$N_{ne} = \frac{N_c}{a + s + 1}$$

**Equation F.8: JHB ND - AX1 $EqN_{n1}$ if AX1 balanced or underloaded**

$$EqN_{n1} = \left(\frac{N_c}{a + s + 1} + \frac{DO_a}{2.86}\right) \times a$$

If AX1 is overloaded then Equation F.9 and Equation F.10 applies. As with the underloaded/balanced scenario, it is assumed that the underflow nitrate is always fully denitrified, by either the AX3 or the subsequent anaerobic reactor (AN). Thus, the $N_{ne}$ is the nitrate produced in the AE ($N_c$) plus the nitrate equivalent of dissolved oxygen in the a-recycle less the denitrification potential of the AX1 ($D_{p1}$), then divided by the zero nitrate flow of the s-recycle (s+1) – Equation F.9. For the $EqN_{n1}$ when the AX1 is overloaded, this is the $N_c$ plus the nitrate equivalent of dissolved oxygen in the a-recycle multiplied by the a-recycle (Equation F.10). Note that these overloaded equations need to be revised for future editions. This however, is not a critical issue, as an overloaded AX1 should never be designed.

**Equation F.9: JHB ND - AX1 $N_{ne}$ if AX1 is overloaded**

$$N_{ne} = \left(N_c + \frac{a \times DO_a}{2.86} - D_{p1}\right)/(s+1)$$

**Equation F.10: JHB ND - AX1 $EqN_{n1}$ if AX1 is overloaded**

$$EqN_{n1} = \left(N_c + \frac{a \times DO_a}{2.86}\right)$$

With the AX1 condition known, the underflow anoxic reactor (AX3) can be evaluated. The underloaded or overloaded condition of the AX3 can be determined in the same way as for the AX1. Assuming that the actual $N_c$ provides a balanced AX1, the required $D_{p3}$ ($D_{p3}$*) to match the equivalent underflow nitrate load is given by Equation F.11.

**Equation F.11: JHB ND - Theoretical balanced $D_{p3}$ ($D_{p3}$*)**

$$D_{p3}^{*} = \left(\frac{N_c}{a+s+1} + \frac{DO_s}{2.86}\right) \times s$$

$D_{p3}$* is compared to the actual $D_{p3}$, given by Equation 8. If $D_{p3} > D_{p3}$* then AX3 is underloaded, i.e. $D_{p3}$ is greater than what is required for a balanced AX3 ($D_{p3}$*). If $D_{p3} = D_{p3}$* then AX3 is balanced. Else, if $D_{p3} < D_{p3}$* then AX3 is overloaded. Unlike the AX1, the equation for the underflow nitrate concentration exiting the AX3 ($N_{ne3}$) is independent of the AX3 state (underloaded, overloaded, or balanced). This concentration is given by Equation F.13, and is simply the equivalent nitrate load on the AX3 (Equation F.12) minus the $D_{p3}$. Note that Equation F.11 is not actually required, in fact the state of the AX3 can be determined by Equation F.13. If $N_{ne3} > 0$ then the AX3 is overloaded, if $N_{ne3} < 0$ then AX3 is underloaded, if $N_{ne3} = 0$ then AX3 is balanced. Technically $N_{ne3}$ cannot be < 0, this is only arises due to the arithmetic. If $N_{ne3} < 0$ then the actual solution is $N_{ne3}$ is = 0.

**Equation F.12: JHB ND - AX3 $EqN_{n1}$ if AX1 is balanced, underloaded, or overloaded**

$$EqN_{n3} = \left(\frac{N_c}{a+s+1} + \frac{DO_s}{2.86}\right) \times s$$

**Equation F.13: JHB ND - AX3 $N_{n,AX3}$**

$$N_{ne3} = \left(\frac{N_c}{a+s+1} + \frac{DO_s}{2.86}\right) \times s - D_{p3} \geq 0$$

# Appendix G. Overview of Design Guidance Content

In the sections that follow, an overview of the content in the *Design Guidance* is provided. Note that not all of the content is summarised here, only most the important items and design windows are presented.

