THE IMPACT OF SLUDGE RETURN LIQUORS IN SOUTH AFRICAN WASTEWATER TREATMENT PLANTS

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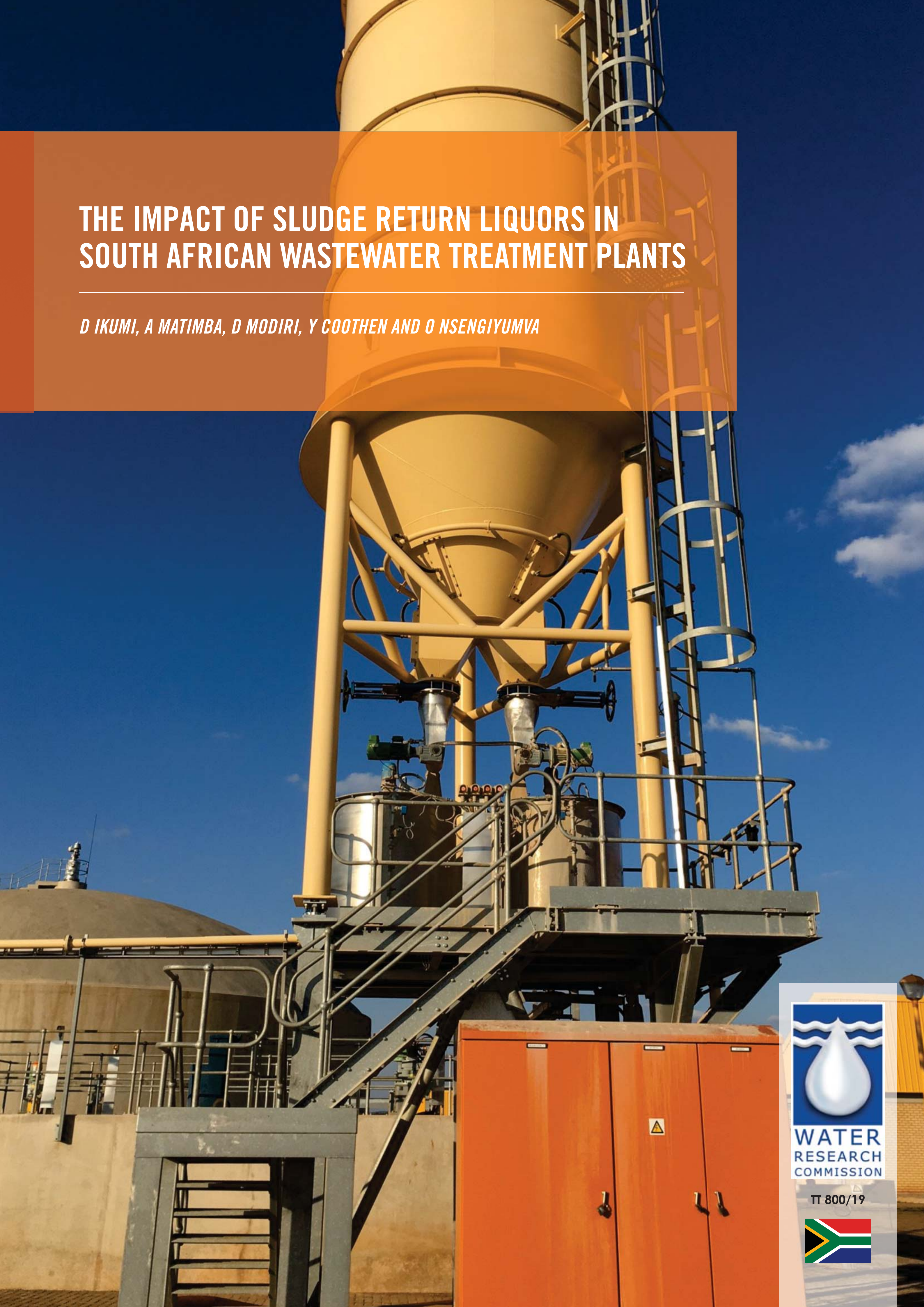

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THE IMPACT OF SLUDGE RETURN LIQUORS IN SOUTH AFRICAN WASTEWATER TREATMENT PLANTS

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Water pollution, particularly, the eutrophication of South Africa's scarce water resources is a major concern due to the threat it poses to our nation's water security. One of the major sources of pollution of surface waters are effluent streams from municipal wastewater treatment plants. Pollution loads, namely phosphorus and nitrogen compounds are the two primary contributors to the eutrophication of surface waters. To combat this problem, the Department of Water & Sanitation is setting more stringent effluent requirements via treatment plant licensing for both inland and coastal regions. At the same time, many of South Africa's treatment plants are approaching or have reached their design load capacity, or are in fact, overloaded. Furthermore, many of these overloaded treatment systems have nutrient removal constraints.

Most treatment plants in South Africa do not consider the return of sludge liquors back to the main plant for further treatment, or when it is applied, the whole infra-structure is not prepared to deal with these additional loads and flows. Unsustainable measures, such as the dosing of costly chemicals (typically metal salts) for phosphate removal, are typically applied at overloaded plants. The causes the capital and operational costs for municipal wastewater treatment plants to run into billions of Rand per annum. There is, therefore, an acute need to look at optimisation measures within treatment systems to reduce the nutrient loads on overloaded treatment plants in South Africa.

The main goal of the research study is to improve the knowledge on the impact and mitigating measures of the sludge return liquors from anaerobic sludge digestion on the wastewater treatment process. During the anaerobic digestion, the organic matter in the sludge is converted into biogas with the stored nutrients in the biomass being released into the water phase. This sludge return liquors should be recycled to the main process train, usually to the head of works or biological reactors, instead of being discharged into ponds or water bodies without any treatment. The additional load from the sludge return liquors may result in a deterioration of the plant effluent quality, due to an overloading of the plant, increase the energy requirements (for aeration) and increase the chemical dosage (metal salts to precipitate phosphorous). Therefore, it is crucial to understand the side-stream technologies available and recognised worldwide, as efficient means to reduce nitrogen and phosphorous concentrations in the sludge return liquors. The current body of knowledge is lacking an integrated overview and study of the relationship between the additional load from the sludge return liquors, rich in ammonia and phosphate, when recycled back to the main plant and their respective impact in the operation of the plants.

Several applicable technologies for side-stream nitrogen removal are based on ammonia oxidation over nitrite and/or nitrogen gas and occurring at high process temperatures (30-40°C). These solutions are marketed as SHARON® and ANNAMOX® and claim high levels of efficiency. However, bottleneck of these solutions is usually the high investment cost and high level of complexity and maintenance requirements. Biological Augmentation Batch Enhanced process, marketed as BABE®, appears as the lower-cost method for nitrogen removal because of its simple operation and allowance for improved nitrification process in the main plant, this is due to the return of augmented nitrifiers from the side-stream treatment. Phosphorous removal solutions for side-stream treatment also has a wide variety of options available; from conventional coagulation, to more complex processes, such as chemical crystallisation in up-flow fluidised bed. Examples of these technologies are marketed as Ostara Pearl®, WASSTRIP®, AirPrex®, Crystalactor®, Calprex™, Phospat™ amongst others. These technologies provide a wide variety of struvite quality, however, the South African market value for struvite recovery and application is not cost-effective when compared to conventional solutions. It is important to keep in mind the potential environmental and economic benefits of the application of sub products, such as struvite. South Africa still

needs to develop regulations for phosphorous recovery and reuse, build governance structures for phosphorous management, encourage trade and use of wastewater sub-products, etc.

This research study investigates the impact of sludge return liquors on the performance of wastewater treatment plants. To reflect the applicable context, a total of six wastewater treatment plants in different geographical locations across South Africa were selected, and their performance assessed. The selection of the plants was made to match as much as possible the following key selections criteria: variability of the locations, variability of the plant's capacity, include biological nutrients (N and P) removal, availability of sludge digestion and dewatering sludge return liquors recycled back to the treatment, availability of design information regarding sizing of the main process units (biological reactors and digesters) and duties of main equipment, availability of reliable flow measurements and analytical data for the process steps in general and in particular for sludge return flows and variability in systems complexity. Based on these selection criteria the plants selected were Plant 'Z' and Plant 'W' in Gauteng, Plant 'K' and Plant 'P' in KwaZulu-Natal, Plant 'C' in Western Cape and Plant 'D' in Eastern Cape. A summary characterisation of the plants is presented below:

- Plant 'Z', located in Gauteng, is designed to treat 85 Mℓ/day using primary treatment, followed by BNR reactors before the mixed liquor settles in a final clarifier. The effluent from the clarifier passes through a disinfection step before discharge. The WAS and PS sludge first passes through a thickening stage before being digested anaerobically. The sludge is dewatered and the return liquor is treated using side stream chemical precipitation. The plant is required to meet an effluent standard of 50 mg/ℓ of COD, 10 mg/ℓ of TSS, 1 mg/ℓ of NH_4, 6 mg/ℓ of $NO_2 + NO_3$ and 0.1 mg/ℓ of PO_4.

- Plant 'W', located in Gauteng, is designed to treat 170 Mℓ/day using primary treatment, followed by BNR reactors before the mixed liquor settles in a final clarifier. The effluent from the clarifier passes through a disinfection step before discharge. The WAS and PS sludge first passes through a sludge flotation stage before being digested anaerobically. The sludge is dewatered. The plant is required to meet an effluent standard of 70 mg/ℓ of COD, 20 mg/ℓ of TSS, 4 mg/ℓ of NH_4, 9 mg/ℓ of $NO_2 + NO_3$ and 0.7 mg/ℓ of PO_4.

- Plant 'K', located in KwaZulu-Natal, is designed to treat 80 Mℓ/day using primary treatment, followed by trickling filters and BNR reactors before the mixed liquor settles in a final clarifier. The effluent from the clarifier passes through a disinfection step before discharge. The WAS and PS sludge first passes through sludge flotation and thickening stages before being digested anaerobically. The sludge is dewatered. The plant is required to meet an effluent standard of 75 mg/ℓ of COD, 25 mg/ℓ of TSS, 6 mg/ℓ of NH_4, 15 mg/ℓ of $NO_2 + NO_3$and 10 mg/ℓ of PO_4.

- Plant 'P', located in KwaZulu-Natal, is designed to treat 25 Mℓ/day using primary treatment, followed by BNR reactors before the mixed liquor goes to the final clarifiers. The effluent from the clarifier passes through a disinfection step before discharge. The WAS and PS sludge first passes through sludge flotation and thickening stages before being digested anaerobically. The sludge is dewatered. The plant is required to meet an effluent standard of 75 mg/ℓ of COD, 25 mg/ℓ of TSS, 6 mg/ℓ of NH_4, 15 mg/ℓ of $NO_2 + NO_3$and 10 mg/ℓ of PO_4.

- Plant 'C', located in the Western Cape, is designed to treat 200 Mℓ/day using primary treatment, followed by BNR reactors before the mixed liquor settles in final clarifiers. The effluent from the clarifier passes through a disinfection step before discharge. The WAS and PS sludge first passes through a thickening stage before being digested anaerobically. The sludge is dewatered and taken to drying beds. The plant is required to meet an effluent standard of 75 mg/ℓ of COD, 25 mg/ℓ of TSS, 10 mg/ℓ of NH_4, 10 mg/ℓ of $NO_2 + NO_3$ and 1 mg/ℓ of PO_4.

- Plant 'D', located in the Eastern Cape, is designed to treat 9 Mℓ/day using BNR reactors, the mixed liquor passes through a disinfection step before discharge into maturation ponds and sludge lagoons. The plant is required to meet an effluent standard of 65 mg/ℓ of COD, 18 mg/ℓ of TSS, 8 mg/ℓ of NH_4, 15 mg/ℓ of $NO_2 + NO_3$ and 1 mg/ℓ of PO_4.

Research indicated that most of the treatment plants were not designed to accommodate the additional loads from sludge return liquors. The return of the sludge liquors, especially from the anaerobic digestion or dewatering, to the main treatment process appears to be a fairly recent practice in South Africa, responding to more stringent environmental regulations to protect water surface bodies. In this regard, it is also noted that the current design and operating approaches are not always correct and often the effect of additional carbon and nutrient loads from the dewatering return liquors have not been previously quantified.

From the site research, the following key findings were noted:

- More stringent effluent requirements are being targeted and removal of nutrients through side-stream treatment solutions may be required to ensure or improve the overall plant compliance. In this regard, several side-stream technologies are available and recognised as efficient to reduce nitrogen and phosphorous concentrations in the sludge return liquors.

- The nature of return liquor flow can vary drastically to the main plant. For example, ammonia load in the influent of the plant can increase from 0.4% to 15% and of orthophosphate load from 0.4% to 52% depending on the anaerobic digestion. This kind of variability has a significant impact on the plant performance, especially if the plant was not initially designed to accommodate the additional loads coming from the sludge return liquors.

- Many digesters at the respective plants perform sub-optimally. If the performance of the digesters is improved, there will be an increase in the ammonia and orthophosphate loads from the sludge return liquors potentially returned to treatment, this will raise the total nutrient loading on the treatment works.

- For majority of the plants operated with sub-optimal anaerobic digesters, and recycling the sludge return liquors back to the main plant, an increase in the aeration demands by approximately 10% is noted. If the anaerobic digestion processes are improved, the aeration energy demand may increase up to 20%.

- Overall, the introduction of return liquor streams back in the process can have important impacts on the performance of wastewater treatment works. In this regard, a means to quantify the impacts of additional streams is not a common practice and was, therefore, developed in this study to guide engineers and decision makers to make cost effective and appropriate technical option for sustainable handling return liquor flows.

The process of developing the impact simulation tool was initiated with the Plant Wide Steady State Mass Balance Model (PWSSMBM) developed at the University of Cape Town in the last two decades. In this research study, a case study was performed on various full-scale South African wastewater treatment plants selected under this research. These case studies involved virtually replication of the selected Wastewater Treatment Works, using a mass balance-based plant-wide mathematical models that link all the various unit processes with the flows connecting them, and evaluating the impact of including sludge return liquors on design and operational variables. The PWSSMBM mathematical model was improved to include the return of the sludge liquors back in the main treatment plant. The calibration of the model was completed using site data from the six plants selected and compared with the BIOWIN model for further confirmation that the mathematical approach was accurate. The simulation made via the PWSSMBM confirmed the findings seen on site regarding the recycling of the sludge return liquors and the results generated from these virtual WWTWs shall be used to inform expert decision-making towards the positive and negative impacts of sludge return liquors.

The ultimate goal of the modelling was the development of a simple, easy to use, decision-making tool to evaluate the impact of sludge return liquors on the overall plant performance, i.e. effluent quality and operational cost. The impact tool is based on scientific principles and makes use of the PWSSMBM, including the most commonly used BNR layouts in the South African context, i.e. UCT, JHB, MLE and 3-stage Phoredox. Two side-stream technologies, struvite precipitation and BABE®, were incorporated in the tool to simulate the impact of treating a certain percentage of the sludge return liquors and calculate its performance indices. The impact tool includes a fractionating module to help improve influent characterisation, especially for treatment works with a lack of site data. These performance indices are a means of evaluating design/control strategies to be implemented in wastewater treatment plants. The two performance indices included are the effluent quality index, calculating the amount of pollutants discharged per day, and the operational cost index, associated with aeration energy costs and methane production. The impact tool was built in a simple and user-friendly interface. It allows process controllers, engineers and decision makers to simulate different side-stream treatment scenarios to select the best technical and economic solution for a new or upgraded plant. The impact tool assumes a relevant role in decision making as well as contributing to educate and capacitate the wastewater treatment sector.

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Appendix 1: Site Research Report

Appendix 2: Results from Modelling Simulation on 6 Selected WWTWs

Appendix 3: Plant Performance Evaluation Tool – User Manual

Appendix 4: Plant Performance Evaluation Tool

LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
ADWF	Average Dry Weather Flow
AerD	Aerobic Digestion
AOB	Ammonia-oxidising bacteria
ASM	Activated Sludge Model
BABE	Bio-Augmentation Batch Enhanced
BNR	Biological Nutrient Removal
BOD	Biological Oxygen Demand
BPO	Biodegradable particulate organics
BSO	Biodegradable soluble organics
C	Carbon
Ca	Calcium
CBIM	Continuity based interface method
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
DAF	Dissolved Air Floatation
DO	Dissolved Oxygen
DS	Dissolved Solids
DSVI	Diluted Sludge Volume Index
DWA	Department of Water Affairs
DWL	Dewatering liquor
DWS	Department of Water and Sanitation
EBPR	Enhanced biological P removal
EPA	Environmental Protection Agency
EQI	Effluent Quality Index
ERWAT	East Rand Water Care Association
FBR	Fluidised Bed Reactor
FBSO	Fermentable biodegradable soluble organics
FSA	Free and saline ammonia
GMP	Good modelling practice
H	Hydrogen
HRT	Hydraulic Retention Time

IAWQ	International Association of Water Quality
IC	Inorganic carbon
ISS	Inorganic suspended solids
IWA	International Water Association
JHB	Johannesburg
K	Potassium
MBR	Membrane bioreactor
Mg	Magnesium
Mℓ/d	Mega litres per day
MLE	Modified Ludzak-Ettinger
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
N	Nitrogen
ND	Nitrification denitrification
NDEBPR	Nitrification denitrification enhanced biological P removal
NH_4	Ammonium
NMBM	Nelson Mandela Bay Municipality
NO	Nitrates or nitrites
NO_2	Nitrite
NO_3	Nitrate
NOB	Nitrite-oxidising bacteria
O	Oxygen
OCI	Operational Cost Index
OHO	Ordinary heterotrophic organisms
OP	Ortho phosphorus
OrgN	Organic nitrogen
OrgP	Organic phosphorus
OUR	Oxygen utilisation rate
P	Phosphorus
P&ID	Piping & Instrumentation Diagram
PAO	Polyphosphate Accumulating Organisms
PDS	Primary Digested Sludge
PHA	Polyhydroxyalkanoates

pK	Negative log to base 10 of dissociation constant K
PO_4	Ortho-phosphate
PO	Particulate organics (BPO+UPO)
PP	polyphosphate
PS	Primary sludge
PSTs	Primary Settling Tanks
PWM_SA	Plant Wide Model – South Africa
R	Number of moles of struvite precipitated
RAS	Return Activated Sludge
RBC	Rotating Biological Contactor
SBR	Sequencing Batch Reactor
SCADA	Supervisory Control and Data Acquisition
SCFA	Short Chain Fatty Acids
SRL	Sludge Return Liquor
SRT	Sludge Retention Time
SS	Suspended Solids
SSTs	Secondary Settling Tanks
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TOD	Total Oxygen Demand
TP	Total Phosphate
TS	Total Solids
TSS	Total Suspended Solids
UCT	University of Cape Town
UPO	Unbiodegradable Particulate Organics
USO	Unbiodegradable Soluble Organics
VFA	Volatile Fatty Acid
VSD	Variable Speed Drive
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WRC	Water Research Commission
WW	Wastewater
WWTW	Wastewater Treatment Works

Symbol	Description
a	molar nitrogen composition of organics in $C_xH_yO_zN_aP_bS_c$
a_recycle	Recycle ratio from the aerobic reactor to the anoxic reactor
a_{opt}	Optimum a-recycle ratio
b	molar phosphorus composition of organics in $C_xH_yO_zN_aP_bS_c$
c	molar sulphur composition of organics in $C_xH_yO_zN_aP_bS_c$
ch	(charge/mol)
ch	(molH/mol)
ch	(molN/mol)
ch	(molO/mol)
ch	(molP/mol)
ch	(molS/mol)
ch	charge composition of organics in $C_xH_yO_zN_aP_bS_c$
f	ortho-P split between $H_2PO_4^-$ and HPO_4^{2-} species
f_c	mass ratio of carbon (gC/gVSS or gC/g organics)
f_{ch}	charge to mass ratio (charge/gVSS or charge/g organics)
f_{cv}	mass ratio of COD (gCOD/gVSS or gCOD/g organics)
f_h	mass ratio of hydrogen (gH/gVSS or gH/g organics)
f_n	mass ratio of nitrogen (gN/gVSS or gN/g organics)
f_o	mass ratio of oxygen (gO/gVSS or gO/g organics)
f_p	mass ratio of phosphorus (gP/gVSS or gP/g organics)
f_s	mass ratio of sulphur (gS/gVSS or gS/g organics)
$f_{S'up(AD)}$	Unbiodegradable particulate COD in influent wastewater as determined with anaerobic digestion models
$f_{S'up(AS)}$	Unbiodegradable particulate COD in influent wastewater as determined with activated sludge models
k_{add}	Specific addition rate of nitrifiers
K_h	first order hydrolysis rate (/d) xi
K_H	specific first order hydrolysis rate [(l/ (gCOD.d))]
K_m	maximum specific hydrolysis rate in Monod kinetics ([gCOD/ (gCOD.d)]
K_M	maximum specific hydrolysis rate in saturation kinetics ([gCOD/ (gCOD.d)]
K_s	half-saturation concentration in hydrolysis rate in Monod kinetics (gCOD/ℓ)
K_S	half-saturation concentration in hydrolysis rate in saturation kinetics (gCOD/gCOD)

K_{spm}	mineral solubility product pCO_2 partial pressure of CO_2 in the gas phase (mol/mol)
pK_{p2}	negative log to base 10 of the 2nd dissociation constant of the OP system
q_{BPO}	polyphosphate content of BPO (molPP/molBPO)
q_{PO}	polyphosphate content of PO (molPP/molPO)
r_h	volumetric hydrolysis rate [gCOD/(ℓ.d)]
S'up(AS)	Unbiodegradable particulate COD concentration of activated sludge (mgCOD/ℓ)
S'upi	Influent unbiodegradable particulate COD concentration (mgCOD/ℓ)
X	molar carbon composition of organics in $C_xH_yO_zN_aP_bS_c$ch (molC/mol)
X_BA	Nitrifier VSS concentration
XBG_PAO	biomass concentration (mgCOD/ℓ in dynamic models or mgVSS/ℓ in steady state models)
XBH_OHO	biomass concentration (mgCOD/ℓ in dynamic models or mgVSS/ℓ in steady state models)
XEG	unbiodegradable endogenous residue from PAO (mgCOD/ℓ in dynamic models or gVSS/ℓ in steady state models)
XEH	unbiodegradable endogenous residue from OHO (mgCOD/ℓ in dynamic models or gVSS/ℓ in steady state models)
XI	Unbiodegradable particulate COD concentration from the influent accumulating in the activated sludge as VSS (mgCOD/ℓ in dynamic models or mgVSS/ℓ in steady state models)
y	molar hydrogen composition of organics in $C_xH_yO_zN_aP_bS_c$
z	molar oxygen composition of organics in $C_xH_yO_zN_aP_bS_c$
µA20	maximum specific growth rate of nitrifiers at 20°C (/d)

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CHAPTER 1: INTRODUCTION

1.1 Background

This research study entails an investigation into the impact of sludge return liquors after sludge treatment on the performance of South African wastewater treatment works (WWTWs). The Water Research Commission (WRC), through this research study aims to generate local knowledge regarding the impact and mitigating measures in the capacity, operation and effluent quality of the wastewater treatment plants, thereby protecting our valuable and scarce water resources.

The main goal of the research study is to improve the knowledge on the impact and mitigating measures of the sludge return liquors (SRL) from anaerobic sludge digestion on the wastewater treatment process. During the anaerobic digestion, the organic matter in the sludge is converted into biogas. As consequence of the digestion process, stored nutrients in the biomass will be released to the water phase. These sludge return liquors will be recycled to the main process train (usually to the head of works or biological reactors) and will be treated in the plant. The return liquors have shown in literature to increase the load up to +70% for phosphorous (Ueno and Fujii, 2001) and 15-20% of the ammonium load (Fux et al., 2002) compared to the normal raw sewage load. The additional load from the sludge return liquors may result in a deterioration of the effluent, due to an overloading of the plant, increase the energy requirements (for aeration) and increase the chemical dosage (metal salts to precipitate phosphorous).

Preliminary research was undertaken to identify other similar studies on the impact of the sludge return flows in the operational performance of the South African wastewater treatment plants, but it was concluded that this subject was not deeply investigated yet.

Considering the foregoing, this research study is aimed at identifying the impact and mitigating measures of the sludge return liquors on the wastewater treatment process within typical South African wastewater treatment plants. In executing this project, a holistic approach was incorporated whereby the entire treatment plant is considered; focusing on the link between the impact of sludge return liquors (from sludge treatment such as anaerobic digestion, gravity thickening and dissolved air flotation systems) on the plant capacity (biological reactors and aeration requirements) and effluent quality. The overall aim and specific objectives of this study are presented in the next section below.

1.2 Aim of the study

The overall aim of this study is to inform municipalities about the impact of sludge return liquors on their wastewater treatment processes and the available mitigating measures including the potential efficiency, sustainability and financial merits of these under South African conditions.

1.3 Specific Objectives

i. To assess the impact of return flows from sludge handling /treatment (such as dewatering liquors and digestion rejection flows) in the WWTW biological treatment.
ii. Use an existing WRC plant-wide model to predict the impact of the sludge handling/treatment return flows on the biological treatment.
iii. Identify the applicable technologies for nitrogen and phosphorous removal from return flows within the framework of South African best practices and operational requirements.
iv. Identify the potential applications for recovered nutrients, legal outlook and market value.
v. Cost balance for nutrients recovery solutions, including capital and operation costs, as well as sell earnings.

1.4 Approach to the study

This research project's execution has been categorised into phases to allow for effective implementation and meeting of set targets, objectives and deliverables. The project phases and associated deliverables are presented below and expanded upon in turn.

Table 1-1: Project phases and deliverables

Phases	Description	Deliverables
Phase 1	Project initiation and site research	Site research report
Phase 2	Model familiarisation & literature review	Draft model and literature review
Phase 3	Model testing and case study/scenario analysis	Technological research report
Phase 4	Reporting and project close-out	Final products: Report and model

CHAPTER 2: LITERATURE REVIEW

Water pollution, and in particular, eutrophication of South Africa's scarce water resources is a major concern due to the threat it poses to our nation's water security (Mathews, 2014). One of the major point sources of pollution loads on surface waters are effluent streams from municipal WWTWs (WRC, 2008). With regards to pollution loads, phosphorus and nitrogen compounds are the two primary causes of eutrophication of surface waters (WRC, 2015). In an effort to combat this problem, the Department of Water & Sanitation (DWS) is setting more stringent effluent requirements via treatment plant licensing for both inland and coastal regions. At the same time, many of South Africa's municipal treatment plants are approaching or have reached their design load capacity or are in fact overloaded (DWA, 2009). Many of these overloaded treatment systems have nutrient removal constraints.

Unsustainable measures such as the dosing of costly chemicals (typically metal salts) for phosphate removal are typically applied at overloaded plants. The capital and operational costs for municipal wastewater treatment runs into billions of Rand per annum (DWA, 2009). There is therefore an acute need to look at optimisation measures within treatment systems to reduce the nutrient loads on overloaded treatment plants in South Africa.

The main goal of the literature review is to evaluate and report on:

1) Typical treatment processes
2) Typical sludge characteristics
3) Typical impacts of nutrients from return liquors
4) Technical and economic comparison of side stream technologies
5) Design models

2.1 Typical treatment processes

The ultimate aim of wastewater treatment is to ensure that domestic and industrial effluents are disposed of without adverse effect of human health or unacceptable damage to the natural environment. Conventional wastewater treatment plants in South Africa (and mostly worldwide) comprises a combination of physical, chemical and biological processes which allow for removal of solids, organics and nutrients from the wastewater (Figure 2-1). In general, wastewater treatment processes are divided into three stages namely:

- Preliminary treatment;
- Primary treatment;
- Secondary treatment; and
- Tertiary treatment.

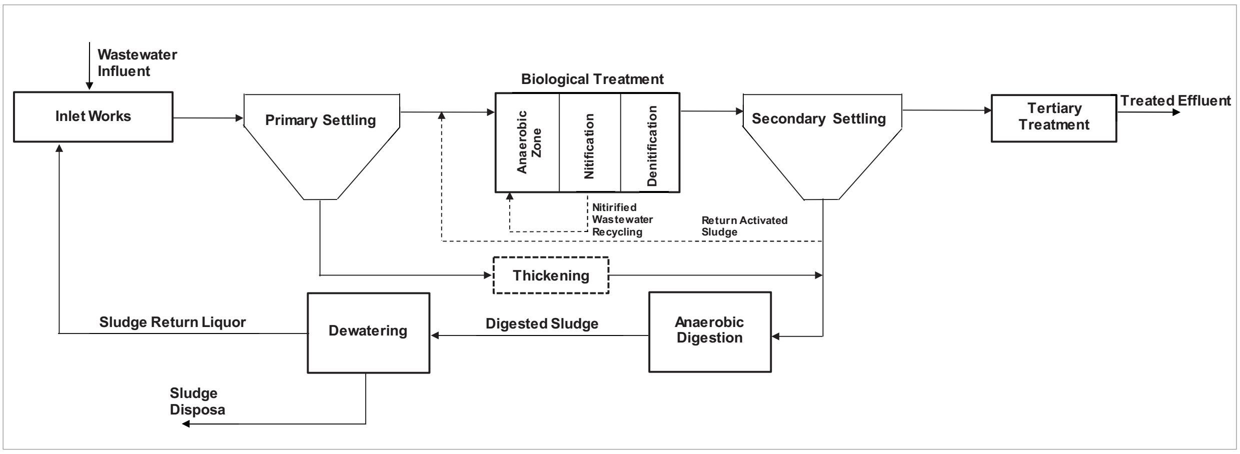

Figure 2-1: Typical wastewater treatment process

2.1.1 Preliminary treatment

Preliminary treatment of wastewater involves the removal of large or heavy solids and grit such as trash, leaves, rags, glass, etc., often found in raw wastewater. These large particles have the potential of causing substantial damage and inefficiency in succeeding treatment processes. Preliminary treatment operations typically include screening, grit removal and flow measurement. Screening operation is typically executed by passing raw wastewater through coarse and/or fine screens majorly consisting of mechanically or manually cleaned bars. Automated mechanically raked bar screens are commonly used in modern WWTWs. Typical openings of coarse and fine screens are ≥ 10 mm and 1.5-6 mm respectively (Nozaic and Freese, 2009). Macerators are sometimes installed to shred large material into smaller pieces, while degritters are typically installed following screening and before primary treatment to ensure the removal of settleable inorganic matter such as sand and gravel usually present in raw wastewater. Grit removal prevents unwarranted abrasion and wear of mechanical equipment, as well as deposition and entrainment of grit in wastewater treatment infrastructure such as pipelines and pumps. In South Africa, the most typical degritters are vortex grit removal systems. Less common types of degritters include horizontal and aerated grit removal systems. Screenings removed from wastewater are typically conveyed to storage waste skips; and thereafter transported to landfill. Grit removed is usually washed in grit classifiers, stored in waste skips and finally disposed in landfill as well.

2.1.2 Primary Treatment

Primary treatment involves the removal of settleable organic and inorganic solids by sedimentation, and removal of suspended materials (scum) by skimming. During primary treatment, the velocity of the wastewater is reduced to allow for settling of heavier organic solids and floatation of lighter materials such as fats, oil and grease in tanks generally referred to as clarifiers or primary settling tanks (PSTs). Suspended solids are sticky and tend to flocculate naturally therefore no chemicals are needed to coagulate the solids unless higher removal efficiencies are required. The floating and settling of the solids takes place through changes in the properties of the organic solids such as size, specific gravity and shape.

PSTs may be round or rectangular basins, typically 3-5 m in depth, with hydraulic retention time (HRT) between 1-2 hours (FAO, 2017). Settled solids referred to as primary or raw sludge are normally removed from the bottom of tanks by sludge rakes that scrape the sludge to a central well from which it is pumped to sludge processing units. Scum is swept across the tank surface by water jets or mechanical means from which it is also pumped to sludge processing units. Under typical operation of PSTs, it is required that settled sludge be removed within 30 minutes to an hour from the time of settling to avoid anaerobic conditions that result in the decomposition of sludge in the PST (Poon and Chu, 1999). Table 2-1 presents typical removal efficiencies that can be achieved in primary treatment without chemical dosing. Colloidal solids which are too fine to settle within the normal detention times of a PST (1-2 hours) are readily passed through the tank and are treated in the secondary treatment process.

Table 2-1: Typical removal efficiencies in primary treatment

Parameter	Efficiency of removal
Settleable solids	90-95%
Suspended solids (SS)	50-60%
Oxygen demand (BOD/COD)	30-35%

Source: Nozaic and Freese (2009)

2.1.3 Secondary treatment

The aim of secondary treatment is to further treat primary effluent from the PSTs thereby removing the residual organics and suspended solids in form of biodegradable dissolved and colloidal solids using a combination of biological processes in anaerobic, anoxic and aerobic conditions. These systems are majorly referred to as activated sludge process. The activated sludge process is designed to grow natural microorganisms (predominantly bacteria) that metabolise the organic matter in the wastewater, thereby producing more microorganisms and inorganic end-products (FAO, 2017). The basic types of suspended activated sludge systems may combine anaerobic, anoxic and aerobic conditions in several compartments depending on the effluent requirements. Other variants of suspended activated sludge processes are oxidation ditches (using simultaneous aerobic and anoxic zones in the orbal basins) as well as sequencing batch reactors and aerobic granulation systems where all processes occur in the same basin. Fixed bed biofilm solutions include the trickling filters or bio-filters and rotating biological contactors (RBC). These biofilm processes differ from the suspended activated sludge mainly in the mode of aeration, the rate at which organisms metabolise the organic matter and the process of sludge formation. It should be noted that typically fixed bed biofilms are not highly efficient removing nutrients. Suspended activated sludge processes generally produce an effluent of slightly higher quality, in terms of these constituents, than bio-filters or RBCs. A combination of two of these processes in series (e.g. bio-filter followed by activated sludge) is sometimes used to treat municipal wastewater containing a high concentration of organic material from industrial sources. Mixed liquor suspended solids (MLSS) gives an indication of the biomass in an activated sludge system. The typical ranges of biomass in suspended activated sludge biological reactors are 3 000 to 5 000 mg MLSS/ℓ, except for aerobic granular systems and membrane biological reactors where it ascends to 8 000 to 10 000 mg/ℓ.

2.1.3.1 Biological nutrient removal

Considering the deleterious effects (such as depletion of dissolved oxygen, eutrophication and increased risk to public health hazards) of nitrogenous and phosphoric compounds on receiving waters, coupled with restrictions placed on the discharge on various nitrogen and phosphorus compounds by regulatory authorities, activated sludge processes are being specifically designed to biologically remove nutrients to comply with permit regulations.

More recently, many of these technologies have been directly incorporated into the secondary processes. Biological nutrient removal processes, when combined with primary treatment, typically remove 85% of the chemical oxygen demand (COD) and SS originally present in the raw wastewater. Sections 2.1.3.2 and 2.1.3.3 provide short descriptions of the biological mechanisms to remove nitrogen and phosphorus from sewage.

2.1.3.2 Nitrification and denitrification

Biological nitrogen removal typically occurs in two subsequent processes: initially nitrification in aerobic conditions and then denitrification in anoxic.

Nitrification is an autotrophic process which involves two steps, first, the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) by the ammonia-oxidising bacteria (AOB); thereafter the oxidation to nitrate (NO_3^-) by the nitrite-oxidising bacteria (NOB) (Shi et al., 2009). This process takes place in the aerobic zone of the activated sludge process. Alkalinity is consumed in this process. For nitrification to take place, there is a need to maintain adequate level of DO. Similarly, pH levels need to be carefully controlled with a narrow range. Per the literature, nitrification occur at pH values of between 6.8 and 8.0, and at a typical range of 7.0 to 7.2 (Metcalf and Eddy, 2003). If the alkalinity is low, it is added in the form of lime, soda ash, sodium bicarbonate, or magnesium hydroxide depending on cost.

Denitrification is a heterotrophic process to reduce nitrate, formed during the process, to molecular nitrogen (N_2) that is released to the air (Van Loosdrecht and Jetten, 1998). To achieve denitrification, an anoxic tank/process is set up after an aeration tank to where the effluent-rich nitrate is recycled and put in contact with the carbon available in the sewage. Alkalinity is recovered in this process and is seen in the increase in pH.

2.1.3.3 Brief description of P release and uptake in the activated sludge

Biological phosphorus removal takes place in two stages where stage 1 takes place in the anaerobic basin of the activated sludge and stage 2 takes place in the aerobic basin of the activated sludge process. The processes and mechanisms for this particular nutrient removal are described and illustrated below.

The anaerobic stage takes place in the absence of NO_3, and O_2 and selects for a group of facultative anaerobic heterotrophs called polyphosphate accumulating organisms (PAOs).

The fundamental process strategy during the anaerobic stage involves the sequestering of short chain fatty acids (SCFAs) such as acetate (CH_3COOH) and propionate (CH_3CH_2COOH). SCFA are stored up in the cells to serve as the carbon and energy source during the growth stage of PAOs. During the sequestering of SCFA in the anaerobic stage, polyphosphate serves as an electron acceptor. The breakdown of polyphosphate results in the release of phosphate (PO_4^-).

The PAOs with sequestered SCFAs are called poly hydroxyalkanoates (PHAs). When PHAs are introduced into an environment with oxygen, i.e. stage 2 (aerobic stage), the sequestered SCFA are used as the carbon and energy source for growth (formation of cell wall structure.). The rapid growth takes place in concert with the uptake of phosphate from the bulk solution. Phosphate is then stored as polyphosphate by the PHAs.

Phosphorus is removed from the system while excess activated sludge is wasted directly from biological reactors or secondary settling tanks.

2.1.3.4 Typical configurations for nutrients removal

A. 3 Stage Phoredox process

The configuration of the 3 stage Phoredox process involves two main recycle streams: the recycle and discharge of nitrate-rich sludge (A-recycle) directly into the anoxic zone and the recycle and discharge of activated sludge, usually from the secondary settlers, directly into the anaerobic zone (Figure 2-2). The major advantage of the Phoredox configuration is that it is compact and optimises nitrogen removal due to the maximal use of the anoxic volume. The main disadvantage is related to the recycle of some nitrates together with the S-recycle stream and potentially affect the anaerobic conditions in the first anaerobic zone.

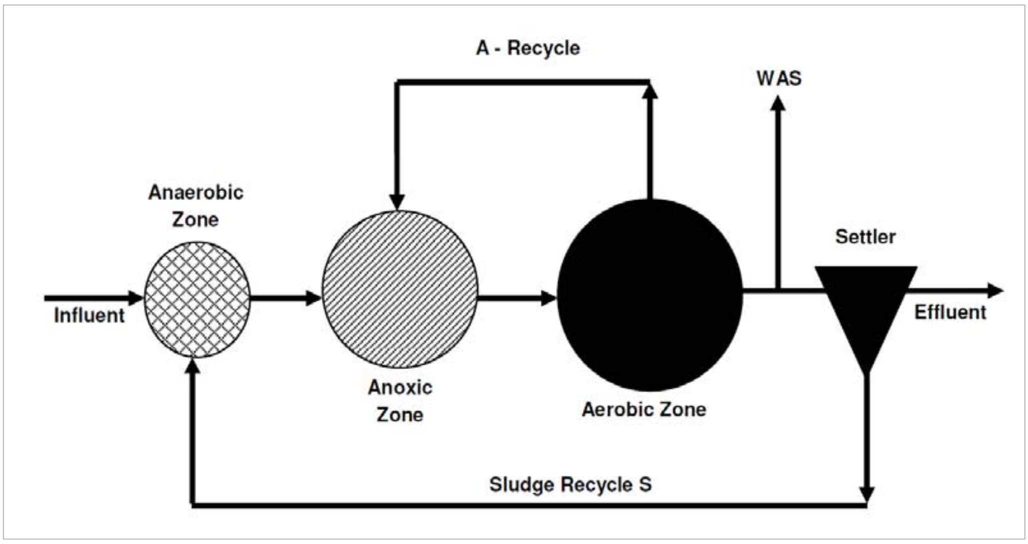

Figure 2-2: Diagrammatic layout of the Phoredox process (adapted from Ekama et al., 1984)

B. University of Cape Town (UCT) process

This process was developed at the University of Cape Town in South Africa. The configuration of the UCT process involves the recycle and discharge of the return activated sludge from the secondary settles (S-recycle) directly into the anoxic reactor, thereby avoiding the anaerobic zone (Figure 2-3). Then the mixed liquor characterised by low nitrate content is recycled (R-recycle) and deposited into the anaerobic zone from the anoxic zone. Considering that the mixed liquor is diluted by the incoming wastewater, the MLSS concentration in the anaerobic zone is significantly lower than in the rest of the reactor. Therefore, to achieve the same anaerobic mass fraction, the volume of the design needs to be proportionately higher.

The rate of recirculation from the aerobic zone to the anoxic zone (A-recycle) must be carefully controlled to ensure that the required nitrate concentration in the effluent is met, and simultaneously the nitrate concentration is the R-recycle is low.

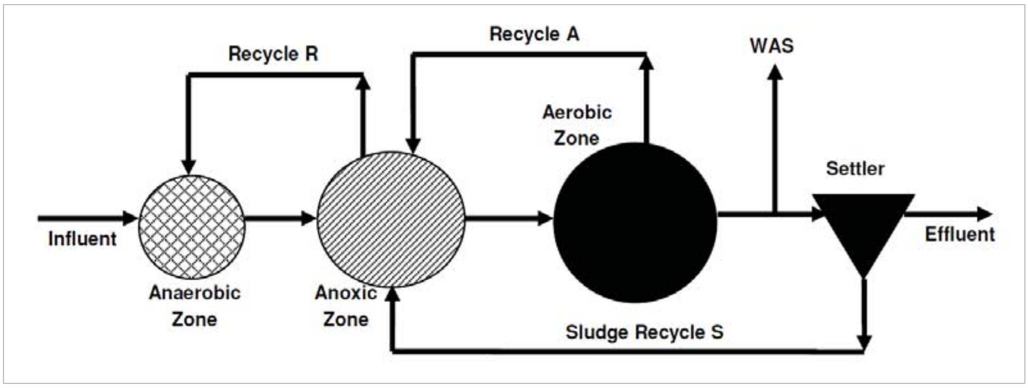

Figure 2-3: Diagrammatic layout of the UCT process (adapted from Ekama et al., 1984)

C. Modified UCT process

The only difference between the UCT and the Modified UCT configuration is that the anoxic zone is divided into two subzones (Figure 2-4). The first anoxic zone is sized to ensure that all the nitrates introduced in the S-recycle are removed so that no nitrates are introduced from the R-recycle into the anaerobic zone via the R-recycle. This configuration was developed to facilitate operation in that the A-recycle rate does not have to be controlled to ensure that the nitrate concentration in the second anoxic zone is always kept to a minimum. However, research at UCT has shown that if denitrification is not complete in an anoxic zone the intermediate products of denitrification (specifically nitric oxide, NO) are trapped intra-cellularly within the heterotrophic organisms when they enter the aerobic zone. This in turn inhibits their ability to metabolise and their growth is inhibited under aerobic conditions. This gives an advantage to filamentous organisms which do not produce NO, with the result that they proliferate at the expense of the floc-forming heterotrophs, thereby creating a bulking sludge.

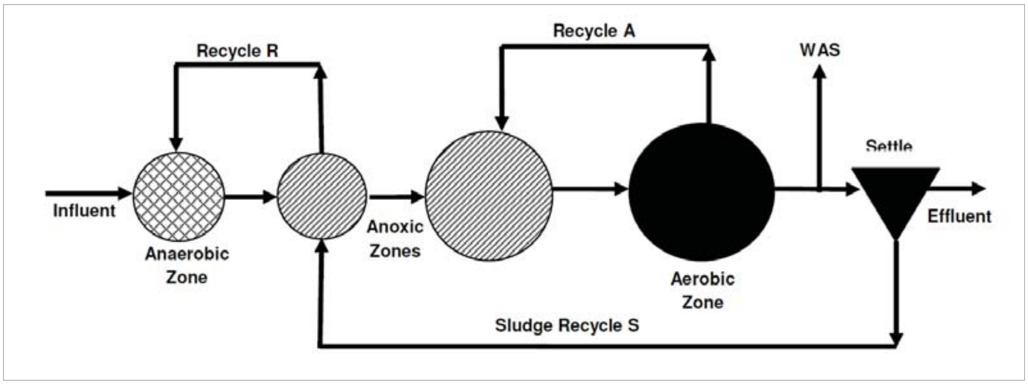

Figure 2-4: Diagrammatic layout of Modified UCT process (adapted from Ekama et al., 1984)

D. Johannesburg (JHB) process

In the Johannesburg process, there is an anoxic zone for the S-recycle stream reducing the oxygen and nitrate content discharged into the anaerobic reactor (Figure 2-5). The MLSS concentration in the S-recycle is significantly higher than in the reactor and therefore the volume of the S-recycle anoxic zone is relatively small.

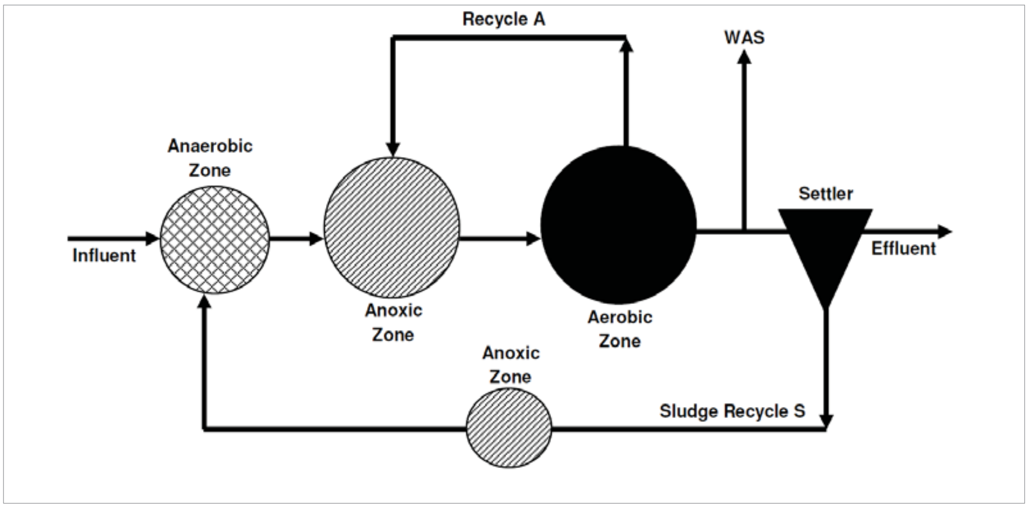

Figure 2-5: Diagrammatic layout of the JHB process (adapted from Ekama et al., 1984)

2.1.4 Tertiary treatment

Tertiary treatment is used to further improve the quality of the secondary effluent before being discharged to the receiving environment. Tertiary treatment processes are usually put in place to remove residual suspended solids, bacteria, viruses, pathogens, heavy metals and dissolved solids. These treatment processes may include filtration, reverse osmosis, disinfection, and maturation ponds, amongst others.

2.1.5 Sludge treatment

Residues generated in the process of wastewater treatment are referred to as sludge. The quantity of sludge generated is directly proportional to the quantity of wastewater treated. Typically, the quantity of sludge generated in the primary treatment range from 0.25% to 0.35% by volume of wastewater and increases to 1.5% to 2.0% after undergoing the activated sludge process (Davies, 2010).

In general, the objectives of sludge treatment are:

- Stabilisation for a controlled degradation of organic constituents and odour removal;
- Volume and weight reduction;
- Hygiene – the elimination of pathogenic organisms;
- Improving of sewage sludge characteristics for the further utilisation or disposal.

Davies (2010) categorised the basic sludge treatment processes into six (6) as follows:

- Preliminary operations
- Thickening
- Stabilisation
- Conditioning
- Dewatering
- Reduction

2.1.5.1 Preliminary operations

Preliminary operations include procedures screening, grinding, degritting, blending, and storage which are usually done to provide a uniform mixture to downstream operations and processes, thereby protecting downstream equipment or facilities.

2.1.5.2 Thickening

Sludge thickening is usually done to increase the solids concentration by removal of a portion of its liquid content (Garg, 2009). This results in a reduction of the volume of the sludge to be sent to subsequent facilities while also improving their operational efficiency. The volume reduction obtained by sludge thickening is of benefit to subsequent treatment processes such as digestion, dewatering, drying and combustion from the following perspectives:

- Capacity of tanks and equipment required;
- Quantity of chemicals required for sludge conditioning;
- Heat requirements and retention time for digestion as well as auxiliary fuel required for heat drying or incineration.

Thickening is usually done where thin sludges (< 2%) are generated, and can be achieved via gravity settling, floatation, centrifugation and gravity belts. Gravity thickening is considered as the simplest and least expensive thickening method (Garg, 2009), and can produce primary thickened sludge of 5-7% while secondary sludge can be thickened to about 4% (Nozaic and Freese, 2009). Table 2-2 presents some available sludge thickening methods and their expected performance.

Table 2-2: Thickening methods used for sludge treatment

Thickening method	Sludge type	Expected performance
Centrifugation	WAS with polymer	8-10% TS for basket centrifuges* 4-6% TS for disc-nozzle centrifuges* 5-8% for solid bowl centrifuges*
Gravity Belt Thickener	WAS with polymer	4-8% TS
Rotary Drum Thickener	WAS with polymer	4-8% TS
Gravity Thickener	PS	8-10% TS
Gravity Thickener	PS & WAS	5-8% TS
Gravity Thickener	WAS	2-3% (Better results reported for oxygen rich activated sludge)
Gravity Thickener	PS, PDS & WAS	8-14% TS
Dissolved air floatation (DAF)	WAS (not usually used for other sludge types)	4-6%

Source: Ontario (2017)

*Solids concentrations for centrifuges without polymer will be reduced.

2.1.5.3 Stabilisation

Sludge is stabilised to reduce pathogens, eliminate offensive odours, and minimise or prevent decomposition. Technologies used to achieve stabilisation include alkaline stabilisation, heat treatment, aerobic digestion, anaerobic digestion and composting. An overview of anaerobic digestion is presented in the next section due to its importance to the objective of this study – the impacts of sludge return flows on South African WWTWs.

A. Synopsis of anaerobic digestion

Anaerobic digestion is a metabolic process applied on wastewater treatment plants to stabilise and reduce of sludge volume that needs to be disposed of. The main goal of anaerobic digestion is to decompose organic matter (solids) to non-cellular end products such as biogas. The process is carried out in the absence of oxygen where a large portion of organic matter is broken down into carbon dioxide and methane gas. About half of the amount is then converted into gases, while the remainder is dried and becomes a residual soil-like material. Sludge can be digested under cold or heated and mixed conditions. Two temperature regimes are used in anaerobic digestion: mesophilic (30-38ºC) and thermophilic (50-57ºC). Although the thermophilic range has the advantages of increased reaction rates that result in smaller digesters, increased solids destruction, and increased destruction of pathogens and better dewatering, they have not found wide application for municipal sludge (Davies, 2010).

The anaerobic digestion process occurs in four steps and these are described below.

- **Hydrolysis**: the breakdown of complex organics such as carbohydrates, proteins and fats into their soluble building blocks such as primary sugars, amino acids and fatty acids respectively.
- **Acidogenesis** (fermentation): the conversion of alcohols fatty acids, amino acids and sugars to volatile acids and gases.
- **Acetogenesis**: the conversion of volatile fatty acids to acetate or CO_2 and H_2.
- **Methanogenesis**: the formation of methane from CO_2 and hydrogen (hydrogenotrophic) and conversion of acetic acid to methane and CO_2 by acetotrophic bacteria.

Typical operating conditions for heated and mixed anaerobic digester a listed below:

- Temperature: 30°C to 35°C
- Average retention time: 15 to 20 days
- Destruction of volatile suspended solids (VSS): 40% to 45% (if both primary and biological sludge are anaerobically digested together).

If required, further stabilisation of the sludge can be achieved in secondary digesters; allowing for the supernatant liquor separation and decantation.

2.1.5.4 Conditioning

Conditioning involves the physical or chemical treatment of sludge to improve its dewatering characteristics. Physical methods for conditioning sludge include heat treatment and addition of fly ash, while chemical methods involve the addition of either coagulants and/or polymers. The method selected influences the thickening or dewatering process and has different impacts on subsequent sludge handling operations and on the treatment plant itself, due to recycle streams (Ontario, 2017).

2.1.5.5 Dewatering

Dewatering is done at WWTWs to further reduce the water content of sludge to meet disposal regulations, enhance handling, minimise transportation costs, prevent leachate from disposal sites, and reduce energy requirements in subsequent processes such as incineration (Davies, 2010). Sludge dewatering technologies include centrifugation, filter presses, and drying beds. The choice of the appropriate sludge dewatering technology depends on several factors which include: the properties of the sludge to be dewatered (i.e. pre-thickened, primary sludge or WAS), available space, desired moisture content of sludge cake. Dewatering may be enhanced by chemical condition, e.g. addition of a polymer (Garg, 2009). It is also important to note that the solids loading rates for dewatering equipment will be reduced if phosphorus removal chemicals (i.e. alum or ferric chloride) are used. This will result in production of cake solids with lower concentration than would be expected without phosphorus removal (Ontario, 2010). Table 2-3 provides the solids capture and typical solids concentrations for various types of conditioned sludge.

Table 2-3: Sludge dewatering methods and performance with various sludge types

Dewatering method	Solids capture (%)	Sludge type	Typical solids concentration
Drying beds	>95%	PS PDS PDS+WAS WAS	50-60%
Belt filter press	85-95	PS or PDS + WAS WAS	14-25% 10-15%
Centrifuge (Solid bowl)	95-99	PS or PDS + WAS WAS (with polymer)	15-30% 12-15%
Filter press	90-95	PS + WAS PDS + WAS WAS	30-50% 35-50% 25-50%
Vacuum filter	90-95	PS + WAS PDS + WAS WAS	10-25% 15-20% 8-12%

Modified from: Ontario (2017)

2.1.5.6 Reduction

Reduction involves processes put in place to achieve the most stable form of residue and to minimise the volume of residue. These processes include composting or thermal reduction processes such as drying or incineration. The end product is stable and may be applied to agricultural land as a fertiliser.

2.2 Typical sludge characteristics for anaerobic digestion

2.2.1 Characterisation of sludge feed to anaerobic digesters

Basically, two types of sludge are produced from the wastewater treatment process namely, primary sludge and biological sludge (also referred to as WAS), captured from the primary and secondary wastewater treatment stages respectively. The two sludge types, upon anaerobic digestion, have different biogas production potential due to their mode of treatment and removal. Primary sludge contains higher biogas production potential because it is captured via gravity, thereby retaining its energy/organic content. Primary sludge is therefore characterised by high organic solids, particulate COD, organically bound nitrogen and phosphate. However, biological sludge has lower biogas potential because the microorganisms in the secondary treatment process have consumed most of their energy content leaving behind mainly inert biomass. Biological sludge is characterised by high concentration of suspended solids, low concentrations of dissolved inorganic nutrients, and low levels of dissolved oxygen (DO). Both primary and biological sludge can directly undergo anaerobic digestion but are in many instances thickened to reduce the volume of the sludge, thereby reducing capital and operating costs associated with sludge processing.

The typical composition of primary, biological and digested sludge as reported by the European Commission, 2001 is presented in Table 2-4.

A: primary sludge, primary sludge with physical/chemical treatment or high pollution load;

B1: biological sludge (low load);

B2: biological sludge from clarified water (low and middle load);

C: mixed sludge (mix of A and B2 types);

D: digested sludge.

Table 2-4: Typical composition of primary, biological, mixed and digested sludge

Parameter	Unit	Class				
		A	B1	B2	C	D
Dry matter	g/ℓ	12	9	7	10	30
Volatile matter	%DM	65	67	77	72	50
Nitrogen	%VM	4.5	7.5	6.3	7.1	6.2
Phosphorus	%VM	2	2	2	2	2
COD	mg/ℓ	110-170	70-100	70-100	N/A	N/A

Extracted from: Gebreeyessus and Jenicek (2016) as reported by the European Commission (2001) after OTV, 1997

2.2.2 *Fate of nutrients (N and P) during anaerobic digestion*

During the process of anaerobic digestion, a considerable amount of the organic matter is transformed into volatile fatty acids (VFAs) by acidogenic bacteria. These VFAs are thereafter metabolised by methanogenic bacteria to produce methane, carbon dioxide and a few other gases. Nitrogen and phosphorus are transformed by these microbial processes but are not destroyed.

Nitrogen in the sludge enters the digester mainly in two forms: ammonium or organic nitrogen. Ammonium is not destroyed during the digestion process, but rather, organic nitrogen is converted to ammonium during protein degradation. Hence, the ammonium level in the digester effluent is typically higher than in the digester feed; typically, twice the amount in the feed (Topper et al., 2017). It is worthy of note that total nitrogen in the digester feed remain equal the total nitrogen leaving the digester given that only a negligible amount of ammonia gas escapes with the biogas.

There is always some solids retention in a digester, especially in plug flow designs. In the digester, solid nutrients can settle. These settled solids make it look as though the nutrient concentration decreased as the sludge passed through the digester. This is usually the case with phosphorus. The microorganisms in the digester do not consume phosphorus. Some phosphorus can be converted to orthophosphate (a soluble form) in the digester, but the total mass remains constant. The total phosphorus in the digester feed equals the P in the effluent in addition to the amount that has settled out as sludge (Topper et al., 2017).

2.3 Typical impacts of nutrients in return liquors

Considering that sludge return liquors contain high concentrations of ammonia and phosphate, and coupled with the fact that research has shown that the current body of knowledge is not fully unaware of the impacts of additional load on wastewater treatment plants. This chapter presents an overview of typical impacts of sludge return liquors on wastewater treatment plants within South Africa. The impacts are obtained from a recent investigative study carried out, the study categorised the impacts of return liquors on WWTWs into the following:

- Impact on influent characteristics
- Impact on aeration demand
- Impact on effluent quality

2.3.1 Impact on influent characteristics

Even in the recent past, sludge return liquors at majority of South African WWTWs were typically not recycled to the main plant (i.e. being discharged into ponds). The most stringent environmental regulations have been changing this scenario and nowadays the new plants recycle return liquors to the head of works, to combine with the incoming raw sewage, or to the biological treatment process. In existing plants, the operational teams typically try to return the liquors back to the main treatment, but very often there are no integrated studies to evaluate if the plant can handle the additional load. In fact, if the plant does not have the extra capacity required, the result will be an overload of the system and therefore non-compliances are detected. It should be noted that most of the treatment plants in South Africa were not designed to accommodate the additional ammonia and orthophosphate loads coming from the sludge returns liquors and thereby the plants require an in-depth investigation to make sure that there is sufficient treatment capacity available in the main or if additional treatment procedures or in some cases reconfiguration of treatment processes are needed.

The outcome of the site research conducted in six South African plants shows the impact result from return liquors in the influent characteristics. The investigations indicated that several WWTWs in South Africa may be operating above their design capacities. Through the site research and the contact with several other wastewater treatment plants during the selection process, it is noted that, historically, most of the treatment plants were not designed to accommodate the additional loads from sludge return liquors. Per the (non-optimal) operating conditions of these six plants, generally the influent characteristics when combined with sludge return liquors increase by 1% to 3% in flow, 5% to 11% in TKN, 3% to 8% in NH_4, 5% to 50% in TP and 10 to 100% in PO_4.

2.3.2 Impact on aeration demand

The investigation conducted at the selected WWTWs across South Africa indicated that most of the plants studied do not treat their return liquors before reintroducing them into the main treatment cycle. With the current approaches of recycling return liquors without side-stream treatment and non-optimal anaerobic digestion processes, the average aeration demand for the plants' biological reactors typically increases by ± 10% when compared with a situation where there are no recycle of return liquors. This aeration energy demand may increase up to 20% as soon as the anaerobic digestion processes are optimised with higher ammonia and orthophosphate loads returned to the biological reactors. With the introduction of side-stream treatment of the return liquors, the aeration demand in the main treatment may be lowered per the efficiencies of the different technologies available.

2.3.3 Impact on biological effluent quality

More stringent effluent discharge requirements with regards to nitrogen and phosphorus have been increasing the need for improved nutrient removal techniques in WWTWs. Consequently, attention is required to optimise the side streams/return flows treatment processes. Through the removal and recycle of extra nutrient load back wastewater treatment process, a substantial improvement in the effluent quality can be anticipated.

Site research conducted at ‘Z’ WWTW indicates that the effluent quality of module 2 (to which return liquor is recycled) is not complying with the nitrate+nitrite and orthophosphate quality standards. It is noted a deterioration in the module 2 biological effluent quality especially in the orthophosphate parameter. This deterioration appears to be coincident with the period when a start-up of the anaerobic digestion and the recycling of the sludge liquors to module 2 were initiated. The overall plant performance regarding nitrogen and phosphorous compliance has been also negatively impacted over the observed period. This proves how important it is to take the correct decisions, find the adequate route and technology to deal with return liquors to avoid a deterioration of the effluent quality.

2.4 Side stream technologies

2.4.1 Nitrogen recovery technologies

Optimal nitrogen removal/recovery is of high importance during wastewater treatment due to its contribution to aquatic eutrophication, and the toxicity and direct threat it poses to aquatic life (Tikilili and Chirwa, 2014). Nitrogen mainly occurs in wastewaters in the form of ammonia and have been removed, in the past, using only conventional nitrification/denitrification. Nowadays, nitrogen removal and recovery can be achieved using more innovative and sustainable innovative technologies. Basically, the innovative technologies are operated in such a way that ammonia is initially partially converted to nitrite and then ammonia and nitrite are directly converted to nitrogen gas.

Drawbacks associated with the conventional method include the following:

- Characterised by high complexities and poor efficiency especially when treating nitrogen rich wastewaters with low C/N ratio, hence its application is limited to wastewater with low nitrogen levels (Tikilili and Chirwa, 2014);
- Lower cost effectiveness (Tikilili and Chirwa, 2014; Sousa, 2016);
- Relatively slow process due to a low microbial activity and yield (Sousa, 2016).

Most of the innovative and sustainable technologies have been designed to overcome the shortcomings of the conventional method. The following sections provide a short description of major nitrogen removal/ recovery technologies which have been implemented on a full scale.

2.4.1.1 SHARON®

SHARON® stands for **S**ingle reactor for **H**igh activity **A**mmonia **R**emoval **O**ver **N**itrite. It is a process that occurs in an entirely mixed reactor without biomass retention. SHARON® was developed to treat ammonium rich side streams from sludge digestion. The ammonia oxidation terminates at the nitrite step by operating the SHARON® process at an elevated temperature (30-40°C) which allows the ammonia oxidisers grow significantly faster than the nitrite-oxidising bacteria (Van Kempen et al., 2001). In this process, the hydraulic retention time (HRT) is equal to solids retention time (SRT), usually between 1 to 2 days, depending on the ammonia concentrations in the side stream and discharge limits. Therefore, the slow-growing nitrite oxidisers are washed out of the system and the ammonia oxidisation is stopped at nitrite (EPA, 2007).

The SHARON® process was first implemented at the Dokhaven WWTW in 1997 with the aim of meeting effluent quality requirements. Average removal efficiencies were estimated to be between 70% and 90% (Hellinga et al., 1998). The technology has been successfully applied at several wastewater treatment plants in the Netherlands, the United States, United Kingdom and Sweden (Thøgersen, 2017). Advantages of the SHARON® process includes; partial oxidation of ammonium to nitrite which results in double saving considering the less aeration-cost requirements for nitrification (offers about 25% savings on energy); less carbon source requirements (40%) for denitrification; insensitivity to high TSS influent concentrations and about 30% reduction in net sludge production (Van Kempen et al., 2001; Van Loosdrecht, 2004; Thøgersen, 2017).

2.4.1.2 ANAMMOX®

ANAMMOX® stands for **AN**aerobic **AMM**onium **OX**idation. The process is a variation on the SHARON® process described in 2.4.1.1. The ANAMMOX® process was the first reported process which converts ammonia to di-nitrogen gas (N_2) (Manipura et al., 2005). The combination of the SHARON® process with the ANAMMOX® has been reported to offer an efficient and cost-effective treat nutrient rich side streams, typically above 500 mg $NH_4 - N/\ell$ (EPA, 2007), but has not been indicated for obtaining strict effluent standards. The process is typically implemented in two treatment steps.

Treatment 1: This step involves the use of the SHARON® process to convert only 50% of the ammonium for production of an ammonium-nitrite mixture. This is achieved by limiting the oxygen supply as the implementation of SHARON®-ANAMMOX® process entails the conversion of only 50% of the ammonium to nitrite.

Treatment 2: In this second step, the ANAMMOX® process converts the ammonium-nitrite mixture produced in the SHARON® reactor to nitrogen gas. The conversion of ammonium and nitrite to nitrogen gas is described by the following formula:

$$NO_2^- + NH_4 \implies N_2 + 2H_2O$$

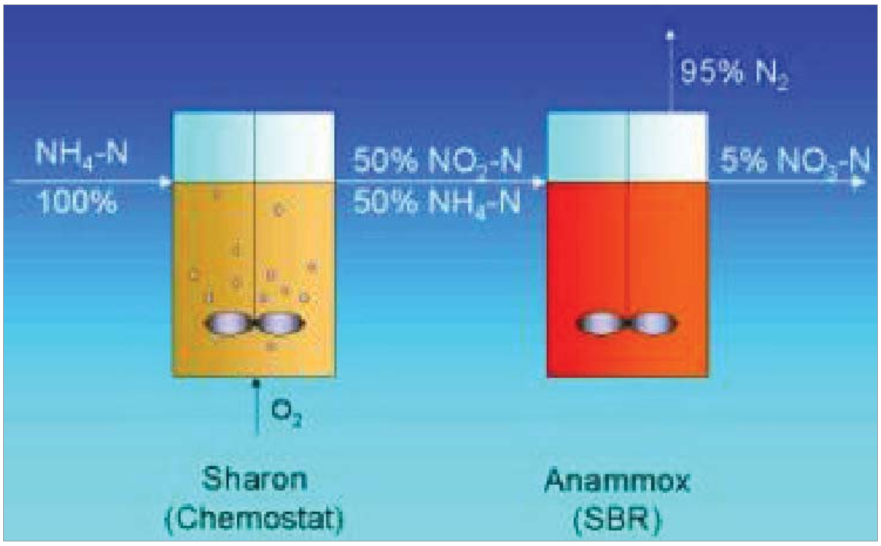

Figure 2-6: The SHARON-ANAMMOX process (EPA, 2007)

A significant number of the SHARON®-ANAMMOX® installations are located in Europe, although the interest in this system seems to be increasing in North America. It is estimated that the total nitrogen removal rate achievable by the combined SHARON®-ANAMMOX® process is 90-95% (Solley, 2000).

The combined process offers higher cost savings (90% OPEX) over the conventional nitrification/denitrification systems in that the process operates under low oxygen concentrations and does not require an external organic source. In summary, the SHARON®-ANAMMOX® process is 90% less expensive than the conventional nitrification-denitrification process (Sousa, 2016).

Research shows that the ANAMMOX® technology has not been commercially implemented in South Africa. However, an experimental study conducted by Tikilili and Chirwa (2014) to determine whether the anammox bacteria are present in some South Africa anaerobic environments, was conducted for the WRC in 2014. Three WWTWs namely Daspoort WWTW, Zeekoegat WWTW and Baviaanspoort WWTW (all in the Gauteng region) were used as case studies. Results obtained from the experiments showed the presence of anammox in the two (Daspoort and Zeekoegat) of the WWTWs, with Daspoort WWTW reported to be characterised by high concentrations of anammox bacteria. Upon additional analysis of the anammox bacteria, results showed that the system was dominated by bacillus species but a considerable amount of Planctomycetes and anammox (5%) was also found. It can be deduced from the results that the amount of anammox biomass recorded are not significant enough to obtain anammox biomass for implementation of the ANAMMOX® process at a commercial scale in South Africa. To achieve this, significant improvements are required.