## G1. System Configuration

The design guidance content for the PWSSD System Configuration window (Figure 6.62) is summarised below.

| Content Title | Content Description |
|---|---|
| MLE | Overview of MLE system, advantages and disadvantages |
| UCT | Overview of UCT system, pros and cons, comparison to MLE |
| JHB | Overview of JHB system, pros and cons, comparison to MLE and UCT |
| 4-Stage BPHO | Overview of 4BPHO system, pros and cons, comparison to MLE/UCT/JHB |
| 5-Stage BPHO | Overview of 5BPHO system, pros and cons, comparison to MLE/UCT/JHB |
| PST | %COD/%N/%P/%TSS removals, change in characteristics, purpose of PST |
| SST | Objectives of SST, overview of 1DFT, comparison to MBRs |
| MBR | Pros and cons, design of MBR systems, when to select MBRs |
| PS AD | Pros and cons of AD, complexity, digester failure |
| WAS AxAeD | Overview of AxAeD process. Complete ND with aeration cycle |
| WAS AD | AD for ND WAS, not NDBEPR WAS. Slower hydrolysis, longer HRT |
| Extended Aeration | No WAS treatment, when to use extended aerations, pros and cons |
| Full (Complete) Mixing WAS + PS | Complete mixing of WAS + PS, must be treated with AD |
| Partial Mixing WAS + PS | WAS + PS AD, and WAS AxAeD, WAS + PS, must be treated with AD |
| Separate WAS and PS | Separate WAS and PS treatment, recommended option for NDBEPR |
| Balancing Tank | Location of BalT, advantages, effect on organic load, aeration, and performance |
| Wasting from AS | Advantages of hydraulic SRT control; when to select this option |
| Wasting from SST | Advantages of WAS from underflow, thickening, problems with SRT control |

## G2. System Design

The design guidance content for the PWSSD System Design window (Figure 6.63) is summarised below.

| Content Title | Content Description |
|---|---|
| PST | Overview, PST input parameters, overflow, SLR for GravThk |
| Flow Equalisation | Overview, how model works, information generated from model |
| Activated Sludge | Goals of AS, information generated from models |
| SST | Goals of SST, purpose of 1DFT, effluent solids prediction, input parameters |
| PS & WAS Treatment | Overview of AD and AxAeD, retention time selection, pros and cons of AD |
| Aeration | Purpose of aeration model, link to balancing tank, peak oxygen demand |
| Cost and Modularisation | Overview of cost estimation, modularisation, and aerators selection |

## G3. PST and Gravity Thickener

The design guidance content for the PST/GravThk design window (Figure 6.26) is summarised below.

| Content Title | Content Description |
|---|---|
| Introduction | Overview of design window and PST/GravThk design process |
| Getting Started | PST/GravThk design process |
| PST Performance | PST performance data, typical/recommended overflow rates |
| Max Diameter | Selection of diameter and effect of weir-loading rate |
| GravThk Performance | GravThk performance data, typical/recommended solids loading rate |

## G4. SST Design

The design guidance content the SST Design and Xt Optimisation design window (Figure 6.30) is shown below.

| Content Title | Content Description |
|---|---|
| Introduction | Overview of design window and 1DFT. Xt optimisation disabled if not selected |
| Getting Started | Step-by-step instructions on entering the input parameters |
| Flux Rating | What is the flux rating and the default/recommended value |

| Content Title (continued | Content Description (continued) |
|---|---|
| Settleability Index Input Options | Selecting Yes or No depending on available settling data |
| Settleability Characteristics | No settleability index available |
| Custom Settleability Characteristics | V0 and n values for settleability groups (good/poor/very poor etc.) for when no settleability index is available |
| DSVI/SSVI/SVI | Definitions of DSVI SSVI and SVI, empirical correlation equations to link them to V0 and n. Why not to use SVI. |
| Flow Rate | ADWF, PDWF, and PWWF. How balancing tank affects these flow rates |
| SHC1 | Definition of SHC1 and how it is used to determine recycle ratios |
| SHC2 | Definition of SHC2 and how it is used to determine SST area |
| Design & Operation | Overview of Design and Operation table on the design summary frame |
| $X_t$ Optimisation | What is $X_t$ optimisation and how the optimum $X_t$ is calculated |
| $X_t$ Optimisation Options | Explanation of the $X_t$ optimisation options, even/odd/equal SSTs or AS reactors |
| Defaults | Default values for SST design |

## G5. Activated Sludge System

The design guidance content for the MLE, UCT, and JHB design windows (Figure 6.4, Figure 6.12, and Figure 6.18) is summarised below.