2.4.1.3 CANON®

The Completely Autotrophic Nitrogen Removal Over Nitrite (CANON®) process comprises the ANAMMOX process in combination with nitrification. The combined process takes place in a single reactor. The process entails partial oxidation of ammonia to nitrite by aerobic ammonium oxidising bacteria (AOB). The nitrite produced is thereafter combined with the remaining ammonia to produce N_2 gas in the presence of anaerobic AOB (Manipura et al., 2005). The process thus requires partial nitrification (to produce nitrite), low dissolved oxygen (< 0.6 to 0.8 mg/ℓ), higher pH (> 7.6), long SRT, and adequate NH_4/NO_2^- ratio. The system requires very low aeration; consuming 63% less oxygen (Tomaszek, 2008). The conversion process that takes place in the CANON® is described by the following formula (Manipura et al., 2005):

$$NH_3 + 0.85O_2 \longrightarrow 0.11NO_3^- + 0.44N_2 + 0.14H^+ + 1.43H_2O$$

The major advantage of the CANON® process is that it does not require the addition of an external carbon source, making it suitable for removal of nitrogen compound from industrial wastewaters characterised by low organic content. It however has sensitive operational characteristics in terms of DO, nitrogen load, biofilm thickness and temperature (Tomaszek, 2008).

2.4.1.4 BABE®

The Biological Augmentation Batch Enhanced (BABE®) process is a new low-cost method for N-removal in wastewater treatment. The process allows for removal of ammonia from the side-stream and improves the nitrifiers that are returned to the main plant, thereby improving the nitrogen removal therein Figure 2-7. The process is carried out in a single batch reactor. It involves combining side streams characterised by high ammonia levels and return activated sludge (RAS) from the main biological treatment process with previously settled sludge in the batch reactor. The RAS serves the purpose of augmenting the bacteria in the settled sludge. The use of the batch reactor allows for long residence times necessary to grow both the nitrifying and denitrifying bacteria. The BABE® process operates at temperatures between 20-25°C; with temperatures lower than 20°C requiring larger reactor volumes (EPA, 2007). However, the impact of the process is insignificant when operated under temperatures higher than the specified range. The process has been found to be more efficient with influent characterised by higher concentrations of ammonia. The technology is particularly appropriate for existing wastewater treatment systems that require a greater nitrogen removal capacity; providing an easy way for upgrade where aerobic SRT is limited.

Full scale implementation of the BABE® process has been reported at the Garmerwolde WWTW in Groningen, the Netherlands. Results showed higher nitrification rate and lower effluent ammonia in the water line where the BABE® process was implemented. The simulation results indicated that better effect of the technology is expected at lower ambient temperatures and smaller volume of the BABE® reactor (Salem et al., 2004). One of the main advantages of the full-scale application of the BABE® process that treats nitrogen-rich side streams is about a 60% reduction in costs (Tomaszek, 2008).

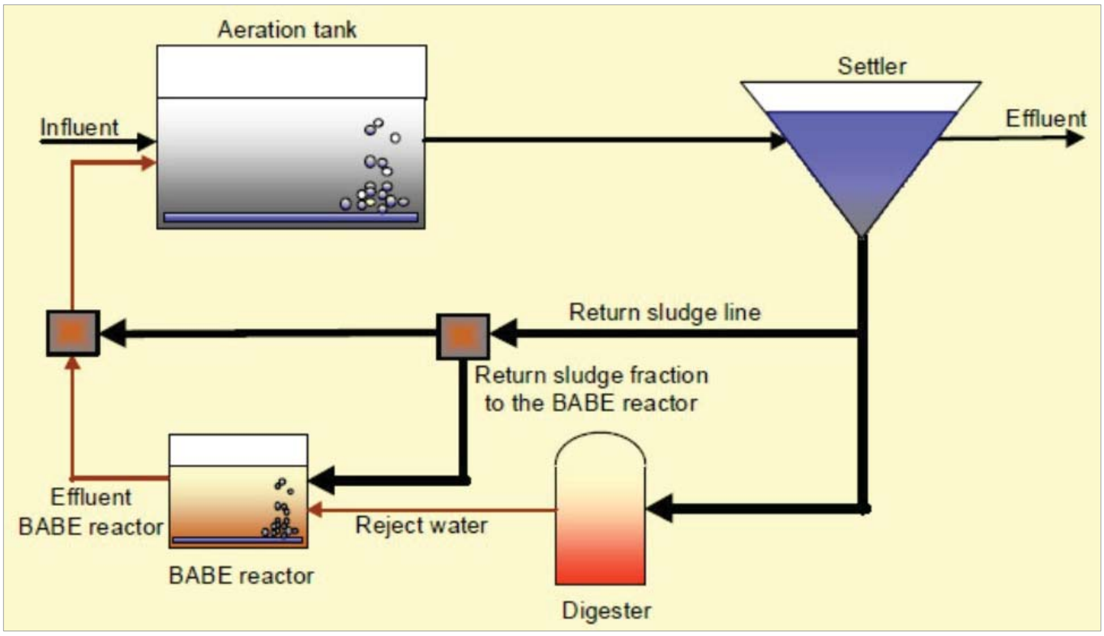

Figure 2-7: Process description of the BABE® process

In addition to the technologies discussed above, other nitrogen treatment options available in the market include but are not limited to: OLAND®, DEMON®, MAUREEN, ANITA™ Mox, Terra-N, etc.

2.4.1.5 Comparison of different nitrogen removal technologies

With respect to the investment and operating costs associated with these technologies, the United States Environmental Protection Agency (USEPA), using costs updated to 2013 prices, reported the SHARON® process to be the cheapest alternative for nitrogen removal in side streams compared with other techniques. The investment costs for a SHARON®/ANAMMOX® installation with a capacity of 1 200 kg ammonium ($NH_4 - N$)/day is estimated at $3 million. Operating costs, on the other hand, are dependent on energy, methanol and caustic chemicals.

Van Loosdrecht and Salem (2006) presented a decision matrix for selection of a sludge water treatment process for the ‘s-Hertogenbosch WWTW in the Netherlands. The decision matrix is summarised in the following table.

Table 2-5: Decision matrix for selection of a sludge treatment process at 's-Hertogenbosch WWTW, Netherlands

Aspect	SHARON	SHARON/ANAMMOX	CANON	BABE
Investment cost	+	0	++	+
Operational cost	++	++	++	++
Allowable increase of load	–	–	–	+
Impact on final effluent	–	–	–	+
Sustainability	0	+	+	0
Ease of retrofitting	+	+	+	0

Notes: ++ = 5; + = 4; 0 = 3; – = 2; – – = 1 (Source: Van Loosdrecht and Salem, 2006)

With reference to the decision matrix presented in Table 2-5, the recommended technology for South Africa in respect of nitrogen recovery from side streams is the BABE® technology. This is because, in general it offers higher benefits in key decision/priority areas which are OPEX, future load increase and impact on final effluent, as well as indicates considerable benefits in terms of investment costs.

2.4.2 Phosphate recovery technologies

Wastewater treatment plants are important sources for phosphorus recovery as the conditions for its formation can be found naturally within the environment of WWTWs (Durrant et al., 1999). Phosphorus is obtainable in various forms as phosphates in wastewater categorised as orthophosphates, polyphosphates and organic phosphates. Research has shown that concentration of total phosphorus in municipal waters range between 5 mg/ℓ to 20 mg/ℓ, with the organic portion estimated to be 1-5 mg/ℓ and the remainder inorganic (Sikosana et al., 2015). Considering the limited availability of phosphorus across the globe, and attendant increase in market price (Oleszkiewics et al., 2015), its recovery is becoming increasingly important. Additionally, the need to comply with discharge limits in terms of phosphorus concentration has further intensified the search for phosphorus recovery technologies within the context of wastewater treatment.

As reported by Cornel and Schaum (2009) and cited by Sikosana et al. (2015), a minimum concentration of 50-60 mg/ℓ of orthophosphates is required for phosphorus recovery to be feasible. It is important to note that to achieve a side-stream with a high phosphate concentration, it is necessary that the process is operated with biological phosphorus removal. However, a process based only on biological phosphorus removal cannot achieve the high demand on low phosphorus content in the effluent. Therefore, the process must be based on partial biological phosphorus removal (Levlin and Hultman, 2003).

This section presents an overview of phosphate recovery technologies available worldwide; subjecting each technology to a multi-criteria analysis based technical, environmental and economic perspectives.

2.4.2.1 Conventional coagulation, flocculation & sedimentation

The most common (conventional) method for phosphorus removal in South Africa is chemical precipitation. This typically involves the application of compounds of calcium, aluminium and iron to precipitate phosphorus at the following critical points: *"prior to primary settling, during secondary treatment or as part of a tertiary treatment process"* (Strom, 2006). The same principals are applicable to the phosphorous removal on side-streams. The chemical process initiates by converting soluble reactive phosphorus to a solid particle followed by removal of the particulate phosphorus by a physical process.

Neethling et al. (2008) provided a list of elements that constitute the chemical process:

- Chemical addition to react with the soluble phosphorus species and produce a solid precipitant;
- Chemical flocculants to capture small particles for removal in solid separation process;
- Chemical removal onto a reactive surface of performed precipitants or other surfaces;
- Solids separation to remove particulate phosphate species;
- Adsorption through the contact of phosphorus in water phase to solid phase, such as the flocs retained on filters.

Typically, chemical phosphorus precipitation achieves 90% efficiency or higher. The major concern with chemical precipitation for phosphorus removal is that it significantly increases that volume of sludge produced and to be disposed thereafter (Strom, 2006).

2.4.2.2 Ostara Pearl® and WASSTRIP®

The Ostara Pearl® process was developed in the University of British Columbia (Canada). The process recovers struvite from the sludge liquor of an anaerobic digester, coming from a WWTP with biological phosphorus removal. The technology is based on controlled chemical crystallisation in an up-flow fluidised bed reactor with multiple reactive zones of increasing diameters. The controlled crystallisation is achieved by a combination of magnesium dose, pH control and by means of a treated effluent recycle. The chemicals used for precipitation and the pH adjustment are $MgCl_2$ and $NaOH$, respectively.

Per Desmidt et al. (2015), advantages of the Ostara Pearl® process include:

- Provides better particle size classification than a typical single diameter fluidised bed reactor, thereby allowing large struvite pellets from 1.5 to 4.5 mm in diameter to be kept in suspension in the bottom of the reactor without washing out fine crystal nuclei from the top of the reactor.
- Filters and dries struvite up to 92% dry solids
- Allows for a high-quality struvite product for sale in premium markets

Drawbacks of the technology, however, include:

- Large footprint
- Requires large reactor sizes
- High maintenance costs associated with struvite processing units

Side-stream with low phosphorus concentration (≤ 10 mg/ℓ PO_4^-P) is considered not economically feasible for struvite production (Nieminen, 2010). The feasibility limit is 20-30 mg/ℓ PO_4^-P, but preferably ≥ 60 mg/ℓ PO_4^-P.

The Ostara Pearl process typically removes 85-90% of the phosphorus from the sludge dewatering liquid (Desmidt et al., 2015). The Ostara Pearl® reactor has been implemented in commercial scale in Edmonton, Canada, Durham, Virginia and Oregon in the United States. The Ostara's Pearl reactor installed at the HRDS Nansemond WWTW in Virginia recovers excess nutrients to help mitigate blockages in the digested sludge pipelines. The full-scale facility extracts up to 85% of the excess phosphates, as 1 650 kg/d high-quality struvite, when operating at a maximum capacity of 416 m^3/d (Sikosana et al., 2017).

Considering the need for integration of biological phosphorus removal into recovery systems to enhance recovery efficiency, technologies are being developed and incorporated as a step into the recovery process for phosphorus release from the biomass (Oleszkiewic et al., 2015). One of the most popular and widely applied technologies for phosphorus release is WASSTRIP. WASSTRIP stands for **W**aste **A**ctivated **S**ludge **STRIP**ping. To further optimise the performance of the Ostara process, it can be combined with the WASSTRIP (Figure 2-8). This can be implemented by sending the excess activated sludge or WAS of a wastewater treatment plant to the anaerobic reactor where phosphorus and magnesium are released (stripped) by the micro-organisms as a consequence of endogenous respiration and fermentation.

Details on WASSTRIP can be found in Desmidt et al. (2015). The combination of the WASSTRIP and the Ostara process has been implemented on a commercial scale at Durham WWTW, Tigard, Oregon, USA and reported to yield a higher struvite production while preventing scaling in the digester and the dewatering apparatus (Schauer, 2012).

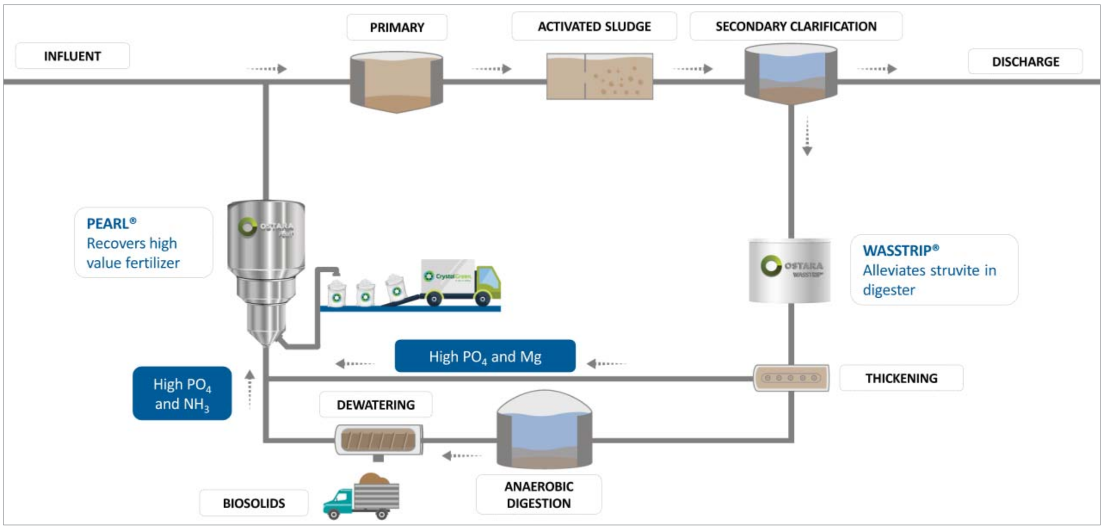

Figure 2-8: Synergistic use of the Ostara + WASSTRIP processes (Clark, 2017)

2.4.2.3 Multiform Harvest™

Multiform Harvest™ technology was initially designed to treat agricultural waste streams, but later extended to municipal wastewater treatment. The technology comprises a conical shaped fluidised bed reactor into which wastewater is pumped for phosphate recovery in the form of struvite (Figure 2-9). It is characterised by a short retention time with no recycle stream. The recovery process is achieved via the addition of magnesium chloride and pH adjustment by caustic solution. The technology is applicable to wastewater supernatant streams such as centrate or filtrate, and could also be integrated into WWTWs using P-release processes on WAS digestion (Oleszkiewic et al., 2015).

The Multiform™ technology has been implemented at full scale majorly in the United States, and precisely at the Yakima and Boise WWTWs located in Washington and Idaho respectively.

The Multiform Harvest™ process at the Yakima WWTW – a 75 Mℓ/day AS plant with AD comprised two reactors with no recycle and a short retention time, operating at 832 kℓ/day and producing a low quality, sand like struvite of about 453 kℓ/day; recovering up to 90% of the influent phosphorus. The construction costs and the final design costs of the Multiform plant was approximated $735 000 and $80 00 respectively, while the operational costs were estimated to be $25 000/year for chemicals and $1 200/year to meet power requirements for pumping. Maintenance costs comprised cleaning chemicals ($1 500/year) and others estimated to be $600 /year (Oleszkiewic et al., 2015).

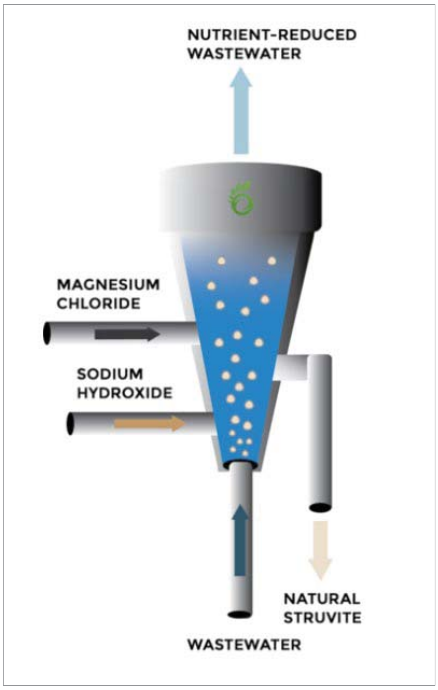

Figure 2-9: Multiform Harvest™ struvite reactor (Multiform Harvest, 2015)

Comparative analysis of Ostara® and Multiform™ on the Cape Flats WWTW, South Africa

Sikosana et al. (2017) conducted a technological and economic pre-feasibility of phosphate recovery at Cape Flats WWTW – a centralised sewage treatment plant located in Cape Town, South Africa. Two options for phosphate recovery (high-grade versus low-grade struvite) were compared to conventional phosphate removal by chemical precipitation using metal salts. The high grade and low-grade struvite was implemented using Ostara process and Multiform Harvest™ respectively. However, the low-grade and high-grade struvite production implementation costs were 10 and 25 times higher when compared with the more familiar, yet less sustainable, chemical precipitation process. In addition, the results revealed that the low-grade struvite production has the potential to produce approximately 470 kg/d of struvite fertiliser, whilst recovering 4-8% of the plant's costs in 20 years from the digesters stream at the 200 Mℓ/d plant.

Although the low-grade struvite production (Multiform Harvest) proved to be the technically more feasible and economically more affordable option from a lifecycle-costs perspective, both technologies were however said to be characterised by high CAPEX and can only be more feasible if implemented on streams with high phosphate loading. In the case of the Cape Flats WWTW, it was also noted that struvite sales cannot recover the facilities operating costs. Analysis show that the operating costs would be significantly higher than the achievable revenue, resulting in a net present cost of R42.3 million for a 20-year period. Consequently, it was concluded that nutrient recovery at the plant would not be economically viable.

2.4.2.4 AirPrex®

AirPrex® is a sludge optimisation process that is installed in between anaerobic digestion and dewatering; recovering high-phosphate mineral struvite (Figure 2-10). The technology involves passing digested sludge through a cylindrical reactor with an inner cylindrical zone mixed by air upflow and a settling zone between this inner cylinder and the outer cylinder. Due to the air bubbles, the sludge is lifted upward in the aerated zone in the middle of the reactor. After reaching the surface, the sludge settles in the tranquil zone in the outer part of the reactor (Desmidt et al., 2015). The boundary conditions for struvite precipitation are thus set by air stripping in the AirPrex® reactor and the addition of a magnesium chemical product. This combination of biological phosphate elimination and the AirPrex® system leads to a 90-95% phosphate reduction in the returned liquor (up to 15% related to the incoming P-load). The optimisation of the sludge and removal of a significant amount of the phosphate before dewatering mitigates the water bounding effect of the phosphate is mitigated before dewatering, thereby ensuring a more efficient dewatering process, and less polymer is required, translating to higher cost savings (CNP, 2017).

Advantages of the AirPrex® technology include:

- Reduced disposal costs by up to 20%
- Reduced polymer consumption by up to 30%
- Reduced maintenance costs by up to 50%
- Allows for generation of high quality struvite

Three full-scale AirPrex® plants are currently operational; two in Germany and one in the Netherlands. In these plants, 80-90% of the phosphate is removed from the liquid phase of the digested sludge as struvite. One of the WWTWs (Mönchengladbach WWTW, Germany) achieved phosphate removal of 90% and regularly resells its high-phosphate fertiliser. The plant's dewatering rate improvement has surpassed 4%; saving more than $850 000 per year in operational costs, as compared to P-removal by means of Ferric chloride (CNP, 2017).

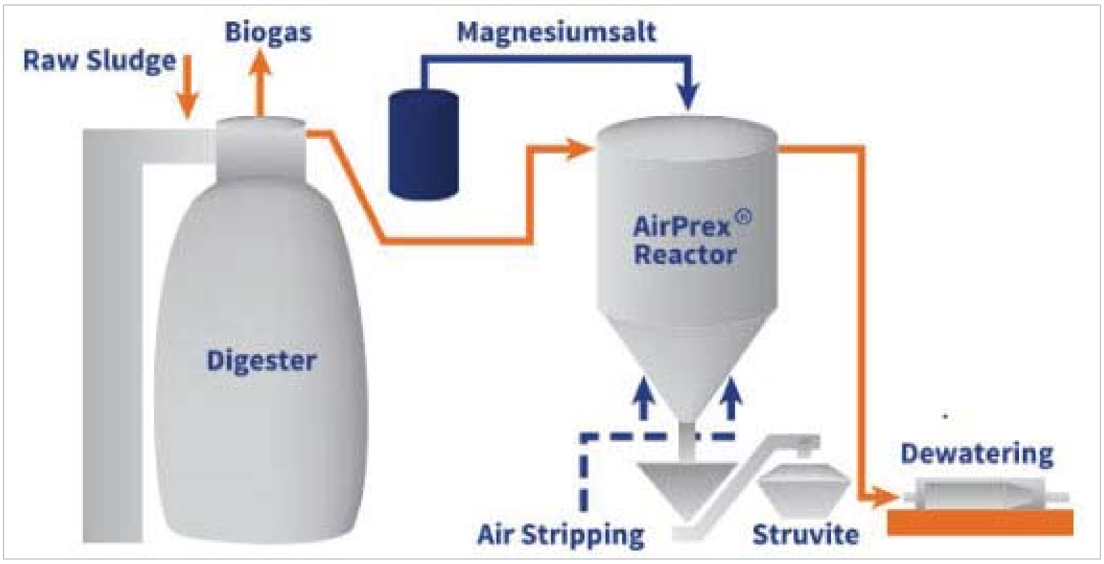

Figure 2-10: AirPrex® process description

2.4.2.5 CalPrex™

CalPrex™ is a calcium phosphate recovery technology process that solubilises sludge's phosphorus and recovers it as brushite, a plant ready fertiliser that can be used without further processing. CalPrex™ works by precipitating dissolved phosphorus in the centrate. The precipitation of the dissolved phosphorus is caused by the addition of calcium hydroxide and calcium chloride. By maintaining the pH of the solution at 6.5, phosphorus is recovered as a brushite crystal ($CaHPO_4 \cdot 2H_2O$).

Benefits of the Calprex™ technology include (CNP, 2016):

- Reduces digester struvite build-up by diverting over 50% of the soluble P from the digester
- Compact footprint
- Reduce 90% of the soluble P in the CalPrex™ reactor
- Reduce up to 50% of the Total P in Biosolids
- Recovers P from non-Bio-P plant
- Recovers P from No/Low ammonia system
- Offers lower chemical cost per P recovered
- Offers lower chloride addition per P recovered

The brushite recovery process perfectly complements CNPs AirPrex® struvite recovery technology. When combined, CalPrex™ + AirPrex® has the potential to offer treatment plants with the significant phosphorous recovery option

2.4.2.6 Crystalactor®

The Crystalactor® is a fluidised-bed type crystalliser for the selective removal and recovery of components from water and wastewater. The Crystalactor® was developed by Royal HaskoningDHV in the Netherlands and has been used since the 90s to recover phosphate from wastewater treatment plants. The Crystalactor® employs four conventional treatment processes including coagulation, flocculation, separation and dewatering; combining them into one.

The chemistry of the process employed in the Crystalactor® is similar to conventional precipitation, involving the dosing of a calcium or magnesium salt (e.g. lime, calcium chloride, magnesium hydroxide, magnesium chloride) to the water. Hence the solubility of the salts is exceeded and subsequently phosphate is transformed from the aqueous solution into solid crystal material. The primary difference with conventional precipitation is, that in the crystallisation process the transformation is controlled accurately and that pellets with a typical size of approx. 1 mm are produced instead of fine dispersed, microscopic sludge particles (Piekama and Giesen, 2001), thereby eliminating troublesome and costly sludge dewatering (Figure 2-11).

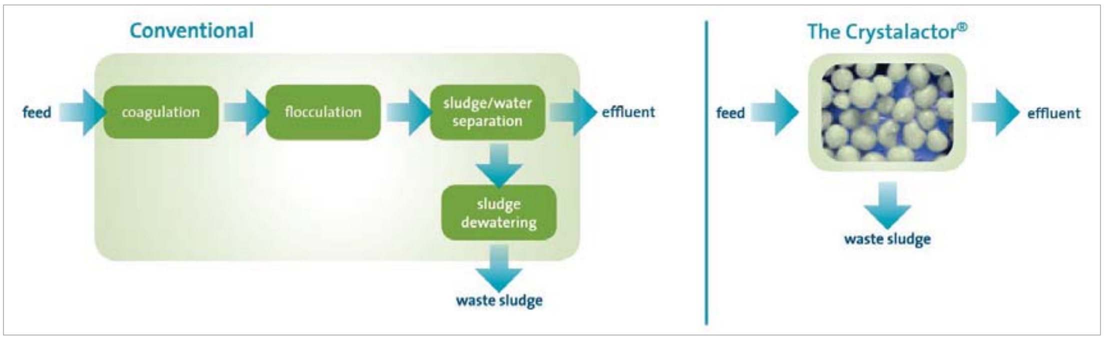

Figure 2-11: Overview of the Crystalactor® process

Depending on the pH and the calcium or magnesium dosage rate, phosphate can be removed from the wastewater down to low concentration levels. In side streams, the combination of the Crystalactor® with biological phosphorus removal renders the phosphorus concentration in the final effluent negligible (Piekama and Giesen, 2001).

This process generates high purity phosphate crystal pellets that allows for re-use rather than bulky sludge generated in conventional phosphate precipitation processes. Details on the working principle of the Crystalactor® can be found in Piekama and Giesen (2001). Major advantages of the technology include:

- Compact installation due to surface loadings of 40-120 m/h
- Offers a cost-effective solution due to relatively low capital and operational expenditure
- Produces no residual waste thereby avoiding bulky sludge disposal
- Produces reusable phosphorus pellets with a high purity
- Produced pellets have extremely low water content (5-10% moisture)
- Phosphate recovery rate can reach 70-80%

The first full-scale application was realised at the Westerbork municipal wastewater treatment plant, The Netherlands in 1988. Phosphate was recovered by crystallisation of calcium phosphate in the effluent of the biological treatment, followed by filtration. The plant operated successfully and removed phosphate from 10 mg/ℓ P (in effluent of biological treatment) to below 0.5 mg/ℓ P (Sikosana et al., 2015). The pellets were re-used by the phosphate processing industry.

The Crystalactor® technology is well established in a range of different applications and is endorsed in Southern Africa from system selection through to full plant engineering and operation (Giesen et al., 2009). The Crystalactor® technology was employed to treat (soften) high calcium underground dolomitic water to potable water standards (SANS 241) at the Sibanye Gold. The aim was to use the treated water to replace fresh water supply from Rand Water. The project demonstrates a good business case for the Crystalactor® with relatively low operating and maintenance (O&M) costs and short payback period for the plant; offering a 50% cost saving on pay per use basis.

2.4.2.7 Phospaq™

The Phospaq™ process, developed in the Netherlands, is applied to recover phosphate from effluents as struvite. The process occurs in an aerated continuous stirred tank reactor (CSTR). The process removes biological degradable COD, phosphate (PO_4^{3-}) and ammonium (NH_4^+) from wastewater. With oxygen, the COD is biologically converted into new biomass and CO_2. By adding magnesium oxide (MgO), phosphate and ammonium precipitate as struvite ($MgNH_4PO_4 \cdot 6H_2O$). This occurs at a pH of 8.2 to 8.3 (Paques, 2017). The CSTR is equipped with separators that retain the struvite which is thereafter harvested from the bottom of the reactor by means of a hydro cyclone, followed by a screw press and conveyed into a container. The dry weight of the harvested struvite is around 50% and the crystals have an average size of around 0.7 mm. The average phosphate removal efficiency is about 80% (Desmidt et al., 2015).

The advantages of Phospaq™ include:

- Combined phosphate- and COD-removal in one reactor
- Aeration provides the oxygen for the biological conversion of COD
- Aeration provides optimal conditions for struvite formation
- Stripping of carbon dioxide raises the pH and stimulates struvite precipitation
- Good struvite quality

The Phospaq™ technology is feasible under the following operating conditions:

- Load: >100 kg P/d
- Concentration: 50 mg/ℓ PO_4^-P

2.4.2.8 NuReSys™

NuReSys™ stands for **Nu**trient **Re**cycle **Sys**tem. The system offers a technology that allows for recovery of phosphates and nitrogen from wastewater and makes it available as struvite. The NuReSys™ process is operated in two reactors. In 2006, the first NuReSys™ plant was designed; operating at a capacity of 120 m³ per hour in a dairy plant, 24 hours 7 days a week. The second plant was started up early 2009 and treats 60 m³ per hour at a potato processing plant in Belgium. Removing (and recovering) P with the NuReSys technology is economically viable starting with a concentration of 40/45 ppm $PO_4^- P$.

In 2013, the NuReSys™ technology was applied on digested sludge at a municipal wastewater treatment plant in Belgium. The digested sludge contains 5-6% suspended solids. The concentration of $PO_4^- P$ was reduced from 220 mg PO_4^-P/ℓ to 30 mg PO_4^-P/ℓ; signifying 86.4% recovery. Similar phosphate recovery rate was recorded in the Netherlands (95%) when applied on centrate generated at a municipal wastewater treatment plant in 2015 (NuReSys, 2017).

2.4.2.9 Seaborne process

The Seaborne process involves a network of unit operations for recovering nutrients from various biomasses such as sludge. The Seaborne process comprise three major stages which include (i) acid leaching; (ii) removal of heavy metals or organic pollutants; and (iii) struvite precipitation. The initial process step involves an acidification of the sludge by the addition of sulphuric acid; resulting to dissolution of the solids and release heavy metals and nutrients. The remaining solids are separated from the flow using a centrifuge and a filter system which thereafter undergoes drying and incineration. There is also a step which allows for stripping of excess ammonium removing NH_3 / NH_4 from the liquid phase.

The Seaborne process was first implemented at full-scale at the Gifhorn WWTW in Germany. The flowchart for the process at Gifhorn WWTW is presented in figure below. The recovery efficiency of the Seaborne process is about 50% (Sikosana et al., 2015).

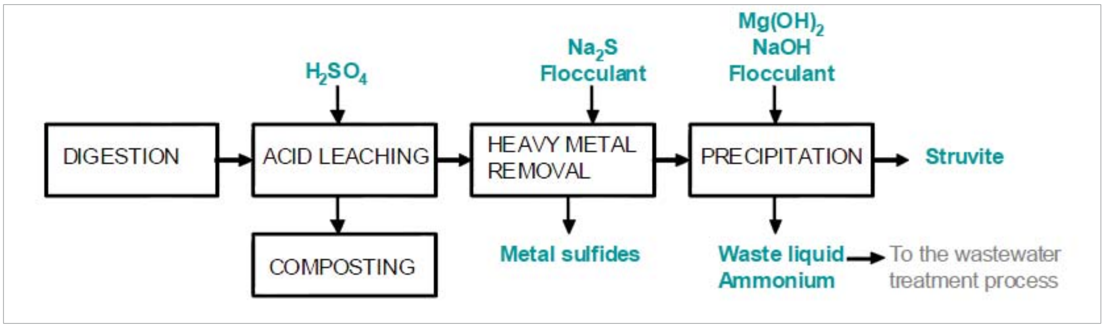

Figure 2-12: Flowchart for the Seaborne process at Gifhorn (Adapted from Nieminen, 2010)

There are other technologies or processes used for nutrient recovery in side-steams, however, due to limited space, only the popular ones are discussed in this study. Other technologies or processes available in the market include Phosnix, Thermophos, VitAG, Neutralizer®, among others. A full description of the technologies can be found in the extended report WRC Report No. TT 661/16 authored by Sikosana et al. (2015).

2.4.2.10 Comparison of different phosphorus removal technologies

It is difficult to select the most suitable technology for use as the technologies reviewed provide a wide variety of struvite quality which ranges from very low to premium grade. Notwithstanding, considering that South Africa has a potentially larger market for lower grade struvite, preference should be given to technologies that offer lower struvite quality to align and satisfy the market demands.

2.4.3 Potential applications for recovered nutrients and cost benefit analysis

2.4.3.1 Final end-products and possible applications/market

Phosphorus can be recovered from side streams and sludge via crystallisation-based processes either as calcium phosphates or as magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$ – also known as struvite).

A. Calcium phosphate

Calcium phosphate is an attractive form of recovered phosphorus because it is directly comparable to phosphate rock (Nieminen, 2010). In general, calcium phosphate can be easily used as raw material for the phosphate industry – for production of phosphoric acid or for cattle food (Desmidt et al., 2015) and in principle, phosphate pellets could be reused either directly (brushite) or after processing by fertiliser (Giesen et al., 2009; CNP, 2016).

B. Struvite

Struvite comprises two primary nutrients – phosphorus and nitrogen, and secondary nutrient magnesium as well as low concentrations of heavy metals and other pollutants (Sikosana et al., 2015). Struvite is thus considered as beneficial to the fertiliser industry as a slow release fertiliser (Nieminen, 2010). Kern et al. (2008) evaluated the uptake rates of nutrients from struvite derived from sewage sludge; using maize and wheat as test plants. A phosphorus uptake of 66.7% and 85.9% was reported, respectively; proving struvite recovered from upgraded sewage sludge as an effective phosphorus fertiliser.

Struvite can also be used as a cost-effective replacement of industrial grade phosphate, when the formation and collection are controlled. Sikosana et al. (2015) summarised market routes for struvite use to include:

- Replacement for secondary phosphate ore;
- Industrial grade phosphate;
- Slow release fertiliser;
- Animal feed additive;
- Fire proof agent and cement adhesive.

2.4.3.2 Market values/ cost-benefit analysis

Full scale implementation of nutrient recovery technologies from wastewater requires proper economic and social feasibility to ensure that, irrespective of technical benefits, the selected technology is technically and economically viable.

- Benefits that can be derived from the implementation of nutrient recovery technologies have been highlighted by Molinos-Senante et al. (2011) to include the following:
- Reduction in chemical costs of wastewater generation due to reduced sludge generation;
- Less landfill area requirements for sludge disposal;

- Improved operation and performance of wastewater treatment plants;
- Offers potential for energy savings
- Reduced maintenance costs at wastewater treatment plants as potential for scaling of pipes and pumps via struvite precipitation reduces;
- Provides a platform for implementation of sustainable development goals by improving environmental quality and fostering food security and social equity via the use of struvite as fertiliser to increase crop yield.

Despite these benefits, research has shown that there are no economic incentives for implementing phosphorus recovery technologies in the wastewater sector as the recovered phosphorus cannot compete with the relatively low cost of phosphate rock (i.e. mined phosphorus) (Mayer et al., 2016). Molinos-Senante et al. (2011) reports the cost of recovering phosphate with wastewater treatment to range from 2 € (R30) to 8 € (R115) per kg of phosphorus, depending on recovery conditions. Rock phosphate prices in the United States were reported at between $35 (R450) and $50 (R643) per ton depending on the purity. These values evidently show that the cost of recovering phosphorus from wastewater is significantly higher than the market price of rock phosphate. Furthermore, mined phosphate rock accounts for approximately 90% of global agricultural food production (Mayer et al., 2016). A study of three technological options (Ostara, Multiform Harvest and conventional chemical precipitation) also shows that the current phosphate market price in South Africa is too low to offset the costs of phosphate recovery (Sikosana et al., 2017).

Mayer et al. (2016) in a comprehensive review opined that implementation of phosphorus recovery and reuse requires an approach that involves total value recovery at local, national, and international scales. The author highlighted that for nutrient recovery to be economically feasible, focus should not be directed solely on technological improvements in wastewater treatment. Technologies must be designed with a focus on the end products and enhancement of total value recovery rather than only s single phosphorus product. The authors submit that *"…P removal alone or recovery of only a single product, for example, struvite, will not improve the economics sufficiently"*. The coupling effective pre-treatments with anaerobic biotechnology such that soluble P is released while simultaneously enhancing energy capture is considered as an approach that offers great promise. For example, a pre-oxidation step offers multiple advantages of mineralising P and N, increasing energy capture, releasing metals from complex wastes, and inactivating pathogens.

The new total recovery paradigm encompasses the following:

- Recovery of phosphorus incorporated in sewage sludge itself
- Recovery of renewable energy (e.g. methane or hydrogen) from waste biomass from P-containing streams
- Recovery of metals and minerals such as K, Ca, Mg, Fe, Ag, Cu, Au, Mn, Zn, Cr
- Recycling and reuse of treated wastewater for non-potable uses, e.g. irrigation or ground water recharge and recreational uses

A number of business models have been developed for resource recovery from wastewater. Based on a quadrant analysis, Mayer et al., 2016 categorised South Africa into quadrant 2 – countries practising considerable water reuse, generally on the basis of need (water stress). Another analysis places South Africa amongst nations that embrace crystallisation technologies as the commonly preferred phosphorus recovery technology as they are based commonly preferred based on cost and energy considerations. Details on business models and system-level assessment tools available for financing phosphorus recovery and cost-benefit analysis can be found in the literature (Mayer et al., 2016). It is therefore necessary to conduct a detailed research that will identify the trade-offs between environmental and economic impacts of a selected technology while also incorporating social impacts.

2.4.3.3 Legal requirements for commercialisation

Research has shown that there is potentially larger market for lower grade struvite in South Africa, with struvite being recognised as a possible replacement for rock phosphate derived fertilisers (Sikosana et al., 2017). Sikosana et al. (2017) in their study reports that despite health and safety concerns, it is likely that struvite will pass toxicity, pathogen and metal content regulation and be comparable to most phosphate fertilisers on the market based on quality. However, asides the need for the identification of trade-offs between techno-economic and social factors (as identified in Section 2.4.3.2), it is important to add that there are currently no South African policies on organic agriculture or certification to position the South African organic market and consumers for the adoption of the end products of phosphorus recovery, e.g. fertilisers produced from sewage (Sikosana et al., 2015). However, the common interest towards the phosphorus recovery in developed economies such as Europe has arisen, and some countries have launched national goals to promote the matter (Nieminen, 2010).

For South Africa to be positioned for full-scale implementation of phosphorus recovery techniques, the following actions need to be taken:

- Putting in place regulations that focus on phosphorus recovery and reuse from waste
- Build governance structures that explicitly addresses long-term phosphorus management
- Promotion recovery of multiple products from sewage sludge
- Encourage trade and use of wastewater-derived products such as struvite by classifying them as recovered products rather than wastes
- Increase competitiveness of wastewater products and promote total value recovery
- Development of national support mechanisms for cost sharing, for example, a fair and equitable distribution of the costs of phosphorus recovery, financing of locale-specific innovations, and market adoption of existing technologies at scale (Mayer et al., 2016)
- Investigate the potential of incorporating N and P recycling early in the process, using techniques such as urine source separation
- Increase public acceptance of materials recovered from waste, including total value of phosphorus recovery, via awareness initiatives

2.5 Design models

Modelling of wastewater treatment processes are well-established as their use enhances the design and operational performance of unit processes within WWTW while also ensuring that plant managers comply with discharge regulations. This section provides a review of existing models used for design and optimisation of operational performance of WWTWs. The focus of this review is on models that have found wide application within the South African context. These models include the IWA AS models, BioWIN, WEST, Plant-Wide Steady-state Model, STOAT, among others.

2.5.1 IWAQ AS and AD models

The IWAQ AS model is a generalised dynamic model of the activated sludge process developed by the International Association of Water Quality (now IWA) Specialist Group and has been notably applied in many countries of the world including South Africa.

The IAWQ AS Model No. 1 – ASM1 can be considered as the reference model as it was the first model to be developed by IWA. ASM1 also received the general acceptance of WWTW modelling, both in the research community and in industry (Gernaey et al., 2004). ASM1, developed in 1987 (Henze et al., 1987), is a bi-substrate model essentially developed for the carbon oxidation process; covering carbonaceous oxidation, nitrification and denitrification. In addition, the model is targeted at yielding a good description of the sludge production, with COD adopted as the measure of the concentration of organic matter (Saleh, 2014). ASM1 has become a reference for many scientific and real-world projects *"and has been implemented (in some cases with modifications) in most of the commercial software available for modelling and simulation of WWTWs for N removal"* (Gernaey et al., 2004).

ASM3, which was developed in 1993, offers an improvement on ASM1 in terms of a storage polymer process in the heterotrophic AS conversion. A second difference between ASM1 and ASM3 is the conversion of the circular growth-decay-growth model, often called death-regeneration concept, into a growth-endogenous respiration model, thereby allowing for easy calibration than the ASM1 model (Gernaey et al., 2004). ASM3 have also been found to have performed better than ASM1 in conditions where the storage of readily biodegradable substrate is significant (i.e. industrial wastewater) or for WWTWs with substantial non-aerated zones (Koch et al., 2000).

AS Model No. 2 – ASM2 and ASM2d shares similar characteristics with Model No.1 as they were both developed to extend the capabilities of ASM1. ASM2 (developed in 1995) has biological phosphorus removal added to it, while ASM2d builds on ASM2, with the addition of the denitrifying activity of PAOs for a better description of the dynamics of phosphate and nitrate (Gernaey et al., 2004).

AD Model No. 1 – ADM1 was developed by IWA as a unified modelling framework for anaerobic digestion (Batstone et al., 2002), and is currently being used as a benchmark AD model (Haile et al., 2015). The capabilities of the model include:

- Ability to simulate both sewage sludge and industrial systems that have different organic feed characteristics.
- Provision of an environment to simulate the effect of different operating parameters (e.g. pH, temperature and mixing) on the performance of a digestion process.
- Allows for improved computational efficiency during simulation especially in terms of numerical stability and computational speed

Drawbacks of ADM1, reported by Batstone et al. (2006) and cited in Haile et al. (2015), include:

- Poor connectivity between the measurement and modelling domains
- Absence of mineral precipitation, as the model comprise only two phases – aqueous and gas
- Inaccurate prediction of digester pH when mineral precipitation occurs
- Non-inclusion of the limitations of high H_2 partial pressure on acid forming bacterial groups

These drawbacks result in model inadequacy with regards to simulation of process failure typical of dynamic conditions, necessitating the need for model improvement.

Despite the wide application of the IWA AS and AD models, some limitations with respect to their use have been identified. One of the drawbacks is based on the fact that the models were developed independently; leading to two distinct developments. In an extensive review conducted by Wu (2015), it was noted that due to the isolation caused by the two distinct developments, the AS and AD models incorporate different variables; resulting to incompatibilities when coupling them. The incompatibility of these models in turn results in inefficiency and added difficulty in an entire WWTW 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. To surmount these challenges, the need for integration of the AS and AD models was identified for modelling of an entire WWTW.

2.5.2 BioWIN

BioWin is a wastewater treatment process simulator that incorporates biological, chemical and physical process models. BioWin is used world-wide to design, upgrade and optimise wastewater treatment plants of all types. The core of BioWin is the proprietary biological model which is supplemented with other process models, e.g. water chemistry models for calculation of pH, mass transfer models for oxygen modelling and other gas-liquid interactions (Envirosim, 2017).

The modules underlying the BioWin user interface are sedimentation models (both primary and secondary) and a comprehensive biological process model (Copp, 2001). BioWin uses an extended version of ASM1 for its biological model. This extended model includes several additional features including biological phosphorus removal, but the BioWin user is able to choose between the full 'CNP' (carbon, nitrogen and phosphorus) model and a reduced version of the model that includes only the carbon and nitrogen removal processes: the 'CN' model.

2.5.3 WEST

WEST stands for Wastewater Treatment Plant Engine for Simulation and Training. WEST is a universal dynamic modelling and simulation package which offers a platform that can, "together with a model base", be used for the task of specifically designing, operating and optimising biological wastewater treatment systems (Vanhooren et al., 2003). The model base in WEST plays a significant role as it describes models in a high-level object-oriented declarative language (MSL – model specification language) which allows for model integration. The model base thus allows for maximum re-use of existing knowledge such as mass balances, default parameters and appropriate ranges. As a result, the model base characterises WEST with an open structure and a user-friendly platform which allows users to use and edit existing models as well as define and test new ones. More details on WEST can be found in Vanhooren et al. (2003) and MIKE (2017).

Dynamic models such as WEST have however been criticised for lacking the capability of designing or sizing the steady state system or determining the capacity of an existing system. They generally require an existing plant design/configuration with all reactors sized, the flow rates quantified, and the influent wastewater characterised in order to initiate any form of simulation (Wu, 2015).

2.5.4 The plant-wide steady-state model

Research has identified the need for a plant-wide model for integrated modelling and design of WWTWs (Haile et al., 2015; Wu, 2015). Unit processes in most of the current models are designed separately, with processes being treated as separate individual units. Upstream processes 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 does not have an integrated cost estimation and optimisation component which can act as a pre-processor to address the challenges of dynamic simulation models such as WEST. 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.

The challenges identified with the use of the IWA and dynamic models has led to the development of a plant-wide steady-state design program that can *"fulfil the missing functionalities of the dynamic simulation software and complement the dynamic models"*, while also making the modelling of WWTWs easier and more efficient (Wu, 2015).

The plant-wide model adopts a mass balance approach which allows for modelling of an entire WWTP. As presented in a WRC Report No. 1620/1/11 by Ekama et al. (2011), the plant-wide model is an integrated WWTW model which incorporates primary sedimentation, activated sludge, nitrification, denitrification, biological excess phosphorus removal, aerobic and anaerobic digestion of primary sludge and/or and waste activated sludge, sludge dewatering and dewatering sludge liquor (N and P) recycling. The plant-wide model was initially developed for modelling of wastewater constituents in terms of carbon (C), nitrogen (N), oxygen (O), hydrogen (H) and total oxygen demand (TOD) but was subsequently extended to include phosphorus (P). Computing a mass balances for these elements, their proportions in the influent and effluent can be tracked throughout the WWTW. According to the WRC report, the plant-wide model is completely general and can accommodate any realistic influent wastewater characteristics and unit operation design conditions. This justifies the selection of the plant-wide model for use in this study.

2.6 Literature Review Conclusion

This literature review forms part of a research undertaken to investigate the impacts of sludge return liquors on wastewater treatment plants in South Africa. The review is therefore aimed at exploring the best available technologies around the world to successfully treat side-streams, some of which create potentially reusable end products. The review also included an appraisal of existing models used for design and optimisation of operational performance of WWTWs.

Findings show that, even though recycling of sludge liquors is increasingly becoming a widely accepted practice in majority of South African WWTWs, there is still a lack of knowledge on its implications on the treatment plants. No doubt, the impacts of sludge liquor recycling places additional load on the treatment process, however most treatment plants do not have the extra capacity required. The end result is an overload of the system and hence non-compliances with regulations. It is also worthy to note that if recycled side-streams are untreated and anaerobic digestion optimised, an increase in aeration energy demand, typically between ± 10% to ± 20% should be expected when compared with a situation where the recycle of return liquors are treated on a side. Solutions in this respect include reconfiguration and upgrade of treatment processes and review of aeration energy demand as well as implementation of viable nutrient recovery technologies.

With reference to nutrient removal/recovery, this study shows that the benefits inherent in side-stream treatment outweigh those offered by conventional methods. Although crystallisation approaches have been tested and proven to be technically capable for nutrient recovery from side-streams, singular focus on struvite or phosphate recovery (considering its relatively low market price) has impeded the economic and social viability of most full-scale solutions. There is a need to look beyond the sole concept of struvite/phosphate recovery and embrace a "total value recovery" paradigm which seeks to maximise the benefits and resources inherent in wastewater treatment as a whole, thereby enhancing its feasibility from techno-economic and social perspectives. Information on legal requirements for commercialisation of resource recovery technologies from wastewater have also been provided to ensure successful full-scale implementation in South Africa.

This literature review therefore provides information on the impacts on return liquors on WWTWs and optimisation measures to reduce the nutrient loads on overloaded treatment plants in South Africa. It also provides techno-economic and social approaches to maximising the benefits inherent in the treatment processes especially as it relates to resource recovery.

CHAPTER 3: IDENTIFICATION AND DESCRIPTION OF CASE STUDIES

This section contains the findings from desktop and on-site analysis of six wastewater treatment plants located within key provinces of the country. The impacts of return liquors on each plant, as well as recommendations for improved operations and management of treatment processes at the selected plants, and in general, at various South African wastewater treatment plants are described.

3.1 Plant Selection

Six WWTPs located in South Africa were selected for use as a case study. Four WWTPs have been selected from Gauteng (two plants) and KwaZulu-Natal (two plants), as well as one WWTWP in the Eastern Cape and one in the Western Cape. These plants were selected based on their relevant treatment capacity, treatment processes and importance of the involved municipalities.

3.1.1 Selection criteria

Key requirements considered in the selection of plants are provided below.

- Availability of sludge digestion and dewatering sludge return liquors recycled back to the treatment
- Biological nutrients (N and P) removal
- Design information regarding sizing of the main process units (biological reactors and digesters) and duties of main equipment
- Availability of reliable flow measurements and analytical data for the process steps in general and in particular for sludge return flows
- System complexity
- Variability of the plant's capacity
- Information on technical performance of the plant

3.1.2 Selected plants

Details on the plants selected as case study in this research are presented in Table 3-1.

Table 3-1: Selected plants used as case study for the impacts of return liquors on SA WWTWs

WWTP	Design capacity	Type of treatment	Effluent standards	Location
'Z'	85 Mℓ/d	Primary treatment BNR reactors Disinfection Sludge thickening Anaerobic digestion Dewatering Side-stream chemical precipitation	COD = 50 mg/ℓ TSS = 10 mg/ℓ NH_4 =1 mgN/ℓ $NO_3 + NO_2$ = 6 mgN/ℓ PO_4 = 0.1 mgP/ℓ	Gauteng
'W'	170 Mℓ/d	Primary treatment BNR reactors Disinfection Sludge floatation Anaerobic digestion Dewatering	COD = 70 mg/ℓ TSS = 20 mg/ℓ NH_4 = 4 mgN/ℓ $NO_3 + NO_2$ = 9 mgN/ℓ PO_4 = 0.7 mgP/ℓ	Gauteng
'K'	80 Mℓ/d	Primary treatment Trickling filters BNR reactors Disinfection Sludge floatation and thickening Anaerobic digestion Dewatering	COD = 75 mg/ℓ TSS = 25 mg/ℓ NH_4 = 6 mgN/ℓ $NO_3 + NO_2$ = 15 mgN/ℓ PO_4 = 10 mgP/ℓ	KwaZulu-Natal
'P'	25 Mℓ/d	Primary treatment BNR reactors Disinfection Anaerobic digestion Dewatering	COD = 75 mg/ℓ TSS = 25 mg/ℓ NH_4 = 6 mgN/ℓ $NO_3 + NO_2$ = 10 mgN/ℓ PO_4 = 10 mgP/ℓ	KwaZulu-Natal
'C'	200 Mℓ/d	Primary treatment BNR reactors Sludge thickening Anaerobic digestion Drying beds	COD = 75 mg/ℓ TSS = 25 mg/ℓ NH_4 = 10 mgN/ℓ $NO_3 + NO_2$ = 10 mgN/ℓ PO_4 = 1 mgP/ℓ	Western Cape
'D'	9 Mℓ/d	BNR reactors Disinfection Sludge lagoon	COD = 65 mg/ℓ TSS = 18 mg/ℓ NH_4 = 8 mgN/ℓ $NO_3 + NO_2$ = 15 mgN/ℓ PO_4 = 1 mgP/ℓ	Eastern Cape

3.2 'Z' Wastewater Treatment Works

The 'Z' WWTP is located in Pretoria North. It lies north of Roodeplaat Dam (refer to Figure 3-1). The plant treats primarily domestic wastewater and some industrial wastewater. The works are owned and operated by the City of Tshwane Metropolitan Municipality (CoT).

In phase 1 of construction the plant (module 1) was designed to treat 30 Mℓ/day using two biological nutrient removal (BNR) reactors, its' start-up was made in June 1990. Due to the lower than initially expected raw sewage concentrations, the current maximum capacity of module 1 is up to 45 Mℓ/day. In phase 2, an additional 40 Mℓ/day module (module 2) was started-up in June 2014, to increase the overall capacity of the works to 85 Mℓ/day.

Phase 3 of construction was planned and designed, but the implementation is currently on-hold. This phase will implement a tertiary level of treatment with additional final settling tanks, chemical precipitation of phosphorous with metal salts and filtration.

Figure 3-1: Aerial view of 'Z' WWTP (Google Earth, 2016)

3.2.1 *Process Description*

A description of the works is indicated below, as per information collected from the Golder Associates Report dated 2007 and from the mechanical operation and maintenance manual available on site. The general process flow diagram of the treatment works is provided in Figure 2 of Appendix 1:

- Inlet works consists of:
  - Three mechanical front raked coarse screens (8 mm) and one manual screen on standby for the overflow.
  - Five vortex degritters.
  - Splitter box to divide the flow per two modules.

  - Fine rotary drum screens (3 mm) upstream of the PSTs (one screen for module 1 and two (duty/standby) for module 2).

- Module 1 consists of:

  - Four PSTs (22 m diameter).
  - PS is not wasted in the PSTs, rather these units are operated as fermenters. The PSTs are on a 4-day retention cycle, where one of the four PSTs pumps the fermented sludge to the balancing tank. There is an option to pump the sludge directly to the biological reactors, digesters or fermenters.
  - Balancing tank (5 000 m^3).
  - Two biological reactors including nitrogen and phosphorus removal (19 575 m^3 each) including 18 compartments divided in 5 anaerobic, 5 anoxic and 8 aerobic zones. Nitrates are recycled with 6 duty a-recycled pumps. Reactors are aerated with fine bubble diffusion and there are 3 duty/1 standby blowers with VSD per reactor.
  - Four final settling tanks (FSTs) (32 m diameter) with two separated units per reactor.
  - Two rapid sand filters with continuous backwash. Each sand filter unit has 114 cells and is 166 m^2.

- Module 2 consists of:

  - Three PSTs (25 m diameter).
  - PS is wasted in the northern most unit to the primary sludge fermenters/thickeners.
  - The other two units are on a 4-day retention cycle, with one of the two PSTs pumps the fermented sludge to the balancing tank.
  - Balancing tank (12 000 m^3).
  - Two biological reactors including N and P removal (19 575 m^3 each) including 18 compartments divided in 5 anaerobic, 5 anoxic and 8 aerobic zones. Nitrates are recycled with 6 duty a-recycled pumps. Reactors are aerated with fine bubble diffusion and there are 3 duty/1 standby blowers with VSD per reactor.
  - Four final settling tanks (35 m diameter) with two separated units per reactor.

- Disinfection consists of:

  - The tertiary effluent and biological effluent from modules 1 and 2 respectively feed into two chlorine contact tanks.
  - Treated effluent is stored in a maturation dam which has an overflow into the Roodeplaat Dam. If the effluent quality is substandard, there is a possibility to bypass the treated effluent and discharge it directly into the Roodeplaat Dam.

- Sludge handling and disposal consists of:

  - Primary sludge from one of the three PSTs in module 2 is pumped to fermenters. The primary sludge is then pumped to the anaerobic digesters.
  - Biological sludge is pumped from the biological reactors to the dissolved air floatation (DAF) tanks in addition to module 1's sand filter backwash.
  - Thickened biological sludge is pumped to the anaerobic digesters.

- Primary and biological sludge are digested in two mesophilic anaerobic digesters including mixing and heating (6 000 m^3 each).
- Digested sludge is stored and mixed in a day tank and is subsequently dewatered in seven belt presses, however, currently only 4 belt presses are operational.

- Return liquors treatment consists of:

  - Dewatering return liquors are taken to two precipitation tanks where a lime slurry is dosed to increase the pH and precipitate orthophosphate. The same precipitation tanks were designed to strip ammonia, but the aeration system was not installed.
  - The precipitate is settled out via two sedimentation/thickening tanks (10 m diameter each).
  - The thickened sludge is transported to the day tank and the treated return liquors are pumped to the beginning of module 2 PSTs

3.2.2 Conclusions and recommendations

The following conclusions regarding the impact of the sludge return liquors in the plant performance were found:

1. The return liquors are only recycled to module 2, causing the influent ammonia and orthophosphate loads in this module to increase by 11% for TKN and 84% for TP. The phosphorous load appears to be extremely high and should be further investigated. To minimise this impact, an equal split between the two modules available should be considered.

2. Module 2s effluent does not comply with the nitrate, nitrite and orthophosphate quality standards. A deterioration in the module 2 biological effluent quality since January 2016 was noted, especially in the orthophosphate parameter. The overall plant performance regarding nitrogen and phosphorous compliance has been also negatively impacted since January 2016. This deterioration appears to be coincident with the start-up of the anaerobic digester and the recycling of sludge liquors to module 2.

3. The efficiency of the sludge liquors treatment facility appears to be negligible and influenced by water dilution from the lime slurry and others not yet quantified. The lime dosing causes critical problems with struvite formation in the return flow pumps and pipelines. The existing sludge return liquors facility requires optimisation and/or replacement.

In addition, the following generic conclusions and recommendations should be noted:

4. The plant is generally well operated and shows a good level of maintenance.

5. The current hydraulic demand in the plant is 69% of the design capacity. The influent flow is split: 40% to module 1 and 60% to module 2.

6. The plant is currently under loaded against its design capacity. The current COD load is only 41%, TKN load is 48% and TP load is 30% compared to the design capacity.

7. Although the plant is under loaded, the effluent quality does not comply with the effluent requirements for N and P. Particularly for N, it implies that the plant cannot handle more N since the denitrification capacity is not sufficient nor is it optimised. It is recommended to evaluate the

denitrification process including the a-recycle capacity, the simultaneous denitrification rate and the readily biodegradable COD fraction available. Regarding orthophosphate removal, it is important to bear in mind that this plant has a very stringent standard requirement (< 0.1 mgP/ℓ). With only biological P removal in place, the plant has been able to meet, on average, a remarkable low orthophosphate concentration of 0.2 mgP/ℓ. Considering the stringent effluent requirements, a chemical precipitation step with metal salts to complement the biological P removal should be considered.

8. The anaerobic digestion process has been running since January 2016 and has not yet been optimised. The digesters operate at ambient temperatures of 20ºC to 25ºC. It is a matter of urgency to bring the boilers and gasholders into operation to increase the process temperature to at least 35ºC. This will improve the digestion stability and increase the volatile solids destruction. Please note, that an optimised sludge digestion process will increase the N and P concentration in the sludge return liquors.

9. The dryness of the dewatered sludge could be optimised since only 13% DS (w/v) has been reached. An optimisation of the polymer dosage and type could also be considered.

3.3 'W' Wastewater Treatment Plant

The 'W' WWTP is located in Klip River in Southern Johannesburg (refer to Figure 3-2). It lies north of Meyerton. The works is owned and operated by East Rand Water Care Association (ERWAT).

'W' WWTP has a total capacity of 170 Mℓ/d. Module 1 was commissioned in 1979 and has a capacity of 40 Mℓ/d. Modules 2 and 3 were commissioned in 1989 and 1993 respectively, each having a capacity of 40 Mℓ/d. The fourth module was completed in 2008 and its capacity is 50 Mℓ/d.

The plant currently treats influent from the Germiston and Alberton areas. The treated effluent is discharged into the Klip River.

Figure 3-2: Aerial view of 'W' WWTP (Google Earth, 2016)

3.3.1 Process Description

A description of the 'W' WWTP is indicated below as per information found in the operation and maintenance manuals for modules 1, 2-3 and module 4 (Mott MacDonald, 2016; Bradford, Conning and Partners, 1994 and Sintec, 2008 respectively). The general process flow diagram of the works in indicated in Figure 18 of Appendix 1.

- The **inlet works** consist of two parallel head of works which split flow between modules 1-3 and module 4:
  - Each module consists of:
    - Three screening chambers1 which each have,
    - A stone trap and trash rack,
    - A fine screen.

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[1] *The head of works for module 4 has three screening chambers but currently only two of the three have screens*

  - Three vortex degritters,
  - At each inlet, there is an overflow weir upstream of the screens which directs excessive inflow to a 19 000 m³ emergency dam.

- **Module 1** consists of:

  - Two PSTs:
    - The tanks are 25 m in diameter,
    - The total usable volume of each tank is 3 252 m³.
  - Two primary BNR reactors and two secondary BNR reactors:
    - Primary reactors have a total volume of 2 690 m³,
    - Secondary reactors have a total volume of 3 250 m³,
    - Primary reactors have 8 surface aerators and secondary reactors have 5 surface aerators.
  - FSTs:
    - Four primary clarifiers upstream of the secondary BNR reactors,
    - Four secondary clarifiers downstream of the secondary BNR reactors,
    - All clarifiers have a 30 m diameter,
    - The total usable volume of each tank is 1 767 m³.

- **Modules 2-3** consist of the following:

  - One balancing tank per module (7 350 m³ each),
  - Two 25 m diameter PSTs per module,
  - Primary sludge screening:
    - Module 2:
      - Single mechanical screen with one manually raked screen on standby.

- **Module 3** consists of:

  - Two identical mechanical fine screens which can each work on a standby or duty basis,
  - Two BNR reactors (one per module with 15 898 m³),
  - Each reactor has 3 aerated zones which have fine bubble diffused air aeration systems,
  - Air provided by five centrifugal blowers (4 duty, 1 standby),
  - Four 25 m diameter clarifiers.

- **Module 4** consists of:

  - Two adjacent balancing tanks (5 250 m³ each),
  - Two 34 m diameter PSTs,
  - A BNR reactor (21 688 m³),
  - Aerated zones equipped with fourteen surface aerators,
  - Four 34 m diameter clarifiers.

- **Disinfection** consists of the following:

  - Two identical 2 000 m³ chlorine contact tanks serve modules 1-3 and 4 respectively,
  - Treated effluent is stored in maturation ponds, which discharge into the Klip River.

- **Sludge handling and disposal** consists of the following:

    - Primary sludge from the PSTs is pumped to anaerobic digesters,
    - Biological sludge is pumped to five 10 m diameter DAF units with 424 m^3 each (1 unit per module except module 4 which includes two units),
    - Thickened biological sludge is pumped to anaerobic digesters,
    - Primary sludge and biological thickened sludge are anaerobically digested in sixteen units:
        - Module 1: four digesters (not heated or mixed),
        - Module 2-3: six digesters (heated and biogas mixed),
        - Module 4: four digesters (heated and pump mixed),
    - Sludge dewatering:
        - 60% of digested sludge is diverted to drying paddies,
        - 40% of digested sludge is mechanically dewatered in four belt presses:
            - Presses operate for 12 hrs per day, 7 days a week.

- **Sludge return liquors**:

    - Sludge return liquors from the DAF units of modules 1-3 are recycled to the beginning of the biological reactors,
    - Sludge return liquors from the DAF units of module 4 are recycled to upstream of the balancing tank,
    - Sludge dewatering returns (filtrate) and wash water (from belt press cleaning) split equally between modules 1-3 and 4 and are recycled to downstream of the inlet works of the respective modules.

3.3.2 Conclusions and recommendations

The site research conducted at 'W' WWTP indicates the following conclusions regarding the impact of the sludge return liquors in the plant:

1. The dewatering return liquors, rich in ammonia and ortho-phosphate, are recycled to the beginning of the treatment process, before primary treatment, and the flow is split: 50% to modules 1-3 and 50% to module 4. Considering that module 4 corresponds to only 35% of the total biological capacity available, the current split of the returns is not proportional and increases the impact of the return liquors on this module, i.e. an additional 17% of ammonia and ortho-phosphate to be treated as well as additional 8% in TSS. At present, this is not critical and does not affect the effluent quality of module 4. In comparison, modules 1-3, with 65% of the biological capacity available, shows an almost negligible impact from the increase of flow and load. Despite the current minimal impact on these modules, it is recommended to make a proportional split of the dewatering returns according to the treatment capacity of the modules.

Only 40% of the digested sludge is mechanically dewatered and the corresponding fraction of dewatering return liquors is recycled. If in future, 100% of the digested sludge is dewatered, an additional 60% of the dewatering returns will be added to the current influent. Thus, increasing the impact on module 4, estimated at a 27% increase in NH_4 and PO_4 each.

2. The DAF returns are also a point of concern, especially the impact on module 1 due to the age of the installation and continuous breakdowns of equipment. The high TSS concentration returned

from the DAF's supernatant indicates a non-optimal efficiency of the floatation units. Therefore, the hydraulic and solids loads should be properly checked as well as the pressurisation systems.

3. Although Plant 'W' is overloaded, the plant's performance is still compliant with the current standard effluent requirements. However, it should be noted that the plant has a relatively lenient requirement for ammonia and if more stringent effluent limits are applied (for example ammonia < 1 mgN/ℓ), modules 1-3 would not be able to continuously comply (refer mainly to the winter season).

In addition, the following generic conclusions and recommendations shall be noted:

4. The plant is generally well operated and shows a good level of maintenance.

5. The current hydraulic demand in the plant is 150% of the total design capacity. Modules 1-3 have a current capacity of 165% of the design flow and module 4 has 112% of its design flow. Also, the ammonia load coming in to modules 1-3 is already at 146% of the design load. ERWAT is already planning the extension of the plant. This will be extremely helpful to alleviate the extra flow currently reaching modules 1-3.

6. The anaerobic digestion process has been running smoothly, with no critical issues encountered. The long sludge retention time in the digesters (> 100 days in the cold digesters and > 30 days in heated digesters) is allowing for 40% of VSS destruction. A higher VSS destruction rate, close to 50-60%, was expected. It is recommended to double check the digestion temperature in the heated digesters and mixing conditions as well.

3.4 'K' Wastewater Treatment Plant

The 'K' WWTWP is located in the KwaZulu-Natal Phoenix industrial/residential area and is owned and operated by eThekwini Municipality. The plant treats mainly domestic sewage from these two areas, and only 10 to 15% of the influent is from industries. The 'K' WWTP has a treatment capacity of 80 Mℓ/d; consisting of a 15 Mℓ/d trickling filter module and a 65 Mℓ/d activated sludge module. The current ADWF is about 57 Mℓ/d. An overview of the 'K' WWTP site is presented in Figure 3-3.

The plant's key unit operations consist of primary sedimentation, trickling filters, AS treatment and AD. The biological effluent is clarified in secondary clarifiers and humus tanks and then discharged into the environment after chlorination. The WAS from the aerobic process is thickened and dewatered using mechanical presses. A portion of the PS (30%) is dewatered and incinerated in a FBR.

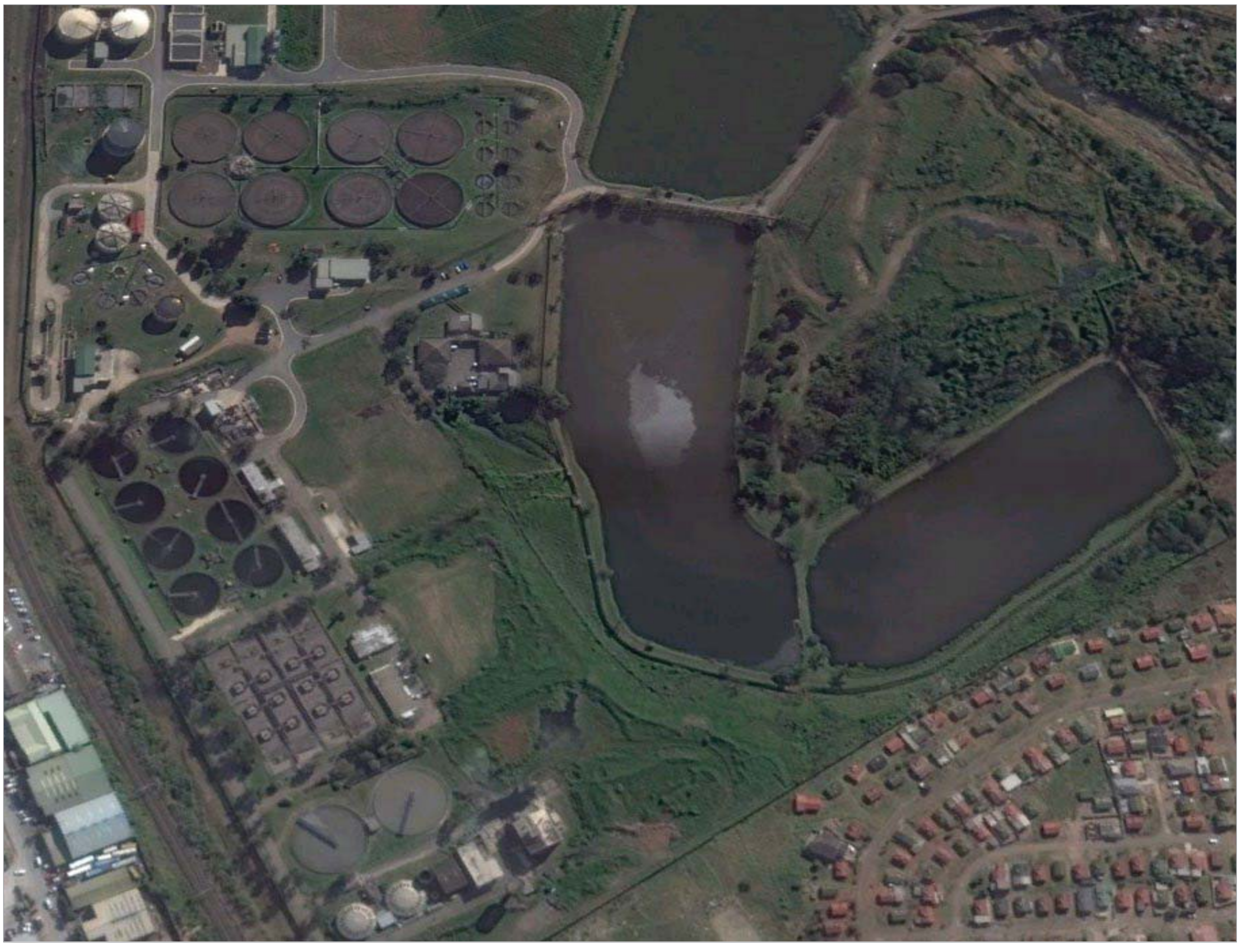

Figure 3-3: Aerial view of 'K' WWTP (Google Earth)

3.4.1 Process description

A description of the works is indicated below as per information retrieved from the plant's as-built drawings. The general process flow diagram of the treatment works is provided in Figure 34 of Appendix 1.