| Content Title | Content Description | Applicability | | |
|---|---|---|---|---|
| | | MLE | UCT | JHB |
| Introduction | Overview of design window | X | X | X |
| Getting Started | Step-by-step tutorial on how to design AS system | X | X | X |
| Configuration | Description of AS system and its pros and cons | X | X | X |
| COD Removal | Overview of the COD removal process | X | X | X |
| N Removal Process | Overview of N removal & nitrification/denitrification | X | X | X |
| P Removal Process | P removal via BEPR | | X | X |
| Nitrification | Conversion of FSA to Nitrate | X | X | X |
| Nitrification Capacity | Importance of $N_c$ and what inputs affect it | X | X | X |
| Denitrification | Denitrification process and its benefits | X | X | X |
| Denitrification Rates | K1/2/3/4 rates and the COD organics associated with it | X | X | X |

| Content Title (continued) | Content Description (continued) | Applicability (continued) | | |
|---|---|---|---|---|
| | | MLE | UCT | JHB |
| Denitrifying PAOs | Why denitrifying PAO's reduce P removal | | X | X |
| Denitrification Potential | Importance of $D_p$ and what inputs affect it | X | X | X |
| P, polyP and ISS of PAOs | P and PP content, how to calculate polyP ISS | | X | X |
| Oxygen Demand | $FO_c$, $FO_n$, and $FO_d$ | X | X | X |
| Alkalinity and pH | Effect of nitrification/denitrification on Alk/pH | X | X | X |
| Settled vs Raw Wastewater | Which system to choose and their pros and cons | X | X | X |
| Sludge Treatment | When to select aerobic or anaerobic digestion of WAS | X | X | X |
| Input Parameters | Overview of the inputs required for the AS system | X | X | X |
| Defaults | Defaults that can be used for the AS system | X | X | X |
| SRT - Sludge Age | SRT selection and its effect on COD rem, $FO_{td}$, and Vol | X | X | X |
| $f_{x1}$ - Primary Anoxic Mass Frac | $f_{x1}$ selection and its effect on N removal | X | X | X |
| $f_{x3}$ - Secondary Anoxic Mass Frac | $f_{x3}$ selection and its effect on N and P removal | | | X |
| $f_{AN}$ - Anaerobic Mass Frac | $f_{AN}$ selection and its effect on P removal | | X | X |
| μAm_20 - Nitrifier Growth Rate | Issues in selecting $\mu_{Am20}$ and its effect on SRT | X | X | X |
| $S_f$ - Safety Factor | $\mu_{Am20}$ uncertainties and dampening of diurnal flow | X | X | X |
| MinT/MaxT - Temperature | Effect of temperature on oxygen demand and sludge mass production | X | X | X |
| a-, s-, & r-recycles | Effect of recycle ratios on N and P removal | X | X | X |
| Dissolved Oxygen | Effect of DO on N and P removal | X | X | X |
| ANn - Anaerobic Zones | Effect of ANn on F-RBCOD conversion in AN | | X | X |
| Total Particulates Conc | Sludge mass distribution, SST design and optimisation | X | X | X |
| AS modules | Effect on AS system design, cost and aeration | X | X | X |
| SRT and $f_{xt}/f_{x1}/f_{x3}$ Design Options | Options on how to select SRT and mass fractions | X | X | X |
| $f_{x1m}$ - Max Primary Anoxic Mass Frac | How $f_{x1m}$ is calculated | | X | X |
| $f_{xt}$ - Total Unaerated Mass Frac | Link between $f_{xt}$ and SRT, nitrification, MinT, importance | X | X | X |

| Content Title (continued) | Content Description (continued) | Applicability (continued) | | |
|---|---|---|---|---|
| | | MLE | UCT | JHB |
| $f_{xm}$ - Max Unaerated Mass Frac | Importance of $f_{xm}$ and parameters that determine $f_{xm}$ | X | X | X |
| Optimise $X_t$ | Explanation of Optimise $X_t$ checkbox and results of checking/unchecking it | X | X | X |
| N Rem State | Underloaded/Balanced/Overloaded and N rem optimisation process | X | X | X |
| $X_t$ Opt State | State of optimisation, optimised or not | X | X | X |
| Volume and Flow | Overview of volume and flow results | X | X | X |
| Reactor Parameters | Explanation of $X_v$, $f_{av}$, $OUR_{td}$, optimum aRec | X | X | X |
| Effluent Conc | Explanation of effluent concentrations | X | X | X |
| Gas and Alk | Stoichiometry model to predict gas production, importance of alkalinity | X | X | X |
| N Removal | How %N removal is calculated | X | X | X |
| P removal | How %P removal is calculated, maximum %P removal for BEPR systems | | X | X |
| Potential, Actual, Unused P Removal | Explanation of potential P removal and the actual and unused P removal of the BEPR system | | X | X |
| PolyP ISS and $f_{xbgp}$ | Max P content, PolyP content, additional ISS mass in BEPR | | X | X |
| Influent Metal Requirements | Influent Ca, Mg, and K requirements for P removal and Poly P formation | | X | X |
| Sludge wasting location | Difference between wasting from AS and from SST underflow | X | X | X |