- Inlet works consists of:
    - Two mechanical stone traps,
    - Three mechanical inlet screens (new works),
    - Two aerated degritters.

- Wastewater treatment consists of:
  - 15 Mℓ trickling filter module:
    - Six PSTs
    - trickling filters
    - humus tanks
  - 65 Mℓ fully aerobic activated sludge module,
  - An aerobic process consisting of 16 aerators arranged in 4 lanes with 4 aerators per lane,
  - Eight SSTs.

- Disinfection consists of:
  - Final effluent from the SSTs is discharged into two maturation ponds which overflow via a third maturation pond into the uMhlangane River.

- Sludge handling and disposal consists of:
  - A portion of the PS (30%) is dewatered and incinerated in a fluidised bed reactor (FBR). The remaining primary sludge from the two PSTs is thickened and anaerobically digested. The FBR unit, however, is currently not in operation due to a planned upgrade to maximise its operations. This has been the situation for over 2 years. Thus, all of the PS now undergoes thickening and is pumped to the anaerobic digesters,
  - WAS is pumped from the SSTs to the DAF unit while return activated sludge (RAS) is recycled to the AS system,
  - Thickened primary sludge is digested in four mesophilic anaerobic digesters including mixing and heating (2 000 m^3 each).
  - Digested sludge undergoes further digestion in two secondary digesters (2 310 m^3 each)
  - Digested sludge is stored in a digested sludge sump which subsequently feeds the dewatering plant. The digested sludge is fed to mechanical screw (Huber) presses via four sludge-feed lines.
  - Biological thickened sludge from the DAF unit is pumped to a secondary sludge feed sump from where it is fed to the dewatering plant and thereafter incinerated or beneficially applied to agricultural land.

- Return liquors treatment consists of:
  - All sludge return liquors from gravity thickeners, DAF, secondary digester and mechanical dewatering are returned upstream of the PSTs included in the AS module.

3.4.2 Conclusions and recommendations

The site research conducted at ‘K’ WWTP indicates the following conclusions regarding the impact of the sludge return liquors on plant performance:

1. The new works receives 100% of the flow and loads from the sludge return liquors. With the sludge return liquors, the influent loads increased by 11.9% for COD, 14.2% for TKN, 36.4% for TP and 17% for TSS. The sludge return liquors from the plant appears to have little or minor impact on the plant as there is no significant increase in influent characteristics observed. This is especially true with regards to the ammonia (2.5%) and ortho-phosphate (4.8%) concentrations.

The only exception is in the case of TP, which increased by 57.5%, showing also an important TSS contribution (20.5%). Low ammonia and ortho-phosphate in the returns can be attributed to the non-digestion of WAS (only PS is digested) and the apparent poor performance of the anaerobic digestion process.

2. Although the concentration of other parameters appears to be insignificant on the plant, it is important to note that, if the WAS from the new plant is to be anaerobically digested in the future, the return liquor concentration is expected to increase significantly, thereby impacting on the nutrient concentration in the aeration basin; requiring higher aeration capacity.

3. The final effluent is in compliance with general discharge standards. However, at the old works, an increased TSS levels in the effluent from the maturation pond was observed. It suggests that the pond may require cleaning.

In addition, the following generic conclusions and recommendations shall be noted:

4. The plant is generally well operated and shows a good level of maintenance.

5. The plant is approaching its design capacity. Changes in the process configuration and increased loads due to return of sludge liquors may necessitate an upgrade of the plant in the near future.

6. For an AS plant that has not reached its design capacity, an ammonia concentration of below 1 mg/ℓ is manageable. Considering the concentration from the AS plant is higher than 1 mg/ℓ, this indicates that there are challenges at either sludge retention time, aeration capacity or potentially toxicity.

7. High TSS in the return liquors indicates that the dewatering can be further optimised. It is recommended to further investigate optimisation. The high TSS in the return liquors lower the SRT, which impacts the nitrification in the process.

8. The digester is performing poorly, with only 23% destruction of VSS while a performance of 40 to 60% can be expected.

3.5 ‘P’ Wastewater Treatment Plant

The ‘P’ WWTP is situated approximately 1 km east of the MR102, Phoenix/Ottawa intersection and approximately 6.5 km from the Gateway Shopping Complex. The plant is owned and operated by the eThekwini Water and Sanitation Department and treats only domestic sewage. The plant, designed for a treatment capacity of 50 Mℓ/d, was constructed in 1987 with a design capacity of 12.5 Mℓ/d, and upgraded to 25 Mℓ/d in 1997. The existing works was designed based on a BNR AS principle, but now operates based on the AS principle with an installed capacity of 25 Mℓ/d. The current average flow into the plant is 24.5 Mℓ/d. With commissioning of an additional 25 Mℓ/d unit underway, the capacity of the works will increase to 50 Mℓ/d.

’P’ WWTPs key unit operations consist of a head of works, primary sedimentation, activated sludge treatment, and anaerobic digestion systems. Currently the works has two PSTs, one activated sludge reactor and three clarifiers. A two-fold increase of these units is expected after the planned commissioning as the new module is a mirror image of the existing plant. Primary sludge is anaerobically digested in two anaerobic digesters, and digested sludge and biological sludge are dewatered before beneficially applied to land.

Figure 3-4: Aerial view of ‘P’ WWTP (Google Earth)

3.5.1 Process description

A description of the works is indicated below as per information retrieved from the as-built drawings and design manual of the plant. The general process flow diagram of the treatment works is provided in Figure 47 of Appendix 1:

- Head of works consists of:
  - Two inlet channels,
  - One hand raked screen,
  - One mechanical screen fitted with screenings washer/compactor unit,
  - Two aerated grit removal chambers,
  - Two screw lift pumps for conveyance of raw sewage to the PSTs.
- Wastewater treatment consists of:
  - Four PSTs,
  - A 25 Mℓ conventional activated sludge process, with nutrient removal capacities,
  - Six SSTs.
- Disinfection consists of:
  - Final effluent from the SSTs is discharged into three maturation ponds which overflow into the river via the third maturation pond.
- Sludge handling and disposal consists of:
  - PS is anaerobically digested in two mesophilic digesters (2 600 m^3 each) including mixing and heating. Digested PS is mechanically dewatered before beneficial application to agricultural land.
  - Three secondary digesters (510 m^3 each).
  - WAS is stored in a sludge sump from where it is pumped to a belt press for dewatering.
  - Primary digested sludge and biological sludge are fed to the dewatering plant consisting of a belt press via two sludge-feed lines.
  - Dewatered sludge is stored in silos before being applied to agricultural land.
- Return liquors treatment consists of:
  - Dewatering sludge return liquors are recycled upstream of the PSTs.

3.5.2 Conclusions and recommendations

The site research conducted at 'P' WWTP indicates the following conclusions regarding the impact of the sludge return liquors on the plant performance:

1. Return liquors recycled upstream of the PSTs are a combination of the belt press filtrate and secondary digester supernatant. The incoming ammonia and orthophosphate loads to the PSTs have an increase of 6.5% and 20% respectively in the influent loads.

2. Currently, the plant is not compliant with the required effluent standard for ammonia. It is evident that that the plant is already overloaded in terms of COD and TKN, without the return of sludge liquors. The overloading is further aggravated by the recirculation of sludge return liquors to the PSTs.

In addition, the following generic conclusions and recommendations shall be noted:

3. The technical performance of the plant is generally good and shows a good level of maintenance.

4. Currently the plant is undergoing an upgrade

5. The current hydraulic demand in the plant is 98% of the design capacity. The current loading for the plant compared to its design capacity is 101% for COD, and 120% for TKN.

6. Although the plant is currently operating above its design capacity, improved process performance is expected upon completion and operation of the new section of the plant. Further optimisation of the process is expected upon installation of VSDs and DO level sensors in the activated sludge process. This may improve the aeration demand of the plant, and hence the electricity consumption.

3.6 ‘C’ Wastewater Treatment Plant

The ‘C’ WWTP lies next to Muizenberg in the Southern Suburbs of Cape Town (refer to Figure 3-5). The plant primarily treats domestic wastewater and some industrial wastewater. The works are owned and operated by the City of Cape Town (CoCT).

The plant was initially designed to treat an ADWF of 150 Mℓ/d and consisted of six parallel modules, each of 25 Mℓ/d capacity. In 1999, an additional two 25 Mℓ/d modules were constructed. Currently, the plant has a total capacity of 200 Mℓ/d over eight parallel modules.

Figure 3-5: Aerial view of ‘C’ WWTP (Google Earth, 2016)

3.6.1 Process description

The treatment process used at the ‘C’ WWTP includes primary sedimentation followed by AS reactors. An extensive maturation pond system is the final treatment step. ‘C’ WWTP was designed for partial denitrification and biological *P* removal. Primary and biological thickened sludge are anaerobically digested followed by mechanical dewatering (out of operation). Currently, the digested sludge is dewatered in drying beds and the filtrate is sent to ponds.

A description of the unit processes and unit operations of the works is indicated below as per the plant operational manual and the general process flow diagram of the treatment works provided in Figure 59 of Appendix 1:

- Inlet works consists of:
  - Five mechanical coarse screens and one manual screen on standby,
  - Two degritting channels with a splitter box.
- Primary Treatment:
  - Eight PSTs (23 m diameter).

- Biological treatment:
    - Eight CAS reactors including anaerobic, anoxic and aerobic compartments (6 × 2 391 m^3 and 2 × 7 675 m^3). Air is provided by fine bubble diffusion aeration,
    - Twenty-two final clarifiers (18 × 26 m diameter and 4 × 31 m diameter).

- Final Treatment:
    - Maturation pond.

- Sludge handling and disposal consists of:
    - PS thickened in three gravity thickeners,
    - Biological sludge thickened in two DAF units,
    - Combined thickened sludge that is anaerobically digested under mesophilic conditions with the provision of heat and mixing (6 × 5 280 m^3),
    - Digested sludge is dewatered in drying beds.

- Sludge return liquors:
    - Return liquors from the gravity thickening and DAF process operations are blended and recycled to the beginning of the biological reactors,
    - The filtrate from the sludge drying beds is discharged into ponds and not it does not return to the treatment works.

3.6.2 Conclusions and recommendations

The site research conducted at 'C' WWTP indicates the following conclusions regarding the impact of the sludge return liquors on the plant performance:

1. Only the return liquors from the gravity thickeners and DAF units are recycled to all bioreactors. The increase in incoming ammonia and orthophosphate loads to the bioreactors are marginal, with negligible impact on the bioreactors. The impact was determined to be 0.4% and 0.3% for ammonia and ortho-phosphate respectively.

2. In the event that filtrate from the dewatering (drying beds or mechanical dewatering) is included, then the impact was determined to be 15% and 52% for ammonia and ortho-phosphate respectively. These are significant impacts on the bioreactors performance, especially because the biological treatment is continuously showing a poor performance. Also, considering this eventual future scenario, the aeration consumption would raise in ± 15% compared with the current situation.

In addition, the following generic conclusions and recommendations should be noted:

3. The technical performance of the plant is satisfactory, there is a need for maintenance and repairs of some unit operations. A tender for the refurbishment of the dewatering operations unit had been put out for this in the year 2017.

4. The current hydraulic demand in the plant is 60% of the design capacity. The current loading for the plant compared to its design capacity is 94% for COD, and 83% for TKN. However,

considering that the plant is non-compliant with the effluent requirements it can be concluded that the plant is operating over its actual capacity.

5. Biological and final effluent quality does not comply with the discharge quality standards. The biological treatment also requires optimisation to improve its performance. A more detailed process audit should be considered.

3.7 'D' Wastewater Treatment Plant

The 'D' WWTP is located within the metropolis of Port Elizabeth. It is in the flood plain of the Swartkops river (refer to Figure 3-6). The plant treats primarily domestic wastewater with some industrial wastewater. The plant is owned and operated by the Nelson Mandela Bay Municipality (NMBM).

Phase 1 of the plant (Unit 1), built in 1977, is a Huisman Orbal Aeration System, designed to treat 1.86 Mℓ/day. Capacity was increased with the addition of a 2.75 Mℓ/day BNR (Ames Costa, Unit 2) reactor in 1977, built to comply with general standards. Considering future growth, the addition of Unit 3, a 4.25 Mℓ/day 3-stage Phoredox reactor was built in 2009. However, the raw sewage flows have been much lower than initially expected, resulting in only the latest BNR reactor being operated.

WAS was pumped to Kuduskloof landfill site until 2009, this was due to the upgrade in 2009 that included a new chlorine contact tank, chemical dosing for the effluent from the oxidation ditch and refurbishment of the sludge lagoon. A further phase envisioned is the onsite dewatering of the WAS from the sludge lagoon as an alternative method of sludge disposal.

Figure 3-6: Aerial view of 'D' WWTP (Google Earth, 2016)

3.7.1 *Process description*

A description of the plant is below, based on site visits and drawings obtained from Hatch Goba. As mentioned, due to low flow (~4 Mℓ/day), only Unit 3 is in operation. Thus, Units 1 and 2 will be discussed briefly and without results. The general process flow diagram of the treatment works is provided in Figure 71 in Appendix 1:

- Sewage is pumped to the plant; this causes the flow to be controlled using a controlled flood peak. On days of power failure, the plant receives no flow.

- Inlet works consists of:
    - Two mechanical front raked coarse screens (8 mm) and a bypass channel for peak wet weather overflow,
    - Two vortex degritters,
    - Flow split with flumes between the units.
- Unit 1 is a Huisman Orbal System, an oxidation ditch type reactor, with horizontal disc aerators, with four 7.1 m diameter Dortmund cone clarifiers are in the centre.
- Unit 2 is an Ames Crosta system with one 23 m diameter clarifier.
- Unit 3 is a BNR plant designed as a 3-stage Phoredox system, for *N* removal, but built with the option of changing to either a UCT or Johannesburg system, should *P* removal be required. According to process controller records, this system is operated at a sludge age of about 30 days. This 3-Stage Phoredox reactor has a volume of 5 400 m^3 with anaerobic, anoxic and aerobic mass fractions of 7.2%. 14.3% and 78.5% respectively. The system has 3 mixers (anaerobic and anoxic zones) and 4 surface aerators with VSDs controlled by influent flow and immersion depth.
- Chemical dosing consists of:
    - Ferric dosing with a 29 m diameter phosphate settling tank (not in operation).
- Disinfection consists of:
    - A chlorine dosing station, shallow mixing channel and chlorine contact tank before entry into the maturation ponds,
    - Maturation is either a pond, or a reed-bed (which had been de-weeded and moved at the time of the site visit, thus currently out-of-use).
- Sludge handling and disposal consists of:
    - Two sludge lagoons (each 61.75 m × 62.1 m × approximately 1.4 m deep), with a multi-level withdrawal of supernatant,
    - No sludge had been removed from the lagoons since pumping to the landfill stopped in 2009. The lagoons overflowed in July 2016. The sludge lagoons require emptying, a contract is currently being arranged by the metro to empty the lagoons and dry the sludge.
- Return liquors treatment consists of:
    - Supernatant of the sludge lagoon, which is returned to Unit 3 at the start of the aeration section.

3.7.2 Conclusions and recommendations

From the site research conducted at 'D' WWTP, the following conclusions and recommendations are applicable:

1. The plant is currently under loaded since the measured raw sewage flow is about half the design capacity. Concentration is within design range.

2. Unit 3, the only unit currently in operation, is running at full capacity with regard to COD and N loads.

3. Unit 3 receives 100% of the flow and loads from the sludge lagoon supernatant, with a contribution of 34% TP. This return flow consumes 5% of the aeration capacity of Unit 3.

4. The P is not removed from the system, as sludge is not removed from the plant, and no treatment of dewatering liquor is provided. Therefore, the effluent P is high.

5. The effluent ammonia, at 5 mg/ℓ is higher than the design of 0.5 mg/ℓ, but within effluent quality limits. Incomplete nitrification in a AS plant, generally points to challenges with aeration or low SRT. This could cause plant instability; therefore, it is recommended to start a second module.

In addition, the following generic conclusions and recommendations shall be noted:

6. The plant is generally well operated and shows a good level of maintenance.

7. The sludge lagoons should be emptied at 5-year intervals as per the design. Note, this mitigating action will likely not be sufficient to ensure compliance with P effluent requirements.

8. Further optimisation of Unit 3 should be checked, as it will determine whether another unit is needed or not.

3.8 Conclusions of the site research

Faced with severe backlogs, inadequately trained operators, poor planning for future demand and growth, drought and badly maintained infrastructure, WWTPs in South Africa are struggling to meet current water demands and effluent requirements (Mema, 2010). This study found that several plants are running above their capacities, such as 'W' WWTP which treats 148% of its design flow; see Section 3.3 and Section 2.7.3 in Appendix 1. Most of the plants in this study, do not treat their return liquors before reintroducing them into the main treatment cycle, results are summarised in Table 3-2 and Table 3-3. Very often, return flows are not recycled and are discharged in ponds and evaporated, infiltrated into the land or discharged to the sea. Seepage and overflowing often causes contamination of ground and surface water (Mema, 2010).

The aim of this study was to assess the impacts of sludge return liquors and how they affect WWTPs operational performance and effluent quality compliance. A total of six plants were investigated from Gauteng, KwaZulu-Natal, the Western Cape and the Eastern Cape. and provide a summary of the report's findings with regards to sludge return liquors.

Through the research conducted in the six national plants and the contact with several other wastewater treatment plants during the selection process, it is noted that most of the treatment plants were not designed to accommodate the additional loads from sludge return liquors. The return of the sludge liquors, especially from the anaerobic digestion or dewatering, to the main treatment process appears to be a fairly recent practice in South Africa. This is in response to more stringent environmental regulations to protect surface water, particularly for inland regions. In this regard, the current approaches are not always correct and often the effects of additional loads from the dewatering return liquors have not been accurately quantified. The current body of knowledge is lacking an integrated overview and study of the relationship between the additional loads from the sludge return liquors and their respective impacts on the plant's biological capacity, aeration capacity and final effluent quality. Usually, these liquors are discharged at the nearest point from the dewatering facility or anaerobic digesters, regardless of where and/or if it will impact only one treatment module or the entire treatment facility.

The following conclusions were drawn from this investigation:

1. Greater consideration must be given to the impacts of return liquors and how they affect compliance with stricter effluent requirements. In plants where the status quo is not sufficient to meet the requirements, the introduction of side-stream treatment of return liquors may be required. Investigation of these treatment methods will indicate how targeted removal of undesirable nutrients may be achieved to ensure compliance.

2. Impacts can vary drastically when additional return liquor streams are introduced. For example, at 'C' WWTP, the filtrate from the currently out-of-operation dewatering system could be returned to the main treatment cycle. This would increase the impact of N from 0.4% to 15% and P from 0.4% to 52%, refer to Section 0. Given this variability, there is a need for a tool or method to quantify the effects of various return streams on the treatment works and develop operational scenarios as a means of guiding sound planning. This will provide greater operational efficiency and flexibility.

3. Many of the anaerobic digesters on the plants are operating sub-optimally with insufficient retention time for their current operating temperatures. If the operating conditions of the anaerobic digestion are improved, it is expected that the N and P loads returned to the main

treatment may increase the raw sewage or primary effluent loads up to 20% and 50% respectively. It is recommended that a separate research project is done on the performance and operation of digesters. The goal would be to identify the most common challenges faced and the preparation of guidelines for operation and troubleshooting of digesters.

4. Comparing the current approaches of recycling return liquors without side-stream treatment coupled with non-optimal AD processes to the situation of return liquors not being recycled at all; the average aeration demand for the plants' biological reactors typically increases by ± 10%. This aeration energy demand may jump to 20%, as soon as the AD processes are optimised, and higher nutrient loads return to the reactors. With the introduction of side-stream treatment of the return liquors, the aeration demand in the main treatment can be lowered according to the efficiencies of different technologies used. Further investigation is required to evaluate the energy requirements of the different treatment methods available and assess the real benefit of such techniques when compared to the combined treatment in the main biological reactor. A cost-benefit analysis to compare the potential aeration savings in the main treatment with the energy requirements for the utilisation of side-stream treatment technologies is recommended.

Although not completely related to the main topic of this research, it was noted that for the majority of the plants, there is poor solids capture in the solid/liquid separation units, such as thickeners, DAF units and mechanical dewatering equipment which are mostly belt presses. With high TSS loads being continuously returned to the main treatment cycle, there are potential impacts on the effluent quality, sludge settleability, sludge retention time and aeration demand. As this is a typical issue in most of the studied wastewater treatment plants, with critical impacts, it is recommended that an in-depth study focused on solids capture in the different units of the sludge treatment be carried out. This study should provide an overview of the observed challenges and a formulation of guidelines to improve those solid/liquid separation techniques.

Table 3-2: Summary of plants researched

WWTP Name	'Z'	'W'	'K'	'P'	'C'	'D'
Type of Sludge: Anaerobically Digested	Primary and biological thickened sludge	Primary and biological thickened sludge	Primary thickened sludge	Primary sludge	Primary and biological thickened sludge	No digesters
Operating Conditions of Anaerobic Digesters	Poor	Fair	Poor	Good	Good	No digesters
Type of Sludge: Return Liquors	DAF and dewatering returns	DAF and dewatering returns	DAF, thickeners and dewatering returns	Digesters supernatant and dewatering returns	DAF and thickeners returns	Sludge lagoon supernatant
Side Stream Treatment of Return Liquors	Yes	No	No	No	No	No
Location where return liquors are introduced	100% in Module 2 upstream of PSTs (dewatering returns) and upstream of BNR (DAF returns)	50% to modules 1-3 and 50% module 4. Upstream of PSTs (dewatering returns) and upstream of BNRs (DAF returns)	100% upstream of all PSTs	100% upstream of all PSTs	100% upstream of all BNRs	100% upstream of BNR

Table 3-3: Summary of plants' return flows impacts

Plant Name	Main Impacts from Sludge Return Liquors
'Z'	Doubling the PO_4 influent load. Affecting PO_4 compliance on Module 2. Negligible efficiency is noted in the existing side-stream treatment.
'W'	Module 4 is high loaded with 50% of returns due to unequal returns distribution. Minimal current NH_4 and PO_4 impact in influent characteristics because only 40% of digested sludge is dewatered. NH_4 and PO_4 influent loads may potentially increase up to 27% if 100% of digested sludge is dewatered.
'K'	Currently only minor impacts on NH_4 and PO_4 influent characteristics are noted because the anaerobic digestion is not optimal and only primary sludge is digested.
'P'	Main impact on $PO_4^{-}P$ influent loads. It is critical to minimise any additional loads to the main treatment since the plant is overloaded even excluding any returned sludge liquors.
'C'	Currently only minor impacts on NH_4 and PO_4 influent characteristics because dewatering liquors are not returned to the treatment. As soon as the filtrate is returned there is potential increase of the influent loads due to the return flows: NH_4 in 15% and PO_4 in 52%.
'D'	Currently only minor impacts on NH_4 influent characteristics because there is no digestion process. The poor sludge wasting from the lagoon is impacting the P effluent compliance.

CHAPTER 4: MODELLING SIMULATION AND RESULTS

This section provides the set of results generated by the virtually replicated full scale systems that were used as case studies (Table 3-1). The supporting files also provided with this report include (i) excel sheets for the mass balance based plant-wide mathematical model, tailored to meet the conditions of the selected wastewater treatment works (ii) a separate report that covers the model implementation methodology and (iii) appendix with detailed information, including equations and references that were used when integrating the various steady state equations towards development of the plant-wide mass balance based model.

4.1 Methodology

Over the past years, WWTP mathematical models have been advancing towards their widespread application for sizing and operation of treatment plants to minimise energy consumption and cost while maximising nutrient recovery and effluent quality. In application of these mathematical models, it has been noted that both steady state and dynamic models complement each other in the process. The Plant Wide Steady State Mass Balance Model (PWSSMBM) is the most useful in sizing the WWTPs (determining the best volumes, recycle rates, etc.) and the Plant Wide Dynamic Model (PWDM), such as PWM_SA, Ikumi et al. (2014) are most useful for operation optimisation and evaluation of system performance with changing flows and loads, i.e. for dynamic conditions.

The importance of modelling the entire WWTP, as a set of interconnected unit operations is based on the capability to track material components throughout the entire plant, hence allowing for the impact of the performance of a single unit operation to be assessed on the downstream unit operations. The performance of the WWTP, including effluent water quality and the costly sludge production and treatment are well predicted by the PWDM.

In the previous phases of the research, the following observations were made:

- There is no established methodology in the municipal wastewater treatment sector to evaluate the impact of recycling Sludge Return Liquors (SRL) back into the WWTP.
- There exists a knowledge gap as to what is best practice for re-routing SRL back into the WWTP.

There is a need to develop a simple PWSSMBM to guide the wastewater process controllers to evaluate the impact of SRL.

4.1.1 Overview of Methodology

Correctly developed plant wide mass balance theories can be applied in the decision-making process for validating the design and the operation of municipal wastewater treatment systems. It is proposed that such a PWSSMBM be implemented as a tool to evaluate the impact of SRL on the WWTW. To achieve the afore-mentioned, the following methodology was implemented:

1. Raw Data received from various WWTWs (including, diurnal samples, grab samples, flow readings and unit process sizes) be scrutinised to be most representative of the system behaviour. This data was then used towards evaluation of the performance of the different WWTWs and was established from the mass balances prepared in the previous phases of the research.

2. The compilation of an integrated plant-wide steady state model, using Microsoft Excel, based on the integrated UCT steady state model equations (Marais and Ekama, 1976; Dold et al., 1980; Wentzel et al., 1990; Ekama, 2009) for various unit processes. The significant steps towards the development of this model are shown in Section 4.1.2 below. The detailed equations used in this model development process are given in Appendix A (part of the support material to this report).

3. Tailor the PWSSMBM to virtually replicate the 6 selected WWTW ('Z', 'W', 'C', 'K', 'P' and 'D'). This required ensuring the influent loads, configuration types, sizing and flows are well represented by the plant-wide steady state model and involved the data reconciliation to allow for (and followed by) comprehensive wastewater characterisation process shown in Section 4.1.2 below.

4. Select the key variables for consideration towards evaluation of the Impact from DWL recycle streams on the AS system. These key variables are described in Section 4.1.4 below and include (1) hydraulic loading rate, (2) organic and nutrient loading rate, (3) optimum aerobic to anoxic nitrate recycle flow rate, (4) oxygen demand and aeration requirements (5) sludge generation and (6) effluent quality, including COD, N and P concentrations.

5. Compare the PWSSMBM predictions to validated model predictions. The PWSSMBM was simulated against dynamic simulation models for AS and AD systems. The Activated Sludge Model No. 2 (ASM2) from the international water association (IWA) Task Group (Henze et al., 1995), with Biowin® as the simulation platform. The ASM2 is a widely accepted model that is broadly applied in NDBEPR system design, operation and process optimisation for activated sludge systems and is commonly used as a base for further model development (Vanrolleghem et al., 2005). This ASM2 model includes the biological growth and death processes for OHO, PAO and ANO biomass (denoted in the models as OHO, PAO and ANO respectively and predicts oxygen demand and sludge production together with storage and lysis of polyphosphate (PP) and poly-3-hydoxyalkanoates (PHA) for PAOs for strictly aerobic *P* uptake BEPR. Very similar results were obtained from predictions of the ASM2 dynamic model and the PWSSMBM. This provided confidence in the data generated, as the PWSSMBM is a steady state model that contains explicit mass balanced equations and has outputs that match closely with the widely accepted ASM2 model, which has a good validation base.

6. Assessment of the impact of varying fractions of recycled anaerobic digestion sludge dewatering liquor on the plant performance when in steady state operation. The 'plant performance' was based on whether there was favourable increase or decrease in the variables shown in (4) above. The calculations used in this stage of the methodology are described in Section 4.1.5 below.

7. Report the findings from (6) above, including a discussion on the possible WWTW operating parameters that could be exploited to mitigate the negative impact of recycling the SRL.

4.1.2 Framework for Impact Assessment of SRL

The primary tool used in this work to assess the impact of SRL is the PWSSMBM.

4.1.2.1 PWSSMBM Data Requirements and Data Output

Figure 4-1 is a pictorial description of the required data inputs by process controllers and the expected data outputs from the PWSSMBM.

Two data sets would be required from the operations team. The first data set denoted (A), in Figure 4-1 below, is conventional chemical and physical influent Wastewater (WW) data. The second data-set denoted B, in Figure 4-1 below, is design and operational data for a given WWTW.

The kinetic and stoichiometric data used in the PWSSMBM would be universal data for South African conditions. Thus, the end-user of the PWSSMBM would not necessarily be required to have knowledge of the stoichiometric and kinetic parameters.

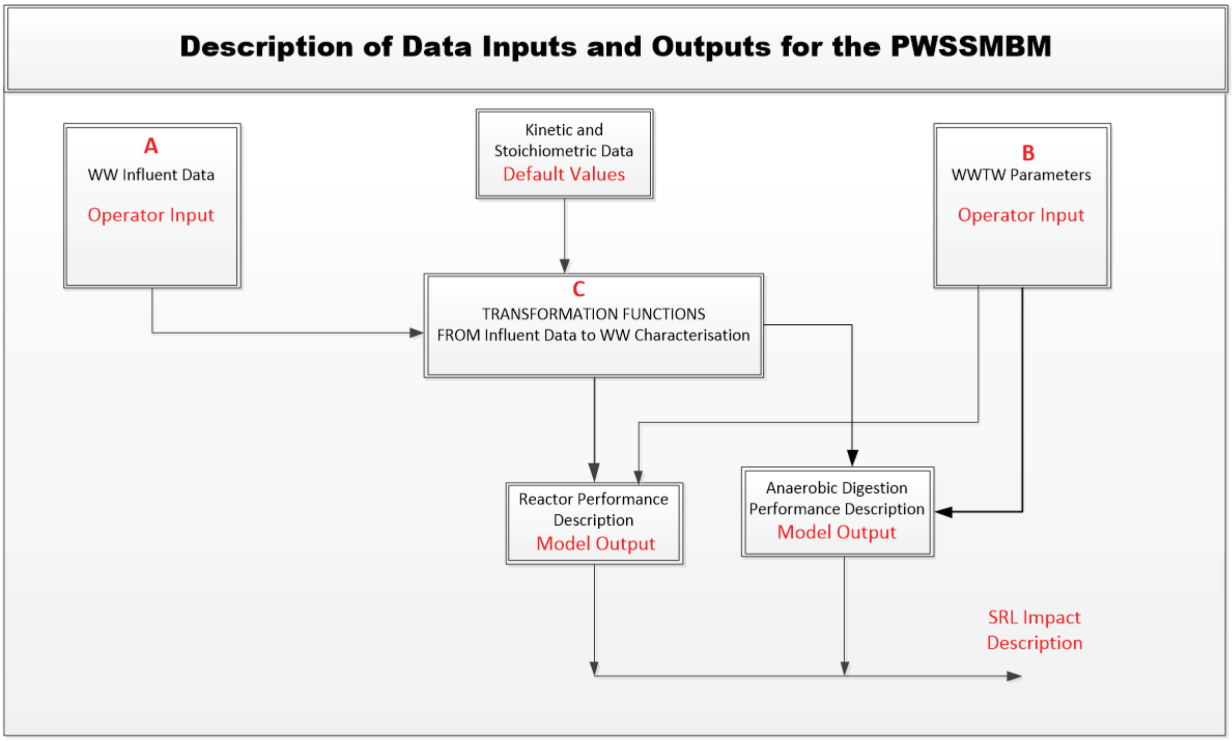

Figure 4-1: Framework for the determination of SRL impact on South African WWTW

The WW influent data and Kinetic & Stoichiometric data would be used to characterise the WW into different biochemical and biological components. The characterised components serve as input data to the reactor and anaerobic digestion model. The predicted SRL composition is the main output from the reactor and the anaerobic digestion calculations.

Sections 4.1.2.2 and 4.1.2.4 below further describe the main input requirements and output data of the PWSSMBM.

4.1.2.2 Required Input Data

The following pre-scribed data inputs are necessary to enable the use of the PWSSMBM.

Influent Wastewater Measurements in a Conventional South African WWTP, Input A

In South Africa, the DWS specify the parameters to be monitored in influent wastewater. Table 4-1 below is a list of parameters specified by DWS and mostly measured by process controllers of BNR WWTWs. The indicated parameters in Table 4-1, define the required inputs in Block A of Figure 4-1.

Table 4-1: Influent WW Chemical and Physical parameters generally measures in SA WWTPs

Parameter	Symbol	Unit
Chemical Oxygen Demand	COD	mgCOD/ℓ
Total Organic Carbon	TOC	mgC/ℓ
Volatile Fatty Acid	VFA	mgCOD/ℓ
Total Kjeldahl Nitrogen	TKN	mgN/ℓ
Free and Saline Ammonia	FSA	mgN/ℓ
Organic Nitrogen	Org N	mgN/ℓ
Total Phosphorus	TP	mg/ℓ
Ortho Phosphate	OP	mg/ℓ
Organic Phosphorus	Org P	mg/ℓ
Total Suspended Solids	TSS	mgTSS/ℓ
Inorganic Suspended Solids	ISS	mgISS/ℓ

Input Stoichiometric and Kinetic Parameters

Table 4-2 below is an indication of the required stoichiometric and kinetic parameters which are used with the data in Table 4-1 above to contribute to the definition of wastewater characteristics. The kinetics seek to describe different micro-organisms found in the BNR reactor, Anaerobic and Aerobic Digester. Described are the kinetics, with associated values, for Ordinary Heterotrophs (OHO), the Autotrophic Nitrifiers and Denitrification kinetics in the anoxic zone.

Table 4-2: Stoichiometric and Kinetic Parameters – Ordinary Heterotrophs, Autotrophic Nitrifiers and Denitrifiers

	Parameter	Symbol	Value
Ordinary Heterotrophs	Yield Coefficient of Active Organisms	YH	0.45
	Endogenous Decay/Respiration Rate	bHT	0.24
	Organic Nitrogen Degradation Rate	KrT	0.015
	Substrate utilisation rate at 20°C	kvT	100
	Endogenous Residue Fraction	f	0.2
	Endogenous respiration rate for OHOS at 20°C	bH20	0.24
Autotrophic Nitrifiers	Maximum growth rate for Nitrifiers at 20°C	FNm20	0.55
	Endogenous Decay Rate of Nitrifiers	bnT	0.04
	Half saturation constant for nitrification at 20°C	Kn20	1
	Yield for Nitrifiers	YA	0.1
	factor of safety	Sf	1.25
	Temperature sensitivity for nitrification	Theta_UA	1.123
	Ammonification rate at 20°C	Kr	15
Denitrification	Temperature sensitivity for initial denitrification in primary anoxic reactor	ThetaK1	1.2
	Temperature sensitivity for second denitrification in primary anoxic reactor	Theta K2	1.08
	Temperature sensitivity for denitrification in secondary anoxic reactor	ThetaK3	1.029
	Initial rapid specific rate of denitrification in primary anoxic reactor at 20°C	K120	0.72
	Second specific rate of denitrification in primary anoxic reactor at 20°C	K220	0.255
	Specific rate of denitrification in secondary anoxic reactor at 20°C	K320	0.072
	Half saturation constant for RBCOD utilisation at 20°C	Kc20	0.06

Wastewater Treatment Operational Parameters, Input B

The operational parameters in Table 4-3 below are required to enable the definition of the Reactor, Secondary Settling tanks and Anaerobic Digesters. The operational parameters are plant specific and would be expected to be different for most WWTWs.

Table 4-3: Activated Sludge Reactor and Secondary Settling Tank Parameters

AS Sizing and Flows	
Parameter	Symbol
Anoxic Vol.	V_ax
Anaerobic Vol.	V_an
Total Aerobic	V_aer
Total Vol. (VAS)	V_AS
Anoxic fraction	f_Xd
Anaerobic fraction	f_Xana
Aerobic fraction	f_Xaer
SST Area	AST
anoxic to anaerobic recycle ratio	r_recy
mixed liquor recycle ratio	a_recy
Sludge underflow recycle ratio	S_recy
Waste Flow rate	Qw

Anaerobic Digester	
Parameter	Symbol
Selected TSS	AD_TSS
Volume	AD_Vol
Sludge age	AD_Rs

4.1.2.3 Description of the Characterisation Procedure

The data in Table 4-1 above input A, needs to be transformed from chemical and physical analysis to influent wastewater characteristics. The influent unbiodegradable fractions ($f'up$ and $f'us$) and mass ratios (f_{cv}, f_c, f_n and f_p) from the data reconciliation process are used to calculate the raw and settled WW inorganic settleable solids (ISS), TKN, FSA, TP, OP and COD (unbiodegradable and biodegradable soluble, settleable particulate and suspended particulate) characteristic components. Figure 4-2 below depicts the typical wastewater fractionation tree for COD, carbon, nitrogen and phosphorus.

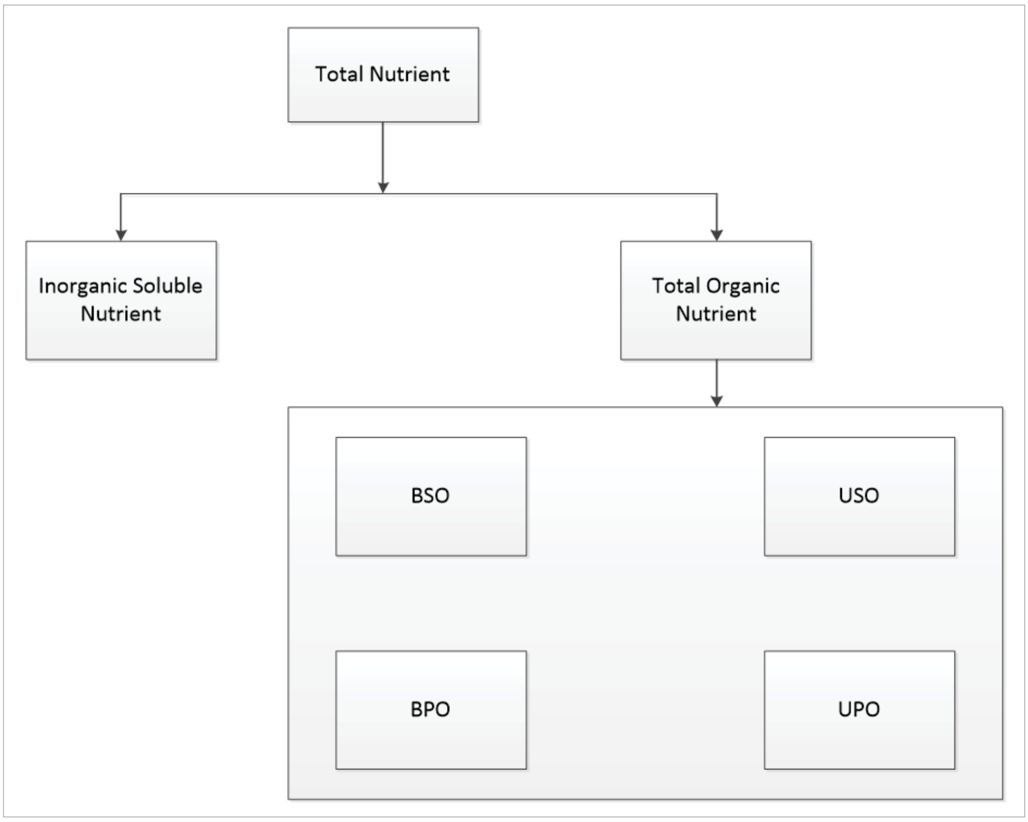

Figure 4-2: Typical fraction found in wastewater (COD, Carbon, Nitrogen and Phosphorus)

These typical characteristics are further broken down to ensure that the characterisation can be used for micro biological kinetic parameters.

The breakdown describes biodegradable, unbiodegradable, non-settleable, settleable and particulate components. Table 4-4 below is a typical breakdown for the characterisation.

To carry out the influent characterisation, the raw measured data from the WWTW and the generally observed wastewater characteristic fractions, obtained from literature (Brink and Ekama, 2010; Poinapen et al., 2010; Sötemann et al., 2006) are used together with the method proposed by Ikumi (2011) towards data reconciliation and sewage characterisation.

Table 4-4: Typical WW Characterisation

Characterisation Component	Acronym
Parameter	**Symbol**
Total COD	S_{ti}
Total Soluble COD (filtered COD)	S_{tsi}
Total Particulate COD	S_{tpi}
Unbiodegradable Soluble COD fraction	$f_{S'us}$
Unbiodegradable Particulate COD fraction	$f_{S'up}$
Unbiodegradable Soluble COD	S_{usi}
Unbiodegradable Particulate COD	S_{upi}
Biodegradable Particulate COD	S_{bpi}
Biodegradable Soluble COD	S_{bsi}

Characterisation Component	Acronym
Fermentable Biodegradable Soluble COD	S_{bsfi}
VFA fraction of COD	$f_{S'bsai}$
COD in Volatile Fatty Acids	S_{bsai}
Total Biodegradable COD	S_{bi}
Readily biodegradable fraction of COD	f_{bs}
Fraction of COD that is BPO	F_{XSP}
Total Unbiodegradable COD	S_{ui}

4.1.2.4 PWSSMBM Output Data

This section indicates the expected output data from the PWSSMBM and describes the assumptions made to perform activated sludge and anaerobic digester calculations.

Activated Sludge Reactor Parameters

To ensure a standardised assessment of AS reactor performance the calculation procedure needs to follow a guideline with fixed criteria.

1. The following assumptions were used to perform the AS calculations:
2. A sludge age of 10 days,
3. The temperature was fixed at 18°C,
4. To determine energy consumption, assumptions were made for vertical aerators and diffused bubble aeration to have a standard oxygen transfer rate (Rstd) of 4 kgO_2/kWh and blower efficiency (BEFF) of 85%.

4.1.2.5 Activated Sludge Reactor Output Data

The following parameter values are derived from the calculations performed for the AS module.

Table 4-5: Activated Sludge Reactor Output Data

	Parameter
1.	Reactor MLSS concentration
2.	Ammonia reactor effluent concentration
3.	Nitrate effluent concentration
4.	Ortho-Phosphate reactor effluent concentration
5.	Denitrification Potential
6.	Oxygen demand for the conversion of COD
7.	Oxygen demand for the conversion of ammonia
8.	Oxygen recovery from denitrification
9.	Total Oxygen demand
10.	Energy demand

4.1.2.6 Anaerobic Digestion Reactor Parameters

To ensure a standardised assessment of AD reactor performance the calculation procedure needs to follow a guideline with fixed criteria.

The following procedure was followed to perform the AS calculations.

1) Sludge Age for heated digesters is 20 days and sludge age for cold digestion is 60 days.
2) Ambient temperature for cold digestion is 18°C.

4.1.2.7 Anaerobic Digester Reactor Output data

The AD input data is determined from the sludge thickening unit operations that are a gravity thickener and a DAF – Parameters such as the flow, TSS, etc. where determined following a mass balance on the unit operations mentioned above. The following parameter values are derived from the calculations performed for the AD module.

Table 4-6: Anaerobic Digester Output Data

	Parameter	Unit
1	TSS (XT)	mgTSS/ℓ
2	VSS	mgVSS/ℓ
3	ISS	mgISS/ℓ
4	COD	mgCOD/ℓ
5	Total N	mgN/ℓ
6	FSA	mgN/ℓ
7	Mg	mgMg/ℓ
8	K	mgK/ℓ
9	Ca	mgCa/ℓ
10	Total P	mgP/ℓ
11	OrthoP	mgP/ℓ
12	Methane Produced	mgCH_4/d
13	Carbon Dioxide Prod.	mgCO_2/d
14	Gas Produced	litres
15	pH After precipitation	
16	Bicarb. Alk , i.e. no P(After precipitation)	mg$CaCO_3$/ℓ
17	Bicarb. Alk , i.e. incl. P(After precipitation)	mg$CaCO_3$/ℓ

4.1.3 PWSSMBM Development for an Operational WWTW

A WWTP comprises a sequence of individual unit operations, e.g. PSTs, AS reactors, SSTs, ADs or AerDs. These individual unit operations are interconnected through a network of flows. The outputs from upstream units become inputs to downstream units.

A common practice at a WWTP is to recycle various liquors, e.g. sludge thickening and anaerobic digestion supernatant, from downstream unit operations to upstream ones. This interconnection of individual unit operations means that design and operation optimisation of one unit may have unexpected and often unforeseen consequences on the technical and economic performance of the other unit.

4.1.4 Activated Sludge (AS) Steady State Model

The AS mass balanced steady state model for Nitrification Denitrification Biological Excess Phosphorus Removal (NDBEPR) is used to calculate the design parameters for AS systems, i.e. volume of reactors, minimum sludge age, oxygen demand, recycles ratios, effluent concentrations, WAS flow and composition, etc., given the influent characteristics, and selected sludge age. This model is essentially the steady state model developed by Marais and Ekama (1976) model for organics removal and nitrification, extended to include denitrification and phosphorus removal stoichiometry (Wentzel et al., 1990; Dold et al., 1992). The steady state model is used in a stepwise way to determine the design parameters of the plant. These steps can be summarised as follows:

- Capacity determination for organics removal
- Nitrification and Determination of sludge age
- Denitrification and optimum nitrate recycle flow

4.1.4.1 Capacity determination for organics removal and sludge production:

The daily load of organic and inorganic material fed into the wastewater treatment plant determines the mass of sludge that shall be produced in the plant. The capacity of a plant is its capability to contain the sludge generated due to the treatment process and maintain good effluent quality. This imposes requirements for the SST surface area, such that sludge overflow to the effluent is avoided. Given the SST surface area and the sludge settleability characteristics, the steady state model considers the maximum concentration of sludge to settle, without overflow, in calculating the allowable flow rate into the SST, hence the maximum flow into the AS system is determined. For this reason, the organic load and sludge settleability becomes significant parameters that dictate the AS system size (Ekama, 2015).

For the given waste characteristics and influent flow rate, the flux of organics entering the reactors for treatment is tracked using the mass balanced model. The unbiodegradable particulates accumulate in the reactors with sludge age, and the biodegradable organics form biomass. The unbiodegradable soluble do not settle with the sludge (i.e. which at SS treatment is mainly biomass and unbiodegradable particulates) but is in the SST overflow that makes up the effluent.

Thus, the daily fluxes of the various organic characteristic components, USO, UPO, BPO and FSO and VFA, have a significant influence on the mass of sludge produced. This implies that there is a limitation on the plant of prescribed reactor volume and SST surface area – on the amount of sewage load, with pre-determined characteristic concentrations, that can be handled for a successful treatment process, within a given system sludge age (R_S). For safe design, the minimum concentration of sludge, to avoid SST overflow, is determined using the PWWF as the flow to the SST and thereafter, the minimum volume of the reactor is used to determine the ADWF.

According to the steady state equations the predicted sludge production, used in capacity determination, is linked to organic removal from the plant, since the biomass grows from complete utilisation of the biodegradable organics in the sewage. Some of the influent N and P are used as nutrients to form part of the biomass, but the plant also functions to remove excess N (through nitrification and denitrification) and excess P (through polyphosphate accumulation). With the plant capacity for organic removal determined, the remaining requirements for N and P removal (such as sludge age and sludge recycle rates and aeration) are superimposed as further calculations in determination of the plant capacity.

4.1.4.2 Nitrification and determination of minimum sludge age

The biological conversion of ammonia to nitrates (nitrification) is carried out by autotrophic nitrifying organisms that grow at a certain rate (sensitive to temperature), hence require to be sustained in the reactor for a minimum period to avoid their washout from the system. Because Nitrifiers are the slowest growing organisms in the system; they dictate the system sludge age (Ekama, 2011). In Appendix A below, the calculation is presented for determining minimum sludge age for maximum nitrification, while also accounting for potential Nitrifiers endogenous mass loss in the system unaerated zones.

According to Ekama and Wentzel (2008), the selected sludge age is to be greater than this calculated minimum for nitrification to allow for greater attenuation in effluent ammonia concentration relative to influent ammonia cyclic flow and load variation. Moreover, using the same equations as in the appendix, for a given sludge age (R_s), the minimum design aerobic sludge mass fraction is calculated on determination of the maximum allowable sludge mass fraction to allow for nitrification (f_{Xm}). Hence for known maximum specific growth rate of Nitrifiers (μAMT), the minimum sludge age influences the unaerated sludge mass fraction (f_{xt}, which when lowered increases the aerobic volume, hence capacity for nitrification) and vice versa. Also, at a given sludge age, increase in the μAMT means higher utilisation of ammonia by Nitrifiers, hence increasing the plant capacity for nitrification. Ideally, once the sludge age is selected, the reactor volume and SST surface area are determined by selecting the reactor TSS that allows for the lowest combined cost of reactor volume and settling tank (Ekama et al., 1997).

4.1.4.3 Denitrification and Optimum Nitrate Recycle Flow

The total N that enters the AS system either ends up being part of the daily sludge waste, i.e. this is the N bound in unbiodegradable organics or that was used in biomass formation (N_s), getting aerobically converted to nitrates or exiting the plant as part of the effluent.

The nitrification capacity (NC) of the system is the potential mass of ammonia converted to nitrate produced due to aerobic nitrification. The N removal from the system depends on the quantity of influent N used for biomass production and extent at which nitrification has taken place in the system. Subsequent to nitrification, is the anoxic conversion of nitrates to nitrogen, which exits the system as gas, i.e. de-nitrification (Ekama and Wentzel, 2008).

For plants that carry out both N and P removal, it is hoped zero nitrate recycle to the anaerobic reactor (i.e. that the recycles to the anoxic reactor do not get overloaded with nitrate). The denitrification potential is the quantity of nitrates that the AS system can convert to nitrogen biologically, in its unaerated (anoxic) zone. The denitrification potential depends on the quantity of organism mass (existing in the anoxic zone), the availability of influent organics for utilisation as substrate and the rate at which these substrates are used catabolically for denitrification.

When the nitrates load recycled to the anoxic reactor equals the denitrification potential of the reactor, the recycle rate to this anoxic reactor is at an optimum (i.e. a_recycle = ao_recycle). Initially, the rapidly biodegradable organics (RBCOD) entering the first unaerated zone could be used for denitrification, as long as nitrates are available in this zone. Therefore, if the anaerobic zone has NO_3 recycled to it, phosphorus accumulating organisms also participate in denitrification, decreasing their potential for P release as they use up RBCOD for denitrification instead of sequestering them.

For 3-stage Phoredox processes such as that currently used in 'Z' WWTW, if NO_3 concentration to the anaerobic zone is significantly high, it could become entirely anoxic – the process configuration becomes similar to the Modified Ludzack Ettinger (MLE) type (with the whole unaerated zone, initially anaerobic and anoxic, becoming essentially all anoxic). As a result of this, minimal amounts of phosphorus will be removed.

If the anoxic sludge mass is sufficient and the a-recycle is less than optimum (i.e. a < ao), then the effluent nitrate is at minimum, such that minimum nitrates get recycled back to the anaerobic reactor and there is low potential for denitrification in SSTs.

In this case, the system is not well suited to participate in efficient P removal. Besides excess nitrate recycle to anaerobic zone, other factors that would reduce excess P removal include low quantities of RBCOD (and acetate) in the influent (for PAO growth) and P limitation in the system (low P content in influent).

The optimum a-recycle ratio (per unit influent flow rate) is calculated using the method presented by Henze et al. (2008), also shown on the appendix. Also considered in this calculation is the influence of the anoxic mass fraction (f_{xd}), which when high, increases capacity for denitrification, to allow for low effluent nitrate (N_{ne}) concentration.

4.1.4.4 Aeration Requirements

The measured oxygen utilisation rate (OUR_m) includes both the oxygen used in nitrification and that used in formation of active mass and its endogenous respiration. With knowledge of the mass of nitrates formed, we are able to calculate the flux of oxygen used in the nitrification process (FOn). We can hence determine the flux of oxygen used in the conversion of organics (FOc) by subtracting the flux of oxygen used in nitrification (FOn) from this total mass of oxygen used (FOm).

The biodegradable COD and TKN loads and their variation over the day for utilisation in biomass growth and nitrification processes set the daily average and peak total oxygen demands (TOD = COD + 4.57 TKN). To determine the peak oxygen demand requires knowing the peak TOD load to system, which is often expressed in the form of its relative amplitude ratio to the average daily oxygen demand.

4.1.5 Anaerobic Digestion (AD) Steady State Model

This worksheet contains the UCT steady state AD model, which is essentially an extension of the one developed by Sötemannet al. (2005). In this steady state AD model, the hydrolysis of a generic particulate biodegradable organics (BPO) in sewage sludge is represented as,

$$C_xH_yO_zN_aP_bS_c$$

Where:

C = *Carbon*
H = *Hydrogen*
O = *Oxygen*
N = *Nitrogen*
P = *Phosphorus*
x = *molar fraction of carbon in elemental formula for organic material*
y = *molar fraction of hydrogen in elemental formula for organic material*
z = *molar fraction of oxygen in elemental formula for organic material*
a = *molar fraction of nitrogen in elemental formula for organic material*
b = *molar fraction of phosphorus in elemental formula for organic material*

$C_xH_yO_zN_aP_bS_c$ can also be expressed as $C_{fc/12}H_{fH/1}O_{fO/16}N_{fn/14}P_{fp/31}$ and if the composition needs to be expressed in terms of C=1 rather than Y=7 then it can be simply found from $C_1H_{Y/X}O_{Z/X}N_{A/X}P_{B/X}$.

The hydrolysis of $C_xH_yO_zN_aP_b$ is the rate-limiting step so that the AD processes that follow it, being much faster, are dealt with stoichiometrically to yield directly the digester end products, i.e. biomass, CH_4, carbon dioxide (as dissolved HCO_3^- and gaseous CO_2), NH_4^+ and water. This extended SS model (Sötemann et al., 2005; Harding et.al. 2009; Ikumi, 2011) comprises three sequential parts:

1) A COD based hydrolysis kinetic part from which the concentration of biodegradable COD utilised, and methane and sludge production are determined for a given AD sludge age (R_s, which is also equal to hydraulic retention time for flow through ADs).

2) A COD, C, H, O, N, P mass and charge balance stoichiometry part from which gas production and composition (or partial pressure of CO_2), NH_4^+ released, biomass produced and alkalinity generated (HCO_3^-, $H_2PO_4^-$ and HPO_4^{2-}) are calculated from the biodegradable COD removal.

3) A three-phase mixed inorganic carbon and ortho-phosphate weak acid/base chemistry part from which the digester pH and mineral precipitation is calculated.

Anaerobic Digestion (AD) Unit Process

The AD system is linked to the AS system for treatment of its waste sludge and/or the primary sludge produced from the primary settling tank. For the AD system to operate stably, it requires good composition of feed sludge, well controlled feeding schedule, good mixing efficiency, optimum, mesophilic (35°C) or thermophilic (55°C) temperature, sufficient hydraulic retention time, controlled pH and alkalinity and well acclimatised biomass (Sacks, 1997).

The calculation of the AD design reactor volume and digester products is based on the selection of the ADs SRT as the principle design parameter and organic loading rate, which in completely mixed AD systems are directly related. In this case, the minimum AD SRT of 30 days was considered, to ensure that the system does not to fail due to the wash out of methanogenic biomass and that the feed sludge is stabilised to a satisfactory extent. With knowledge of the feed flow rates of WAS and PS to the AD, the flux of all AD influent components are determined and applied to the AD model for conditions where the both PS and WAS are blended in one digester. However, the model is flexible enough to allow for the PS to be digested separately from the WAS. The sludge concentration to the AD shall need to be agreeable, here a maximum of 50 000 mgTSS/ℓ was selected.

Despite the cost effectiveness of having higher solids concentration in the AD, over-thickening of the AD feed sludge could interfere with effective mixing, which helps to reduce most of the accumulating scum and grit dispersed through the digesting tank. The steady state AD model UCTSDM, of Ekama (2009); Harding et al. (2011); Ikumi (2011), was used to determine the quantities of residual biodegradable organics, nutrients released to form effluent products, digester pH, digester alkalinity, carbon dioxide evolved and methane production for the plant treating WAS.

4.1.6 *Calculation Procedure to Evaluate the Impact of SRL*

- Input waste characteristics were modified using the mass balance equation below.

$$Influent\ Load + Return\ sludge\ liquor\ Load = New\ Load$$

$$(C_i \times Q_i) + (C_{RT} \times Q_{RT}) = (C_N \times Q_N)$$

Where:

C_i = Concentration of COD, Nitrogen and Phosphate in influent flux – mg/ℓ

C_{RT} = Concentration of COD, Nitrogen and Phosphate in return flux – mg/ℓ

C_N = New Concentration to the activated sludge system

Q_i = Influent flowrate – Mℓ/d

Q_{RT} = Return flowrate – Mℓ/d

Q_N = New flowrate to the activated sludge system

- The fractions of each input characteristic change following the introduction of a side-stream flux. The equation used to modify the influent characteristics following flux from the return flows is shown below;

$$(C_i \times Q_i) + (C_{RT} \times Q_{RT}) = (C_N \times Q_N)$$

- New Concentration

$$C_N = \frac{(C_i \times Q_i) + (C_{RT} + Q_{RT})}{Q_N}$$

- At a selected percentage of side-stream treatment, new concentrations for each module can be calculated as shown in the equation below.

$$C_N = \frac{(C_i + Q_i) + [(C_{RT} + Q_{RT}) \times Selected\ \%]}{Q_N}$$

The percentage side-stream treatment (varies from 0% treatment to 100% treatment). 0% side-stream treatment means that 100% of the return sludge liquors are being recycled back to the activated sludge system.

- Calculation of percentage impact

$$\left[\frac{P_N - P_i}{P_i}\right] \times\ 100\% = \%\ impact$$

Where:

P_N = Selected parameter at selected percentage side-stream treatment

P_i = Selected parameter at 100% side-stream treatment (0% recycle)

4.1.7 Variables Used to Evaluate the Impact of SRL

The following variables were selected in the process of evaluating the impact of recycling SRL:

1) Impact of recycled SRL flows against the plant hydraulic capacity. The SRL is sourced from:

   i. the outflow from the DAF thickener of the WAS and,

   ii. the outflow from the thickener of the AD effluent.

   The volume of solubles generated from (i) and (ii) above are usually slightly less than the volumes of the inflow to the thickening process (i.e. WAS flow and AD effluent flows). The WAS flow and AD flow rates are usually significantly smaller than the AS influent flow rate, hence it is expected that the recycles from these flows shall not have a significant impact on the hydraulic retention time in the AS system. With this established quantitatively, it is possible to distinguish from the influent loads whether the high concentrations of nutrients recycled are the main cause to alterations in the AS system performance.

2) Organic and Nutrient Loading: Under ideal operating conditions it is expected that the soluble COD of the WAS and the AD effluent shall be equal to the unbiodegradable solubles, with all biodegradable solubles utilised very rapidly in the reactors. This unbiodegradable soluble COD usually contributes very little to the total influent COD. The nutrients, N and P measured mainly as free and saline ammonia (FSA) and orthophosphates (OP), are expected to be present in larger quantities, mainly from the recycled AD effluent solubles which are collected after the thickening of AD effluent. The concentration of this nutrients may vary according to (1) the system sludge age (the higher the ADs Rs, the more time allowed to break down the biodegradables in the feed) and the (2) composition of the AD feed (with more N and P bound in the biodegradable organics, the more nutrients that are released in the AS).

3) Optimum aerobic to anoxic nitrate recycle rate: The increase in influent N, due to the quantities of ammonia recycled upstream from dewatering liquors, is expected to result in higher generation of nitrates in the aerobic zone of the AS system. Because, ideally it is the concentration of nutrients recycled from the AD that are much higher than the concentration of biodegradable organics (theoretically expected to be zero), the increase in nitrates generated (which are electron acceptors in anoxic conditions) is not matched with increase in biodegradable organics (which act as electron donors). Hence, for a constant anoxic mass fraction, the capacity for denitrification is not altered and may require that the loading rate of nitrates to the anoxic zone to be slowed down such that it is matched against the strength of the biodegradable organics.

4) Oxygen Demand: It is expected that the increased ammonia loads due to the dewatering liquor recycles shall result in a higher aeration demand, due to the requirement of oxygen by aerobic nitrifying organisms to convert the ammonia to nitrates. This nitrification oxygen demand contributes towards the aeration energy required in the AS system.

5) Sludge generation: As the biodegradable organics recycled with dewatering liquors is expected to be very low (close to zero), the sludge generation with growth of heterotrophic biomass in the AS system is not expected. However, the autotrophic nitrifying organisms may increase with the higher concentrations of ammonia brought by the recycle streams. If, to avoid poor effluent quality, readily biodegradable organics would be dosed to enhance denitrification and phosphorus removal, the sludge generation with growth of heterotrophs would increase and affect the system total solids concentration.

6) Effluent Quality: Under ideal theoretical conditions, the effluent COD is not expected to increase due to dewatering liquor recycles. However, if this recycles result in the overloading of N and P, beyond the system's capacity for their removal, poor effluent quality may be observed. The system's capacity for removal of nitrates and phosphates may be enhanced with dosage of readily biodegradable organics, but this also has a limitation according to the maximum TSS generation allowed for the plant. The dosage of organics would cause an increase in TSS generation a due to biomass growth. If this TSS goes beyond the required limit that can be accommodated by the plant secondary settling tank area, the sludge would overflow from the SST into the effluent to result in poor effluent quality. For the purpose of consistency and simplicity the dosage of organics has not been included in this exercise. However, the changes in effluent quality due to N and P recycle in dewatering liquor can be observed.

4.1.8 Impact of SRL on WWTPs at 0% Side-stream Treatment

The table below summarises the impact of SRL on the influent, biological capacity and effluent parameters on all the WWTPs under investigation at 0% side-stream treatment.

Table 4-7: Summary of impact of SRL on WWTWs at 0% side-stream treatment

Impact On SRL at 0% Side-stream Treatment							
Parameter		**'W'**	**'Z'**	**'P'**	**'K'**	**'C'**	**'D'**
Influent	Flow rate	4.2%	7.5%	3.3%	5.7%	3.8%	1.9%
	COD	0.7%	0.9%	0.4%	0.5%	0.7%	0.1%
	Ammonia	9.1%	15.7%	10.4%	13.1%	19.1%	0.0%
	PO_4	235.0%	125.0%	1.0%	4.21%	129.0%	0.0%
Biological Reactor	a-recycle	-29.0%	-51.0%	-38.0%	0.0%	-76.0%	40.0%
	Total Oxygen Demand	2.2%	4.5%	2.9%	2.6%	1.7%	0.1%
	Aeration Power Requirement	2.2%	4.5%	2.9%	2.6%	4.5%	0.1%
	SS Produced	15.1%	0.0%	0.1%	1.1%	13.2%	1.1%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	6.1%	8.5%	12.2%	4.0%	5.7%	-2.2%
	PO_4	0.0%	790.1%	0.0%	1.2%	0.0%	0.0%

4.2 Results

Detailed results for the different WWTP can be found in Appendix 2. This section will present a summary of the impact of sludge return flows for each of the treatment plants.

4.2.1 Summary of Impacts of SLR on the WWTP 'W's Activated Sludge System

The table below summarises the percentage impact at a given percentage side-stream treatment starting from 0% side-stream treatment to 100% side-stream treatment. The table shows both the average impact and the impact for each module at Plant 'W'.

Table 4-8: Percentage impact at given percentage side-stream treatment at WWTP 'W'

Percentage Impact at given Percentage Side-stream Treatment at WWTP 'W'							
Parameter		**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Influent	Flow rate (Average)	4.2%	3.3%	2.5%	1.7%	0.8%	0.0%
	COD (Average)	0.67%	0.5%	0.4%	0.3%	0.1%	0.0%
	Ammonia (Average)	9.1%	7.5%	5.7%	3.8%	2.1%	0.0%
	PO_4 (Average)	234.7%	117.0%	73.3%	41.9%	18.4%	0.0%
Biological Reactor	a-recycle Average)	-29.5%	-25.1%	-20.3%	-14.5%	-7.7%	0.0%
	Total Oxygen Demand (Ave.)	2.2%	1.8%	1.4%	0.9%	0.5%	0.0%
	Power Requirement (Ave.)	2.2%	1.8%	1.4%	0.9%	0.5%	0.0%
	SS Produced	15.1%	7.6%	4.8%	2.7%	1.2%	0.0%
Effluent	COD Average	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	6.1%	5.1%	4.1%	2.9%	1.5%	0.0%
	PO_4 (Average)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The highest impact was observed for influent phosphate load at 235% of the effluent ammonia concentration

4.2.2 Summary of Impacts of SRL on the WWTP 'Z's Activated Sludge System

The table below summarises the percentage impact at a given percentage side-stream treatment starting from 0% side-stream treatment to 100% side-stream treatment at Plant 'Z'.

Table 4-9: Percentage impact at given percentage side-stream treatment at WWTP 'Z'

Percentage Impact at given Percentage Side-stream Treatment at WWTP 'Z'							
Parameters		**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Influent	Flow rate	7.5%	6.0%	4.5%	3.0%	1.5%	0.0%
	COD	0.9%	0.7%	0.5%	0.3%	0.2%	0.0%
	Ammonia	15.7%	10.0%	5.6%	2.5%	0.6%	0.0%
	PO_4	124.8%	79.3%	44.3%	19.6%	4.9%	0.0%
Biological Reactor	a-recycle	-51.0%	-37.1%	-23.2%	-11.3%	-2.6%	0.0%
	Total Oxygen Demand	4.5%	2.9%	1.6%	0.7%	0.2%	0.0%
	Power Requirement	4.5%	2.9%	1.6%	0.7%	0.2%	0.0%
	SS Produced	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	8.5%	4.4%	1.5%	-0.3%	-0.8%	0.0%
	PO_4	790.1%	508.7%	288.4%	129.5%	32.8%	0.0%

The major impact was observed for influent PO_4 load and effluent PO_4 were the impact was 125% and 790% respectively.

4.2.3 Summary of Impacts of SRL on Influent Characteristics at WWTP 'P'

The table below summarises the percentage impact at a given percentage side-stream treatment starting from 0% side-stream treatment to 100% side-stream treatment at Plant 'P'.

Table 4-10: Percentage impact of SRL at given side-stream treatment at WWTP 'P'

Percentage Impact at given Percentage Side-stream Treatment at WWTP 'P'							
Parameter		0%	20%	40%	60%	80%	100%
Influent	Flow rate	3.3%	2.6%	2.0%	1.3%	0.7%	0.0%
	COD	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%
	Ammonia	10.4%	6.7%	3.8%	1.7%	0.4%	0.0%
	PO_4	0.8%	0.5%	0.3%	0.1%	0.0%	0.0%
Biological Reactor	a-recycle	-37.8%	-25.7%	-15.0%	-6.6%	-1.4%	0.0%
	Total Oxygen Demand	2.9%	1.8%	1.0%	0.5%	0.1%	0.0%
	Aeration Power Requirement	2.9%	1.8%	1.0%	0.5%	0.1%	0.0%
	SS Produced	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	12.2%	7.3%	3.6%	1.1%	0.0%	0.0%
	PO_4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The major impact was observed for influent ammonia load and effluent nitrate were the impact was 10.4% and 12.2% respectively.