## G6. Anoxic-Aerobic Digestion

The design guidance content for the WAS AxAeD design window (Figure 6.37) is summarised below.

| Content Title | Content Description |
|---|---|
| Introduction | Overview of design window and input parameters, extension of AS model |
| Getting Started | Step-by-step information of designing AxAeD |
| Design Options | Difference between fixed $SOUR_e$ and fixed HRT options for AxAeD design |
| SOURe | Explanation of $SOUR_e$, recommended value |
| HRT | How HRT affects design, effluent sludge stability, and HRT selection |
| Content Title (continued) | Content Description (continued) |

| | |
|---|---|
| N | How number of digesters in series affects volume, HRT, and oxygen demand |
| Thickened WAS concentration | How influent WAS concentration affects volume and oxygen demand |
| Nitrification Stoichiometry | Bioprocess stoichiometry equation for nitrification |
| ND Stoichiometry | Bioprocess stoichiometric equation for nitrification and denitrification |
| WAS flow to PS | Only available for partial mixing selection. How WAS flow to PS affects AxAeD design and volume |
| Defaults | Default inputs for the AxAeD model |

## G7. Anaerobic Digestion

The design guidance content for the WAS AD, PS AD, and WAS + PS AD design windows (Figure 6.42, Figure 6.47, and Figure 6.48) is summarised below.

| Content Title | Content Description |
|---|---|
| Introduction | Overview of the three parts of AD model, required inputs |
| Getting Started | Required inputs and recommended values |
| HRT | Link between HRT and effluent solids quality |
| Thickened WAS concentration | How influent WAS concentration affects AD |
| %WAS flow to PS AD | How influent mixing affects AD, slower WAS hydrolysis rate, longer HRT if WAS + PS AD selected |
| Block Diagram | Explanation of WAS block diagram, conversion of $X_{bh}$ to COD concentration |
| SS Kinetic Hydrolysis | Overview of kinetic hydrolysis part of AD model |
| Stoichiometry | Overview of stoichiometry part of AD model, explanation of E |
| Weak Acid/Base Chemistry | Overview of acid/base part of AD model to predict pH, stable pH range |
| Design Summary | Highlights important items in design summary |
| Defaults | Default values for AD |

## G8. Aeration

The design guidance content for the Aeration design window (Figure 6.50) is summarised below.

| Content Title | Content Description |
|---|---|
| Introduction | Overview of aeration design window and aeration model |
| Getting Started | Step-by-step guide for using model and for the inputs required |
| Site Altitude | Link between site altitude, air pressure, and saturation concentration of $O_2$ in water |
| Alpha and Beta | What is alpha and beta, default recommended values/ranges |
| DO ($C_L$) | Dissolved concentration in reactor |
| $R_{std}$ | Standard oxygen transfer rate |
| Efficiency | Mechanical efficiency |
| Compartments | How compartmentalisation affects aeration, recommended aeration split between compartments. Difference between compartmentalisation and modularisation. |
| Peak OUR | How peak OUR factor is calculated for flow-balanced and non-flow-balanced systems |
| $R_{act}$ | Actual oxygen transfer rate |

## G9. Capacity Estimation

The design guidance content for the CapEst window (Figure 7.1) is summarised below.

| Content Title | Content Description |
|---|---|
| Introduction | Overview of CapEst design window |
| System Configuration | Overview of MLE/UCT/JHB systems and discussion on their capacities relative to each other |
| Physical Systems | PST and SST, how PST affects capacity, change from raw to settled and change in sludge mass production, objectives of SST, bottleneck usually at SST |
| Other Options | Wasting from underflow or from AS has no effect on capacity |
| Aerobic $X_t$ Limiting | $X_t$ scenario, finding ADWF to obtain a certain $X_t$ |
| SST Area Limiting | SST area scenario, finding ADWF for a specified SST area |
| Aeration Limiting | Aeration scenario, finding ADWF to a specified aeration system size |
| AS System Parameters | Overview of AS parameters required for CapEst, SRT, volume, modules, mass fractions, and recycle ratios |
| Mass Fractions Calculator | Errors when entering volume fraction as mass fractions, for UCT/JHB mass fractions do not equal to volume fractions |
| $OUR_{td}$ | Discussion of the parameters required to estimate nitrification and denitrification oxygen demand so that $OUR_{td}$ can be calculated for the aeration model |
| SST Parameters | Overview of SST parameters required for CapEst, DSVI/SVI/SSVI, SST area and quantity |

| Content Title (continued) | Content Description (continued) |
|---|---|
| Flow Factors Selection | How flow factors can be selected, either specified or taken from WWChar |
| Aeration System Parameters | Overview of aeration parameters |