4.2.4 Summary of Impacts of SRL Return Liquors at WWTP 'K'

The table below summarises the percentage impact at a given percentage side-stream treatment starting at 0% side-stream treatment at Plant 'K'.

Table 4-11: Percentage impact of SRL for given side-stream treatment at WWTP ''K'

Percentage Impact at given Percentage Side-stream Treatment at WWTP 'K'							
Parameter		0%	20%	40%	60%	80%	100%
Influent	Flow rate	5.7%	4.6%	3.4%	2.3%	1.1%	0.0%
	COD	0.5%	0.4%	0.3%	0.2%	0.1%	0.0%
	Ammonia	13.1%	8.4%	4.7%	2.1%	0.5%	0.0%
	PO_4	4.2%	2.7%	1.5%	0.7%	0.2%	0.0%
	Total Oxygen Demand	2.6%	1.7%	0.9%	0.4%	0.1%	0.0%
	Aeration Power Requirement	2.6%	1.7%	0.9%	0.4%	0.1%	0.0%
	SS Produced	1.1%	0.9%	0.6%	0.4%	0.2%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	4.0%	1.7%	0.1%	0.0%	0.0%	0.0%
	PO_4	1.2%	0.0%	0.0%	0.0%	0.0%	0.0%

The major impact was observed for influent ammonia load were the impact was 13.1%.

4.2.5 Summary of Impacts of SRL on WWTP 'C's Activated Sludge System

The table below summarises the percentage impact at a given percentage side-stream treatment at Plant 'C'.

Table 4-12: Percentage impact for selected side-stream treatment at WWTP 'C'

Percentage Impact at given Percentage Side-stream Treatment at WWTP 'C'							
Parameter		**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Influent	Flow rate	3.8%	3.0%	2.3%	1.5%	0.8%	0.0%
	COD	0.67%	0.53%	0.40%	0.27%	0.13%	0.00%
	Ammonia	19.1%	12.9%	7.4%	3.3%	0.8%	0.0%
	PO_4	129.0%	55.0%	24.5%	9.5%	2.2%	0.0%
Biological Reactor	a-recycle	-76.1%	-55.5%	-34.5%	-9.1%	-2.1%	0.0%
	Total Oxygen Demand	1.7%	3.1%	1.8%	0.8%	0.2%	0.0%
	Aeration Power Requirement	4.5%	3.1%	1.8%	0.8%	0.2%	0.0%
	SS Produced	13.2%	6.0%	2.9%	1.3%	0.4%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	5.7%	5.3%	4.4%	3.2%	1.7%	0.0%
	PO_4 (Average)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The major impact was observed for influent phosphate load were the impact was 129%.

4.2.6 Summary of Impacts of SRL on Influent Characteristics at WWTP 'D'

The table below summarises the percentage impact at a given percentage side-stream treatment at Plant 'D'.

Table 4-13: Percentage impact of SRL for given side-stream treatment at WWTP 'D'

Percentage Impact at given Percentage Side-stream Treatment at WWTP 'D'							
Parameter		**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Influent	Flow rate	1.9%	1.6%	1.2%	0.8%	0.4%	0.0%
	COD	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	PO_4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biological Reactor	a-recycle	40.4%	36.3%	36.3%	16.2%	8.2%	0.0%
	Total Oxygen Demand	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
	Aeration Power Requirement	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
	SS Produced	1.1%	0.4%	0.3%	0.2%	0.1%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	-2.2%	-1.8%	-1.5%	-0.9%	-0.5%	0.0%
	PO_4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The highest impact was observed for a-recycle at 40%.

4.3 Discussion

This section consolidates the reasoning behind the findings from the results for the six plants in this research. These findings are discussed according to the variables of importance, influent parameters, biological treatment capacity and effluent quality.

4.3.1 Influent Parameters

4.3.1.1 Influent Flow rate

The influent flow rates increase due to SRL recycled from dewatering liquor. However, this doesn't impact the hydraulic capacity of the plant because SRL flow rate is significantly smaller than that of the settled wastewater influent to AS system.

The general trend observed on all the plants is a decrease in the flow rate to the AS system following treatment of SRL. Significant impact was observed for Plants 'Z' and 'K'. The major impact on flow rate was observed for Plant 'Z' were the impact was 7.5% and this is because all the SRL is recycled to Module 2 of the WWTP.

The impact at Plant 'W' was 4.2% and it is important to note that this is the average for the whole WWTP. The individual impacts on the 4 modules are presented in Table 3.3 where the impact on module 1 was 2.36%, module 2 and 3 was 4.89% and finally, on module 4 was 5.27%. The high impact on module 4 is because the module receives 50% of SRL.

4.3.1.2 Influent COD Load

The impact of SRL on the COD load is a result of the hydraulic component of the load. The general trend observed on all the plants is a decrease in the influent COD load to the AS system following treatment of SRL. Theoretically, there was no significant impact observed on the concertation at any of the WWTPs. This is because the only organic component of the COD found in the SRL is the unbiodegradable soluble (USO) COD – (S_{usi}) which remains constant throughout the plant and is relatively much lower than the total influent COD. The particulate and biodegradable components of organic material will maintain their COD load (in mgCOD/d) regardless of the change in return liquor flow. However, their concentrations shall decrease with increased flow rate, by inclusion of the return streams, due to the dilution effect caused by the addition of the hydraulic flow rate from the SRL because the return streams do not contribute to their concentration.

It is important to note that the COD load for WWTP 'D' decreases with higher sludge lagoon supernatant returns, unlike at the other plants, as there is no AD at WWTP 'D' – hence no dewatering liquor from AD effluent. Theoretically, this load has a similar concentration to that of the effluent, hence is not a significant value.

It is also important to note that the given theoretical observations, assuming ideal working AD conditions and 100% efficiency in sludge thickening processes, may in some cases not be reconciled with practical occurrences. This is because of the inefficiencies in the AD process would result in presence of biodegradable soluble organics in the SRL, which would in turn result in higher reactor solids generation and higher oxygen demand.

4.3.1.3 Influent Ammonia Load

The impact of SRL on the influent ammonia load is a result of the both the FSA concentration and the hydraulic component of the load. FSA is released during AD is recycled back to the plant in SRL following dewatering.

The general trend observed on all the plants is a decrease in the influent ammonia load to the AS system following treatment of SRL except for Plant 'D' where the impact is 0% and this is because there is no AD at the WWTP. The most significant impact was observed at Plant 'C' that digests both PS and WAS, where the impact was 19.1% followed by Plant 'Z' which has an impact of 15.7%, where all the return flow of the SRL are recycled to module 2.

4.3.1.4 Influent Phosphate Load

The impact of SRL on the influent phosphate load is a result of both the phosphate concentration (PO_4) and the hydraulic component of the load. The PO_4 is released during AD, with the breakdown of P binding organics, remain in the aqueous phase and this is recycled back to the plant in SRL following dewatering.

The general trend observed on all the plants is a decrease in the influent PO_4 load to the AS system following treatment of SRL except for Plant 'D' where the impact is 0% (there is no AD at this WWTP).

The impact for Plant 'P' and Plant 'K' is 1% and 4.21% respectively, this is small compared to Plant 'W', Plant 'Z' and Plant 'C', because Plant 'P' and Plant 'K' only digest PS. The PS has no polyphosphate to be released in AD and a much lower phosphorus mass fraction than WAS (i.e. fp_bpops < fp_oho) and hence significantly less P is released per PS VSS hydrolysed in AD than per WAS VSS hydrolysed.

The impact of SRL on influent phosphate load observed at Plant 'W', Plant 'Z' and Plant 'C' were 235%, 125% and 129% respectively, this is due to the WAS being anaerobically digested at the WWTP. As a result of anaerobic digestion of the WAS, the flux of phosphates into the system is beyond the removal capacity of the PAO biomass generated in the system. Thus, the influent P that is not removed, i.e. used as nutrients for biomass growth or as PP accumulated by PAOs, reflects in the effluent.

4.3.2 Biological Treatment Capacity

4.3.2.1 A-recycle

The impact of SRL on the a-recycle is a result of the nitrification capacity. The general trend observed on all the plants is an increase in optimum a-recycle rate (ao_recycle) for AS system following treatment of SRL except for Plant 'D' where the impact is 40% as there is no AD system in this plant.

The most significant impact was observed at Plant 'W', Plant 'Z', Plant 'K' and Plant 'C' where the impact is -29%, -51%, -38% and -76% respectively.

Due to the higher ammonia flux recycled to the AS system, a higher concentration of nitrates is generated given that, ideally, there is sufficient aeration. As a result of complete nitrification (this is possible with the sludge age not too low and the appropriate design aerobic mass fractions, as described by Henze et al. (2008)) a higher nitrate load is recycled to the anoxic zone.

The optimum nitrate recycle ratio (ao_recycle) is determined with the nitrate (electron acceptor) loaded to the anoxic zone matched to the anoxic biomass (facultative OHOs – the work force) and organic load recycled to the anoxic zone (electron donor used by the facultative OHOs to break down nitrate to N_2 gas for N removal – these organics can be readily utilisable (soluble) or slowly utilisable (particulate). The more biomass (i.e. the work force) and readily biodegradable organics available in the anoxic zone, the higher the capacities for nitrate utilisation hence increasing the acceptable nitrate recycle load.

Because the plant's organic (electron donor) strength for nitrate removal remains unchanged, the calculated optimum nitrate recycle flow rate (ao) is decreased to ensure that the nitrate load to the anoxic reactor is maintained despite increases in aerobically generated nitrate concentrations. This allows for a sufficient nitrate to organic load balance that allows for optimum removal of nitrates, hence good effluent quality. Hence, for a system with operational parameters, such as nitrate recycles remaining unchanged, despite the increased return flows, poorer effluent quality is predicted. As the nitrate load decreases, following side-stream treatment to remove ammonia, the nitrate concentration generated in the aerobic zone decreases so to maintain the load to the anoxic zone, the ao_recycle increases as exhibited in all ao-recycles except at the 'D' WWTP.

The optimum recycle rates indicate the critical point over which the denitrification occurs efficiently, i.e. the practical recycle flow rates (aprac) can be kept below the ao value to ensure maximum denitrification. However, because in current practice the high level of control that could be implemented with the presence of sensors and actuators is not achieved in developing countries, the practical nitrate recycle rate was left to be the same and the ao was calculated as a reference to ideal conditions and to justify reasons (if any) of high effluent nitrate concentrations.

4.3.2.2 Total Oxygen Demand and Aeration Power Requirement

The impact of SRL on the TOD is a result of oxygen utilisation for nitrification. The general trend observed on all the plants is a decrease in the TOD for the AS system following treatment of SRL. There was no significant impact observed on any of the WWTPs. However, the highest impact was observed for Plant 'Z' with a 4.5% impact and this is because of the high ammonia load being recycled to module 2 AS system. Moreover, some of this oxygen is recovered with denitrification due to the facultative OHOs utilising the nitrates generated (instead of oxygen) for organic breakdown (Henze et al., 2008).

The lowest impact was observed at Plant 'D' as 0.1% and this is because influent ammonia load is low and the changes are marginal.

The calculated TOD is expected to increase with higher flux of nutrients recycled to the AS system, because the increased ammonia load shall utilise more oxygen for the process of nitrification. It should be noted that in some cases the plants require dosage of readily biodegradables to enhance the capacity for denitrification; it would result in a further increase of oxygen requirement, for breakdown of added organics

Because under ideal conditions, only unbiodegradable soluble organics are recycled from the AD, there is no expected increased growth of heterotrophic biomass in the AS system. However, the autotrophic microorganisms (nitrifiers) that utilise the ammonia had increased growth. Moreover, in cases where readily biodegradable organics (in case the SRL is upstream of failing AD systems) or particulate biodegradable organics are present in the SRL, the total oxygen demand would increase significantly.

Recycling significant quantities of ammonia via SRL would result in increased energy requirements to ensure oxygen is available to meet nitrification demands. In this case, the flux of oxygen decrease is marginal (relative to the requirements with 100% recycle) as per the influent ammonia flux being similarly marginal If the aeration capacity is not able to cater for the added ammonia load then the ammonia would end up in the effluent (autotrophic nitrifying organisms are obligate aerobes and require a dissolved oxygen concentration > 2 mgO/ℓ to cater for nitrification).

4.3.2.3 SS Produced

The impact of SRL on the SS produced is a result of nitrification. The general trend observed on all the plants is a decrease in the SS produced in the AS system following treatment of SRL except at Plant 'Z' where it is 0%. The most significant impact was observed for Plant 'W' with 15.1% impact because of the high ammonia load being recycled to the modules and supplying ammonia for the nitrifiers. The lowest impact was observed at Plant 'P' as 0.1% because there no ammonia recycle as there is no AD.

4.3.3 Effluent Quality

4.3.3.1 Effluent COD

This predicted value is the COD concentration of the unbiodegradable organics from the influent, assuming that all influent biodegradable soluble organics have been utilised in the AS system. The steady state model assumes ideal operation of the AS system, such that if the sludge age is greater than 3 days (Marais and Ekama, 1976), then the effluent COD mainly comprises of USO. This USO flux into the AS system increases with the recycle of the liquors from DAF, GTs and DWL from the AD back to the AS system, but the concentration doesn't change therefore the impact on all the plants is 0%.

4.3.3.2 Effluent Ammonia

There was no impact of SRL on the effluent ammonia concentration. The general trend observed on all the plants is a constant effluent ammonia concentration from the AS system.

The constant effluent ammonia concentrations at the plants are because if the reactor ammonia concentration is greater than 4 mgN/ℓ, the autotrophic nitrifying organisms (ANOs) would nitrify at their maximum rate (μA). As a result, increasing the influent ammonia concentration cannot increase their rate of ammonia utilisation (Van Haandel et al., 1981). However, the decrease in ammonia concentration below this result in drastic reductions in ANO growth rates – hence it is usually difficult to obtain effluent ammonia concentrations of below 1 mgN/ℓ. Moreover, the derived stoichiometric formula for prediction of effluent ammonia (see Appendix 1) shows that its concentration is independent of the ANO yield and influent ammonia concentration but decreases with increase in the system sludge age (Van Haandel et al., 1982; Henze et al., 2008). Hence it is expected that the increase in ammonia load to the AS systems shall not result in changes with effluent ammonia concentration as long as the system sludge age is kept consistent.

In addition, the constant ammonia concentration is a result of the simplicity of the steady state model, which allows it to be effective as a design tool (provides design parameters to ensure plant capacity for treatment given effluent quality requirements) as opposed to dynamic simulation models (which can predict the changes in effluent quality given changing flows and loads). In this case, the steady state model, checks the given sludge age and aerobic mass fraction (f_{xa}) of microorganisms to be within the calculated critical values for maximum nitrification of a given influent N load and temperature. Because these parameters (R_s and f_{xa}) were above minimum and were not adjusted with changing return flows, the effluent ammonia concentration remained at a constant minimum. However, in practice variations in effluent ammonia concentration are observable for variety of reasons, including (1) the dissolved oxygen not being available to all active sites of ANO biomass (in the SS model it is assumed that the DO measured in the mass liquid is available to ANOs that are ideally positioned on the outer zones of the biomass flocs (2) great variations in cyclic flows and loads in the AS system.

4.3.3.3 Effluent Nitrate

Some of the nitrates generated aerobically are recycled to the anoxic zone. The optimum rate of nitrate recycle that would allow for all the nitrates to be utilised in the anoxic reactor, hence minimum effluent nitrate concentration, is determined by matching the nitrate load to the anoxic reactor against its denitrification potential. The denitrification potential is governed by the anoxic mass fraction of biomass (facultative OHOs) and the substrate available (electron donor) to convert nitrates (electron acceptor) to nitrogen gas. Hence because the anoxic mass fraction and influent biodegradable COD are maintained (i.e. the denitrification potential stays the same), the increase in aerobic nitrate concentration requires a reduced flow of nitrates to the anoxic zone such that the nitrate load continues to match the denitrification potential. This reduces the optimum nitrate recycle ratio.

If the calculated ao is lower than the practical nitrate recycle rate (aprac), then the effluent nitrate concentration is not at its minimum and continues to increase with continuous reduction in ao. If the effluent nitrates are significantly high, it could result in (1) rising sludge problems due to the denitrification occurring in the secondary settling tanks (i.e. N_2 gas is produced and pushes the sludge over the SST to the effluent) or (2) reduction in anaerobic mass fraction hence potential limitation of P removal from the system (i.e. recycle of significant quantities of nitrates to the anaerobic zone would result in its conversion to more of anoxic state hence PAOs do not have their competitive advantage due to the lower potential of PAO anaerobic metabolism). Both these results would lead to overall poor effluent quality:

1) resulting in increased effluent solids and COD concentration and

2) would result in poor effluent OP concentration.

The ao could be matched to aprac by dosing of readily biodegradable substrates (e.g. acetate) to the anoxic zone, but this would significantly increase the operational costs (de Keteleet al., 2018). If the practical aerobic-anoxic recycle rate (aprac) is lower than the optimum recycle rates then the effluent nitrate concentration shall be at its minimum. If the aprac is increased above the ao value, then the anoxic zone gets overloaded with nitrates, which results in higher effluent nitrate concentrations. The 'W' WWTP always has ao values higher than aprac and predicted minimum effluent nitrate concentrations. This minimum effluent nitrate is increased with increase in nitrification capacity, when the aeration for conversion of ammonia to nitrates is not limited.

4.3.3.4 Phosphates

The side-stream treatment has no predicted impact on the effluent phosphates as the effluent OP remains at 0 mgP/ℓ. However, there are chances that, for non-ideal scenarios, the effluent OP would increase with increased flux of SRL. The possible causes are inefficient metabolism of P accumulating organisms (PAOs) due to high nitrates, recycled anaerobically and utilisation of organics by ordinary heterotrophic organisms (OHOs).

The OP in the effluent would change according to the capacity of the plant for P removal. This capacity is taken in the SS model to reach its maximum when the population of PAOs have taken up the maximum quantities of OP allowable, 0.35 mgP/mgPAOVSS, Wentzel et al. (1990). The higher the population of PAOs, the better the capacity towards P removal. This population is calculated in the model according to how much readily biodegradables are sequestered for PAO utilisation towards their growth. For a system that has less quantity of substrate available for PAOs, there is potential for the capacity being exceeded, hence more OP reflects in the effluent.

4.4 Conclusions

Table 4-14 describes the theoretical impacts for each of the plants under investigation.

Table 4-14: Description of the theoretical impacts of the plants under investigation

Plant Name	Theoretical Impacts
'W'	Flow rate increases by 3.3% if 100% SRL is returned. Influent NH_3 and PO_4 increase by 10.4% and 1% respectively% if 100% SRL is returned.
'Z'	Flow rate increases by 0.9% if 100% SRL is returned. Influent NH_3 and PO_4 increase by 15.7% and 125%% respectively% if 100% SRL is returned. Effluent PO_4 increase by 790%.
'P'	Flow rate increases by 0.9% if 100% SRL is returned. Influent NH_3 and PO_4 increase by 15.7% and 125%% respectively% if 100% SRL is returned. Effluent ammonia increases by 1152% when 100% SRL is returned.
'K'	Flow rate increases by 5.7% if 100% SRL is returned. Influent NH_3 and PO_4 increase by 13.1% and 4.21% respectively% if 100% SRL is returned. Effluent PO_4 increases by 1.2% when 100% SRL is recycled.
'C'	Flow rate increases by 3.8% if 100% SRL is returned. Influent NH_3 and PO_4 increase by 19.1% and 129% respectively% if 100% SRL is returned.
'D'	There is no impact of ammonia and PO_4. There is no impact on effluent ammonia and PO_4.

The conclusions shall give a general overview of the theoretical results touching the following items:

1. The main impacts associated to the recycling of SRL under the several studies are brought about by the increased influent flow rate and higher flux of ammonia and phosphates, to the system. The ammonia has a direct impact on the aeration requirements of the AS system, with more oxygen required to meet the increased nitrification capacity and ensure good effluent quality. With the increase in nitrates generated and the denitrification potential maintained, the optimum nitrate recycle flow rate to the anoxic zone is reduced to ensure that maximum N removal is achieved. If this calculated ao is less than that the practical implemented nitrate recycle flow rate from aerobic to anoxic zone, there is a risk of nitrate overload to the anoxic zone resulting in high effluent nitrates. The high nitrates may also have an indirect effect to effluent quality by (1) causing the problem of rising sludge from the SST, i.e. when the retention time in the SST allows for denitrification to happen there causing N_2 gas to push up the sludge to be settled towards the effluent, and (2) inefficient P removal when large flux of nitrates get recycled to the "anaerobic" zone.

2. The requirements for P removal include anaerobic uptake of readily biodegradable organics to form high energy storage compounds (poly-hydroxy-butyrate, PHB), with release of polyphosphates (PP), by PAOs and the subsequent aerobic utilisation of PHB for growth of PAOs with the storage of PP. Because the PAOs can only store a maximum of 0.35 mgP of PP per unit PAO mass (Wentzel et al., 1990), a significant increase in influent P requires substantial substrate allocation towards PAO biomass growth, such that they can continue the removal of the excess P. Ideally, the recycling of SRL does not result in increased load for readily biodegradable organics – hence the PAO biomass growth cannot increase to match the P removal demands. This results in poor effluent quality.

3. To ensure effluent quality, the aeration must be increased to accommodate the higher influx of ammonia via SRL. In this study, the increased aeration demands are less than 10% higher than the original aeration requirements (without SRL). Moreover, to reduce the nitrate and OP effluent

concentrations, it would be necessary to dose readily biodegradable organics to the anoxic and anaerobic zones respectfully. This together with the costs of increasing aeration capacity of the plant may have a significant impact on the cost of operation. The next phase of this project intends on quantifying whether the cost benefits with treatment (without SRL) far outweighs the cost without treatment, towards projecting if it would be beneficial to treat SRL. The treatment of SRL can also be beneficial to generate income from harvesting nutrients from the side-stream flows.

CHAPTER 5: DECISION-MAKING TOOL & MANUAL

Wastewater treatment plant models have been used by consulting engineers and researchers for process evaluation. However, there has been a recent growing interest from different stakeholders, i.e. plant operators, supervisors and municipalities, in using these models over the past 10 years (Menniti et al., 2018). According to Lizarralde et al. (2018), these tools are being primarily used to help them make better decisions with respect to capital and operational costs of treatment plants so that the ever-rising stringent effluent quality standard can be met. The challenge, however, is that the developed steady-state plant-wide models such as the work of Wu and Ekama (2015) are too complex to be used by newly interested stakeholders who do not necessarily have enough technical expertise in using these tools. The success of these tools depends on how well they can be used by these new stakeholders while producing appropriate results.

The mathematical plant-wide steady-state models have been simplified into a simple tool that will be used evaluating the impact of return dewatering liquor on the overall plant-wide performance (i.e. effluent quality and operational cost). This tool was developed based on scientifically sound mass balance information. The evaluation process entails contrasting the effect of having side-stream treatment or not having one to the plant performance.

The tool can be found under Appendix 4 and the complete manual under Appendix 3.

5.1 Tool objective

The integrated steady-state model equations that virtually replicate the entire WWTP processes are streamlined further to suit the potential user. This simple tool will be used for evaluating the impact of return dewatering liquor on the overall plant performance, that is the effluent quality and operational cost. The tool was developed on the scientific principle of strict material mass and charge balance. The evaluation process entails contrasting the benefits, in terms of the plant's performance, of having a side-stream treatment process against not having this treatment.

5.2 Tool limitation

The tool was developed for South African plants and is limited to:

- Four commonly used biological nutrient removal layouts, namely, UCT (VIP), JHB, MLE and 3-Stage Phoredox.
- Two side-stream treatment technologies, namely, struvite precipitation and BABE® (Bio-Augmentation Batch Enhanced).
- Evaluating and providing rough educated estimates of the plant's performance. Therefore, this tool is not to be used for design.

5.3 Model Simplification

The simplification of the current plant-wide steady-state mathematical model was accomplished through collaboration with different stakeholders. There has been an ongoing discussion on the complexity of modelling tools for the past few years due to the new interest in using these models by stakeholders, who do not have the expertise in the processes happening in them. In a recent debate about the issue of simplicity versus complexity of these models at the WWTmod2016 (Lizarralde et al., 2018), 56% of modellers voted for developing more detailed complex models, while 44% voted against such a motion. Some of the concerns raised were:

- How complex should these models be and yet applicable?
- Can we trust the results from these models?
- Can these complex models be calibrated for practical use?
- How much information can these models provide?

In addition to the issues raised around the complexity of steady-state models, there are challenges that must be overcome such as the stakeholder's limited technical knowledge and the lack of confidence in the model outcomes. The process of model simplification into a design evaluation tool was achieved through three development processes, these were the:

- Development of an influent wastewater fractionator,
- Development of a user-friendly interface, and
- Validation of the simplified model.

5.3.1 Wastewater Fractionator

Wastewater fractionation is done primarily to reconcile influent data so that the different constituents of the influent can be identified. A fractionator model was developed with the aim of reconciling the influent data measurements and to generate outputs that will be used as inputs in the plant-wide models. Figure 5-1 summarises the process of the model development from data reconciliation (fractionator) to the plant performance evaluation.

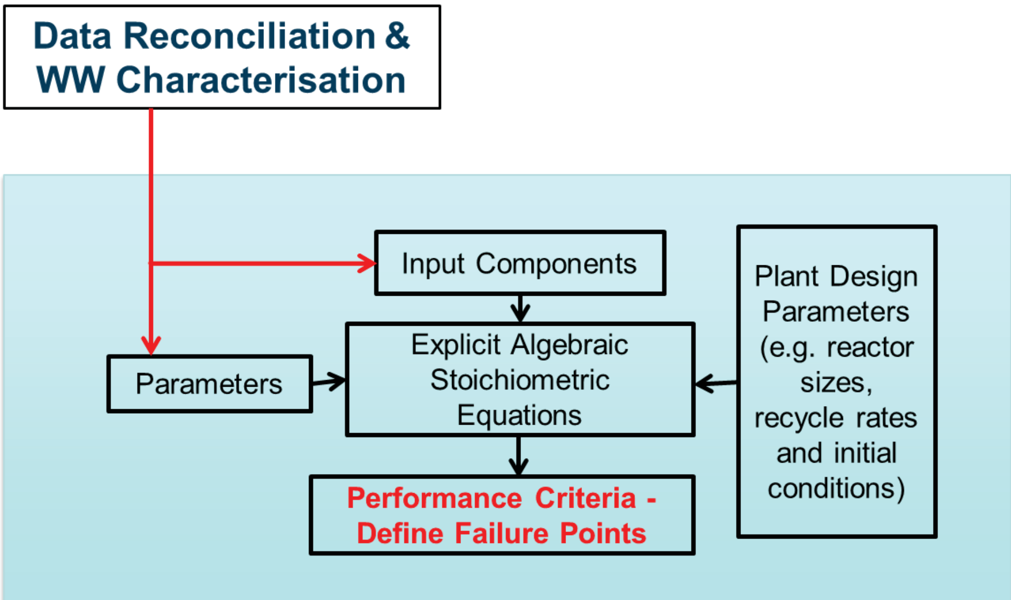

Figure 5-1: Summary of the tool development process

Rieger et al. (2010) states that the model results are only as good as the input data. Data reconciliation at the treatment plant is a key element to achieving accurate model results. The mass balance over the full-scale plant and fractionator outputs are compromised if the input plant data is poor. It is recommended that the process of data reconciliation should be done cautiously to avoid errors in flow measurements, analysis and sampling.

5.3.2 User-interface

The development of a suitable user-friendly interface was done with the intent of bridging the gap in knowledge between modellers and stakeholders. Menniti et al. (2018) recommend that to overcome the challenge of model simplification and uptake by stakeholders, the modeller should work closely with the involved stakeholders and that the model's outcome accuracy should be made clear in the development stage of the model. Furthermore, stakeholders should be trained on how to use the models where necessary. Several stakeholders were selected based on the knowledge levels, from those with a background in mathematical modelling to those with no modelling background, so that they could be involved in the tool development process. The collaboration with stakeholders was facilitated by two final year undergraduate students, Olando (2018) and Seroalo (2018), who conducted stakeholder interviews.

The overall impression was that the tool will be very useful in the industry. The feedback from the stakeholders as discussed by Olando (2018) and Seroalo (2018) is summarised below:

- It was mentioned that the tool would be useful to process controllers who have limited experience with plant modelling.
- The wastewater characterisation would provide knowledge on the composition of the wastewater in each plant.
- It was then recommended that the EQI and OCI indices should be used as a benchmark for municipal treatment indicators (Olando, 2018).
- Other feedback relating to the tool interface and changes in the tool, such as allowing the user to enter the effluent quality standards are incorporated in the final tool.

5.3.3 Model Implementation

To generate confidence on the model predicted outputs three steps were used; (i) fractionator validation, (ii) calculation of material mass balances over unit processes, i.e. model verification, (iii) qualitative observation, narrow-based model calibration, against selected full-scale systems. From this validation process, the model predicted results were found to be within an acceptable range of the actual full-scale system results.

5.3.3.1 Fractionator validation

The fractionator was first validated by noting whether it qualitatively predicted the outputs within acceptable ranges. Figure 5-2 to Figure 5-5 compares the influent raw COD, TSS, TKN and TP measurements with their respective interpolated and fitted values for plant A.

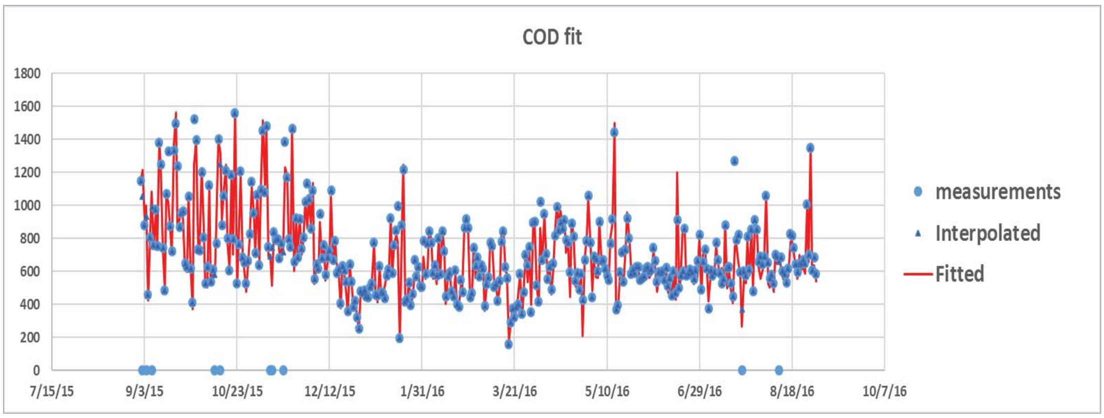

Figure 5-2: Comparison between measured, interpolated and fitted COD values

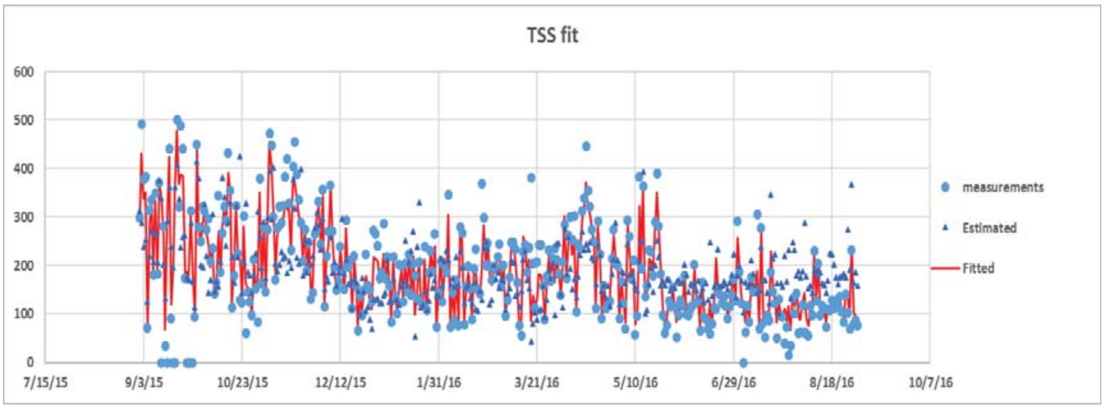

Figure 5-3: Comparison between measured, interpolated and fitted TSS values

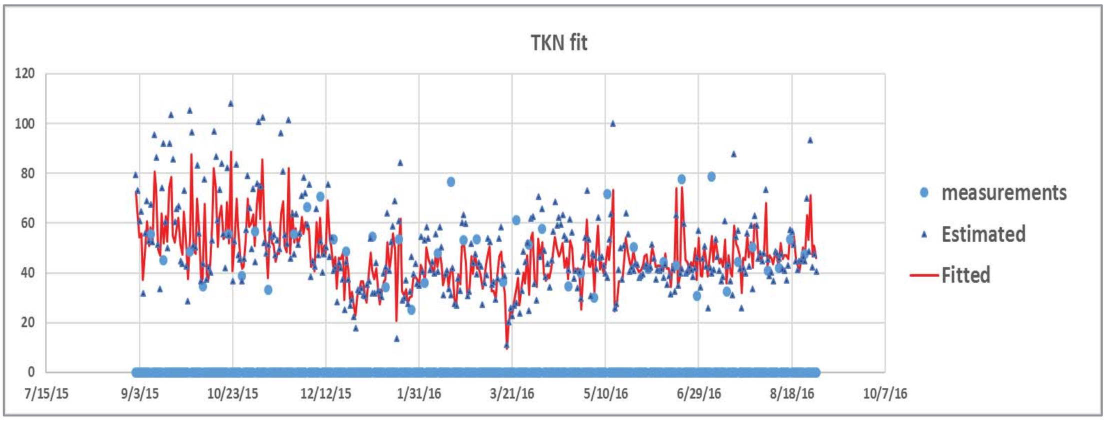

Figure 5-4: Comparison between measured, interpolated and fitted TKN values

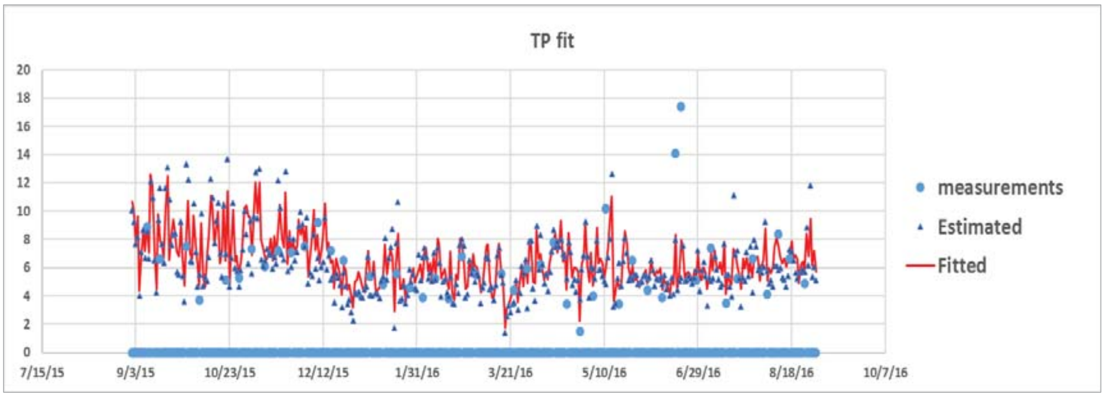

Figure 5-5: Comparison between measured, interpolated and fitted TP values

The accuracy of the fractionator model depends on the influent measurements available. The lower the accuracy of the influent measurements, the wider the range between the measured data and the interpolated and fitted values, i.e. the less accurate the fractionator outputs, thus the less accurate the model prediction.

5.3.3.2 Mass balance

To ensure that the mathematical steady state models were scientifically sound, material and energy balances were checked over the various unit processes to affirm the conservation of mass and charge at 100%, besides COD balance which was achieved at an acceptable value of 99.99%. Table 5-1 to Table 5-4 show the results of this model verification process.

Table 5-1: COD balance

Constituent	Value	Units
Total influent COD	6 537.51	kgCOD/d
Total effluent COD	184.03	kgCOD/d
Total COD of in the waste flow	2 793.82	kgCOD/d
Nitrification oxygen demand	427.03	kgCOD/d
Carbonaceous oxygen demand	3 132.28	kgCOD/d
Total COD out	6 537.16	kgCOD/d
COD balance over the plant	99.99	%

Table 5-2: Nitrogen balance

Constituent	Value	Units
Total Influent Nitrogen	379.00	kgN/d
Total nitrogen in the effluent	58.23	kgN/d
Total Nitrogen in the waste flow	191.79	kgN/d
Total nitrogen denitrified in the anoxic zone	128.99	kgN/d
Total nitrogen out	379.00	kgN/d
Nitrogen balance over the plant	100.00	%

Table 5-3: Phosphorus balance

Constituent	Value	Units
Total influent phosphorus	94.55	kgP/d
Total phosphorus in the effluent	3.24	kgP/d
Total phosphorus in the waste flow	91.30	kgP/d
Total phosphorus exit system	94.55	kgP/d
Phosphorus balance over the plant	100.00	%

Table 5-4: Metal balance

Constituent	Value	Units
Magnesium Removed	14.35	kgMg/d
Magnesium Wasted	14.35	kgMg/d
Mg Balance	100.00	%
Potassium Removed	19.44	kgK/d
Potassium Wasted	19.44	kgK/d
Potassium Balance	100.00	%
Calcium Removed	5.07	kgCa/d
Calcium Wasted	5.07	kgCa/d
Ca Balance	100.00	%

5.3.3.3 Qualitative observation

The model results were compared to those obtained in practice. This was achieved through feedback from different stakeholders that were involved in the tool development process. The comparison confirmed that the model results are acceptable.

5.4 Side stream treatment

Dewatering liquors resulting from the sludge treatment process, contain high concentrations of ammonium and phosphates. The common practice of recycling the dewatering liquor back to the reactor, can potentially overload the system resulting in an increased aeration demand and non-compliance to effluent quality standards.

Side stream treatment is useful for the mitigation of the negative effects of recycling dewatering liquor by removing or recovering nutrients from the digester effluent. The two side stream treatment processes included in the tool are the BABE® technology and struvite precipitation.

5.4.1 BABE®

The BABE® process is a new low-cost method for N-removal in wastewater treatment. It allows for the removal of ammonia and the improvement of nitrifiers that are returned to the reactor via the recycle. The process consists of combining the sludge dewatering liquor with a fraction of the return AS from the BNR reactor into a nitrifying batch reactor with a short retention time, see Figure 5-6. To include denitrification, an anoxic tank is added to the process.

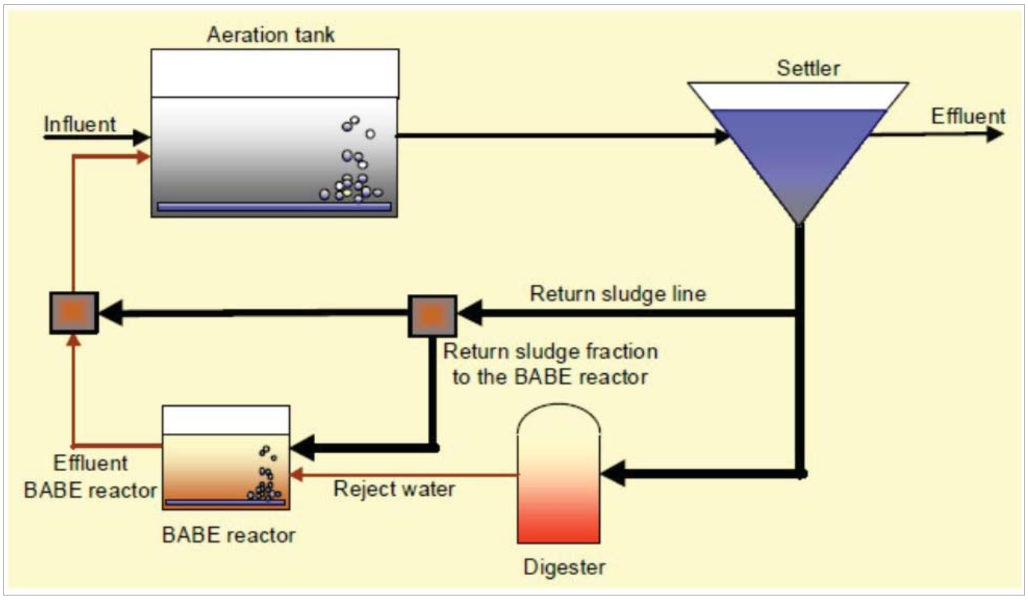

Figure 5-6: BABE® process

With the implementation of the side stream BABE® process, the introduction of a new term in the nitrification mass balance equation is required (Eq. 1). This term is known as the specific addition rate of nitrifiers (kadd). It accounts for the nitrifiers grown in the side-stream reactor that are recycled back to the mainstream reactor. The kadd ratio is the concentration of nitrifiers grown to the total concentration of nitrifiers (Salem et al., 2003).

$$\frac{dX_{BA}}{dt} = growth - decay - wasting + addition \qquad \text{Eq. 1}$$

Eq. 1 shows the mass balance equation for the population of nitrifiers in the mainstream reactor, with the term "addition" referring to the specific growth rate kadd. From the equation the formulae for minimum SRT, effluent ammonia concentration, etc. can be derived for steady state conditions.

5.4.2 Struvite precipitation

Struvite, also known as magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$), is a phosphate mineral that precipitates during the anaerobic digestion of sludge in the presence of magnesium ions.

Controlled struvite precipitation in the side stream, that contains high concentrations of ammonium and phosphates, helps to reduce the nutrient load on the BNR reactor. Additionally, the struvite crystals precipitated can be used as a fertiliser.

$$RMg^{2+} + RNH_4{}^{+} + 6H_2O + \big((1-f)\cdot R\big)HPO_4{}^{2-} + \big((1+f)\cdot R\big)HCO_3{}^{-} + (f\cdot R)H_2PO_4{}^{-} \longrightarrow 6MgNH_4PO_4 \cdot 6H_2O + \big((1+f)\cdot R\big)H_2CO_3 \qquad \text{Eq. 2}$$

Provided that the ionic product of magnesium, ammonia and phosphate exceeds the thermodynamic solubility of struvite, precipitation will occur (Loewenthal, Kornmüller & Van Heerden, 1994). By maintaining a pH of 7 and dosing magnesium (if required), struvite precipitates as shown in Eq. 2. With the number of moles of struvite (R) precipitated calculated, the effluent ammonia and ortho-phosphates can be determined.

5.5 Performance indices

Performance indices are a means of evaluating design/control strategies implemented at wastewater treatment plants (WWTP). The performance indices incorporated in the tool are the effluent quality index (EQI) and the operational cost index (OCI). Both the EQI and OCI are dependent on the limited predictions of the steady-state plant-wide modelling, thus should only be used as an estimate.

5.5.1 EQI

The EQI standardises the pollutants discharged by applying weighting factors to each pollutant based on their relative environmental impact. The result is the number of pollutants (in terms of kg) discharged per day. The EQI formulation provided by de Ketele, Davister & Ikumi (2018) based on the previous work by the International Water Association (IWA) Benchmark Simulation Modelling (BSM) task group (Jeppsson et al., 2007) is shown in Eq. 3. Since the tool is based on a steady-state model, the actual calculation is done without time steps.

$$EQI = \frac{1}{T\cdot 1000}\int_{t=0\ days}^{t=365\ days} \big(\beta_{TSS}\cdot TSS(t) + \beta_{COD}\cdot COD(t) + \beta_{FSA}\cdot FSA(t) + \beta_{NO}\cdot NO(t) + \beta_{OP}\cdot OP(t)\big)\cdot Q_e(t)\cdot dt \qquad \text{Eq. 3}$$

The β factors for each pollutant in the EQI calculation are shown in Table 5-5. These factors are directly related to the effluent concentration limits (e.g. $\beta_{FSA} = \frac{COD\ conc}{FSA\ conc} = \frac{30}{1} = 30$). The β factors give an indication of how harmful pollutants are relative to COD; the larger the β factor, the more harmful the pollutant is.

Table 5-5: Beta weighting factors (Adapted from de Ketele, Davister & Ikumi, 2018)

Pollutant	Concentration limit (mg/ℓ)	Default β-factor
COD	30.00	1
FSA	2.00	30
OP	1.50	30
NO	2.50	20
TSS	30.00	3

5.5.2 *OCI*

The OCI is a measure of the operational cost of implementing a design or control strategy at a WWTP. It is formulated as shown in Eq. 4.

$$OCI = (AE + PE - MP + ME + HE) \cdot Energy\ cost + SP \cdot Sludge\ disposal\ cost + EC \cdot Carbon\ cost \quad \text{Eq. 4}$$

Where:

AE = *Aeration energy (kWh/d)*

PE = *Pumping energy (kWh/d)*

SP = *Sludge produced (kgTSS/d)*

EC = *External carbon addition (kgCOD/d)*

ME = *Mixing energy (kWh/d)*

MP = *Energy from methane produced (kWh/d)*

HE = *Total heat energy required in the anaerobic digester for sludge treatment (kWh/d)*

In this tool, the OCI is limited to energy costs, specifically the aeration energy and methane production.

5.6 Tool Results

The impact of return dewatering liquor on the overall plant performance was analysed for three South African wastewater treatment plants A, B and C. Table 5-6 and Table 5-7 summarise the influent wastewater information and the general input parameters for the three plants.

Table 5-6: Plant information

Parameter	Units	No side-stream treatment process	Struvite precipitation	BABE Process
Minimum sludge age for nitrification	days	8.35	8.35	8.24
Optimum a-recycle ratio	_	1.06	1.56	1.53
Carbonaceous Oxygen demand	KgO/d	7 459	7 459	7 459
Nitrification oxygen demand	KgO/d	5 265	4 812	4 771
Peak oxygen demand	KgO/d	9 766	9 552	9 500
Aeration Power Requirements	kW	488	478	475

Table 5-7: General input parameters

Parameter	Value at 20°C	Unit
Design Sludge Age, SRT	10	d
Factor of safety	1.25	Constant
Number of Anaerobic Reactors in Series	2	-
Population	5 000	
Energy cost	62.03	c/kWh
System Temperature	18	°C
Aeration power	1.2	kgO_2/kWh
Diluted Sludge Volume Index	160	mℓ/g
Peak factor (PWWF/ADWF)	2.0	-

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5.6.1 *Biological Nutrient Reactor*

The biological reactor results for plants A to C, for treating all the dewatering liquor (100%) in a side-stream treatment process before recycling to the mainstream biological reactor are summarised in Table 5-8 to Table 5-10.

Table 5-8: Biological reactor results for plant A

Parameter	Units	No side-stream treatment process	Struvite precipitation	BABE process
Minimum sludge age for nitrification	days	8.35	8.35	8.24
Carbonaceous Oxygen demand	KgO/d	7 459.00	7 459.00	7 459.00
Nitrification oxygen demand	KgO/d	5 265.00	4 812.00	4 771.00
Peak oxygen demand	KgO/d	9 766.00	9 552.00	9 500.00
Aeration Power Requirements	kW	488.00	478.00	475.00

Table 5-9: Biological reactor results for plant B

Parameter	Units	No side-stream treatment process	Struvite precipitation	BABE process
Minimum sludge age for nitrification	days	8.35	8.35	8.26
Carbonaceous Oxygen demand	KgO/d	9 794.00	9 773.00	6 102.00
Nitrification oxygen demand	KgO/d	4 347.00	4 162.00	4 126.00
Peak oxygen demand	KgO/d	11 730.00	11 641.00	7 958.00
Aeration Power Requirements	kW	587.00	582.00	398.00

Table 5-10: Biological reactor results for plant C

Parameter	Units	No side-stream treatment process	Struvite precipitation	BABE process
Minimum sludge age for nitrification	days	4.45	4.45	4.38
Carbonaceous Oxygen demand	KgO/d	873.00	866.00	866.00
Nitrification oxygen demand	KgO/d	596.00	658.00	658.00
Peak oxygen demand	KgO/d	1 107.00	1 174.00	1 174.00
Aeration Power Requirements	kW	55.00	59.00	59.00

5.6.1.1 Minimum sludge age

According to Ekama and Wentzel (2008), the sludge age in the biological reactor is controlled by nitrification process. Nitrification is accomplished through two subsequent processes; the first being the conversion of FSA into nitrite by AOBs, then the conversion of nitrite to nitrate by the NOBs. The minimum sludge age needed for the completion nitrification process is affected by the specific growth rate of the nitrifiers.

The results in Table 5-8 to Table 5-10 show a decrease in the minimum sludge age required for nitrification for both the struvite precipitation and BABE® processes compared to the case of no side-stream treatment process. This can be attributed to the reduction of the N load in the recycled dewatering liquor caused by these two processes. The BABE® process, in addition, recycles nitrifiers produced in the BABE® reactor to the mainstream reactor. On the other hand, the untreated dewatering liquor contains high concentrations of N and P with no organics. The recycle of this untreated dewatering liquor overloads the plant's capacity for BNR resulting in the higher minimum sludge age required for nitrification. The BABE® process achieved the lowest minimum sludge age for nitrification because it removes more N content than struvite precipitation and it recycles nitrifiers to the biological reactor.

5.6.1.2 Oxygen demand

The oxygen demand, hence the aeration power requirements, decreases when the dewatering liquor is treated in a side-stream process. The AD of WAS produces a dewatering liquor rich in N and P compared to the influent concentration. The return of this dewatering liquor without treatment, it can overload the plant and increase the oxygen demand. Incorporating a side-stream process reduces nutrients being returned to the plant and thus a reduction in the oxygen demand (Section 5.6.2). The BABE® process produced the least oxygen demand for plant A and B as it recycled lower N loads compared to the struvite precipitation process. It was not clear why the oxygen demand for plant C increases with the use of side-stream treatment process.

5.6.2 Anaerobic Digestion

The composition of the dewatering liquor from the AD, before it undergoes a side-stream process for plant A to C is shown in Table 5-11 to Table 5-13. This dewatering liquor is rich in N and P concentrations compared to the influent concentrations.

Table 5-11: Dewatering liquor composition of plant A

Parameter	Units	Anaerobic digester	Struvite precipitation
COD	mgCOD/ℓ	70.00	70.00
FSA	mgN/ℓ	255.00	175.00
Mg	mgMg/ℓ	767.00	726.00
K	mg K/ℓ	59.08	59.08
Ca	mgCa/ℓ	18.52	18.52
OrthoP	mgP/ℓ	162.00	53.01
pH	-	6.86	7.00

Table 5-12: Dewatering liquor composition of plant B

Parameter	Units	Anaerobic digester	Struvite precipitation
COD	mgCOD/ℓ	52.00	52.00
FSA	mgN/ℓ	287.00	155.00
Mg	mgMg/ℓ	995.00	878.00
K	mgK/ℓ	299.00	299.00
Ca	mgCa/ℓ	127.00	127.00
OrthoP	mgP/ℓ	460.00	150.00
pH	-	6.79	7.00

Table 5-13: Dewatering liquor composition of plant C

Parameter	Units	Anaerobic digester	Struvite precipitation
COD	mgCOD/ℓ	32.76	32.76
FSA	mgN/ℓ	235.00	183.00
Mg	mgMg/ℓ	180.00	180.00
K	mgK/ℓ	734.00	734.00
Ca	mgCa/ℓ	325.00	325.00
OrthoP	mgP/ℓ	0.00	0.00
pH	-	6.90	7.00

Recycling such a high N and P liquors to the plant poses a problem to the WWTP performance, resulting in poorer effluent and high operational costs (Vogts, 2015 and Ekama, 2017). The impact of recycling the untreated dewatering liquor to the plant performance is observed in the effluent quality results. There is an improvement in the effluent quality when BABE® and struvite precipitation processes are used to treat the liquor before recycling it to the reactor, seen in Table 5-14 to Table 5-16 (Section 5.6.3).

5.6.3 *Effluent Quality*

The effluent quality of the three plants was compared to the special limit for the effluent quality. The values highlighted in red are those where the special limit standards are exceeded. The struvite precipitation and BABE® processes for plant A added a benefit of lowered N and P concentrations in the effluent, respectively. However, for the plant B and C, side-stream treatment processes resulted in lowered P concentration in the effluent, while nitrate concentration increased.

Table 5-14: Effluent quality of plant A

Parameter	Units	Standard effluent quality	No side-stream treatment	Struvite precipitation	BABE® process
COD	mgCOD/ℓ	30.00	70.00	70.00	70.00
Ammonia	mgN/ℓ	2.00	2.20	2.20	2.20
NO_3	mgN/ℓ	1.50	5.10	4.75	4.76
PO_4	mgP/ℓ	2.50	0.89	0.91	1.16

Table 5-15: Effluent quality for plant B

Parameter	Units	Standard effluent quality	No side-stream treatment	Struvite precipitation	BABE® process
COD	mgCOD/ℓ	30.00	52.00	52.00	52.00
Ammonia	mgN/ℓ	2.00	2.20	2.20	2.10
NO_3	mgN/ℓ	1.50	6.14	6.79	6.72
PO_4	mgP/ℓ	2.50	12.17	6.74	8.91

Table 5-16: Effluent quality for plant C

Parameter	Units	Standard effluent quality	No side-stream treatment	Struvite precipitation	BABE® process
COD	mgCOD/ℓ	30.00	32.76	32.76	32.76
Ammonia	mgN/ℓ	2.00	0.60	0.60	0.60
NO_3	mgN/ℓ	1.50	5.49	6.07	6.07
PO_4	mgP/ℓ	2.50	2.09	1.46	1.46

5.6.4 *Plant Performance*

5.6.4.1 EQI

The effluent quality index (EQI) decreases, i.e. improves with an increase in the percentage of return liquor treated in the side-stream treatment process. The struvite precipitation process achieved lower EQI than the BABE® process for plant A and B because of better effluent quality. For plant A, there was a decrease in EQI from 8 800 to 8 300 kg pollutant per day and 8 900 to 8 400 kg pollutant per day for struvite precipitation and BABE® processes, respectively. For plant B, EQI decreased from 8 300 to 6 000 kg pollutant/day and 7 800 to 7 400 kg pollutant per day for struvite precipitation and BABE® processes, respectively. The poorer the effluent quality, the higher the effluent quality index (section 5.5.1).

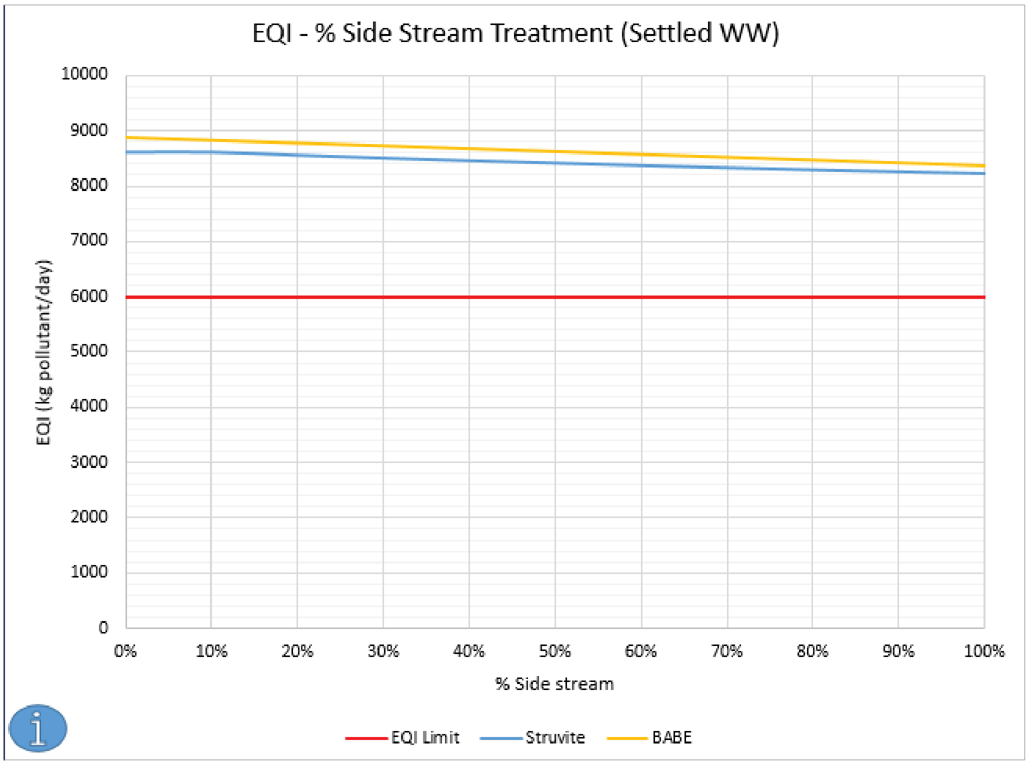

Figure 5-7: EQI variation with the percentage of dewatering liquor treated for plant A

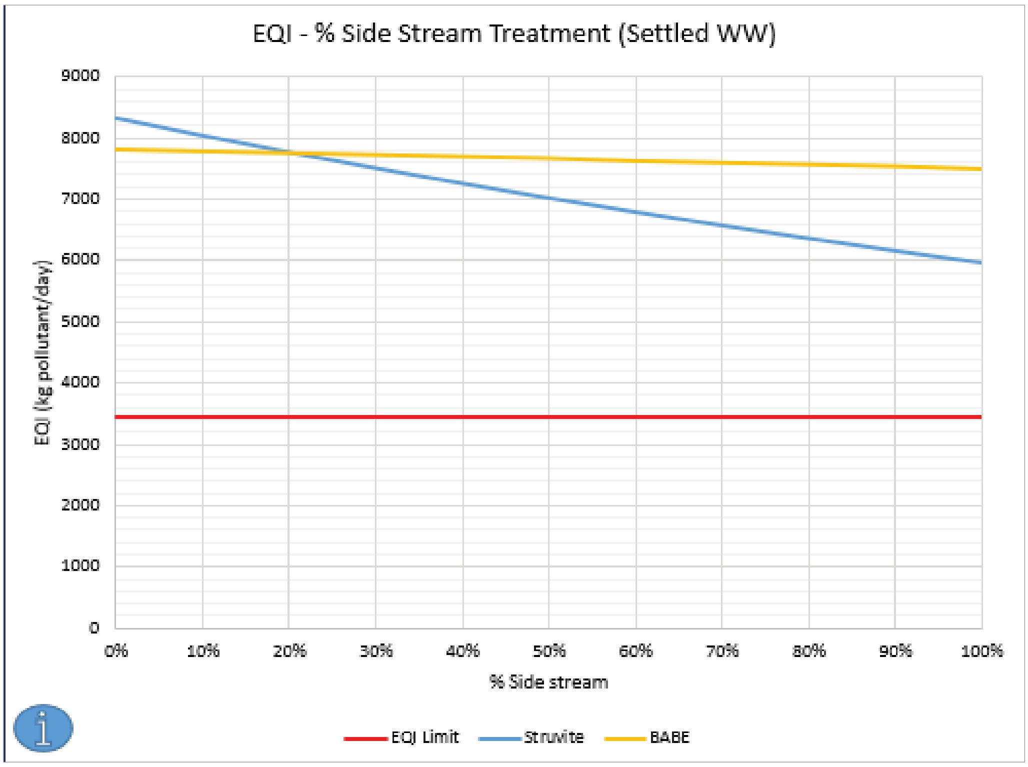

Figure 5-8: EQI variation with the percentage of dewatering liquor treated for plant B

For plant C, both the struvite precipitation and BABE® process achieved similar results. This is due to similar effluent quality from both processes, as summarised in Table 5-16. The EQI decreases from 712 to 624 kg pollutant per day for both struvite precipitation and BABE® processes.

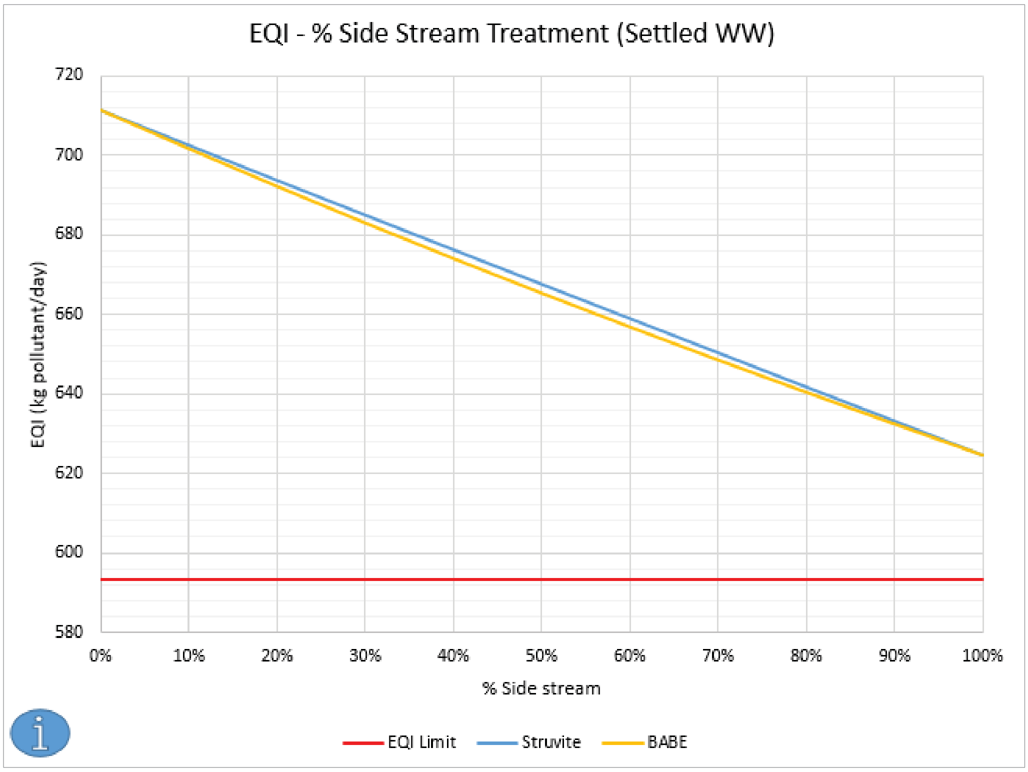

Figure 5-9: EQI variation with the percentage of dewatering liquor treated for plant C

5.6.4.2 OCI

There is a variation in the operational cost index (OCI) results for the three plants for both struvite precipitation and BABE® processes due to highly variable influent wastewater characteristics. The BABE® process achieves lower OCI than struvite precipitation process. The BABE® uses the same quantity of oxygen in the breakdown of ammonia, in the dewatering liquor, and more oxygen for endogenous respiration of the biomass added from the AS system. In comparison, struvite precipitation uses ammonia directly (from aqueous NH_4 to solid phase struvite, $MgNH_4PO_4 \cdot 6H_2O$) without imposing significant increase in aeration energy requirements

For plant A, OCI increased from R 2 150 to R 2 160 for the BABE® process as the percentage dewatering liquor treated increases. For the struvite precipitation process, OCI increased between 0% and 20% of treated dewatering liquor and decreased thereafter.

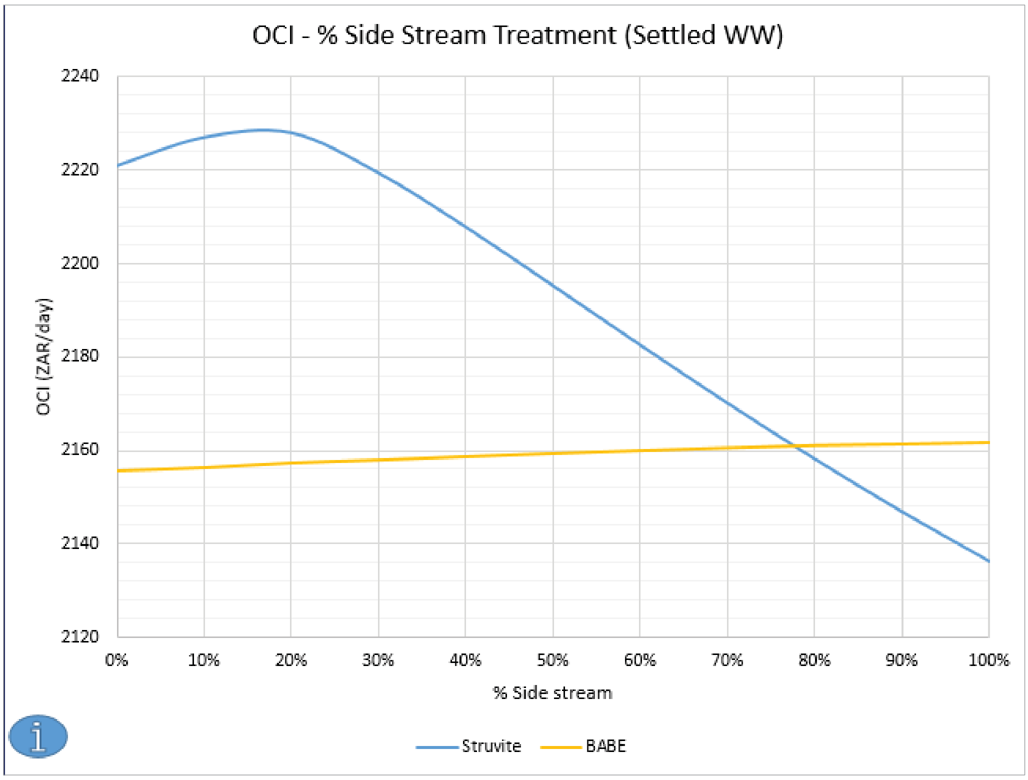

Figure 5-10: OCI variation with percentage treated dewatering liquor for plant A

For plant B, there is a marginal decrease in the OCI increases with increase in the percentage dewatering liquor treated for both struvite precipitation and BABE® process (Figure 5-11).

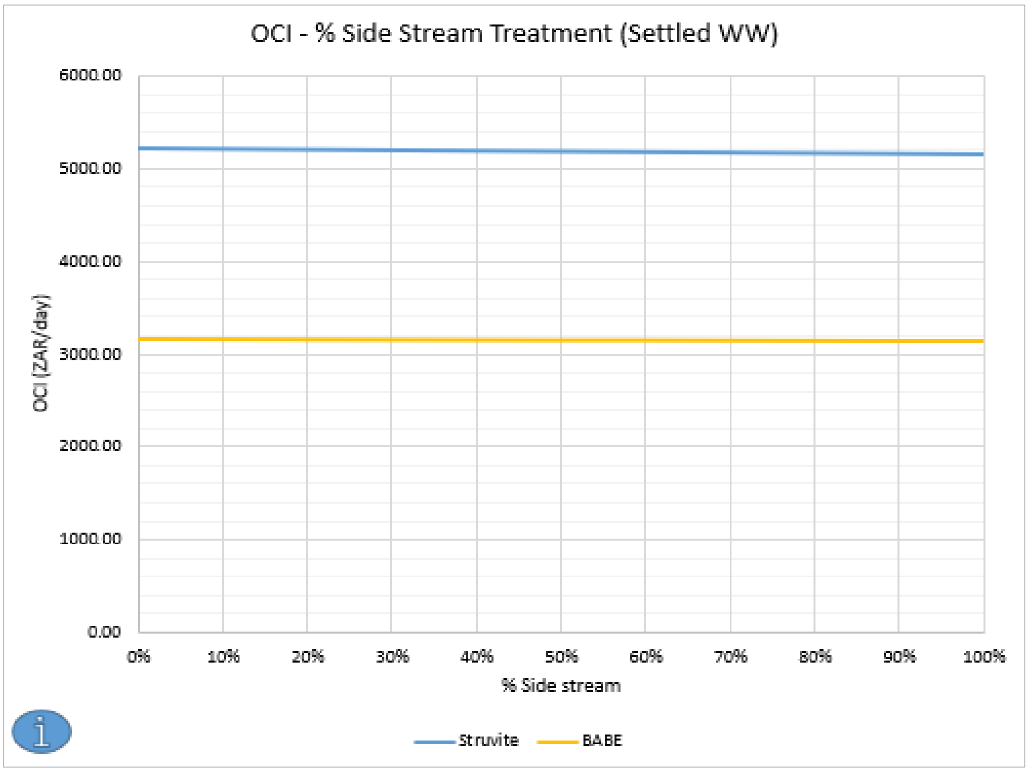

Figure 5-11: OCI variation with percentage treated dewatering liquor for plant B

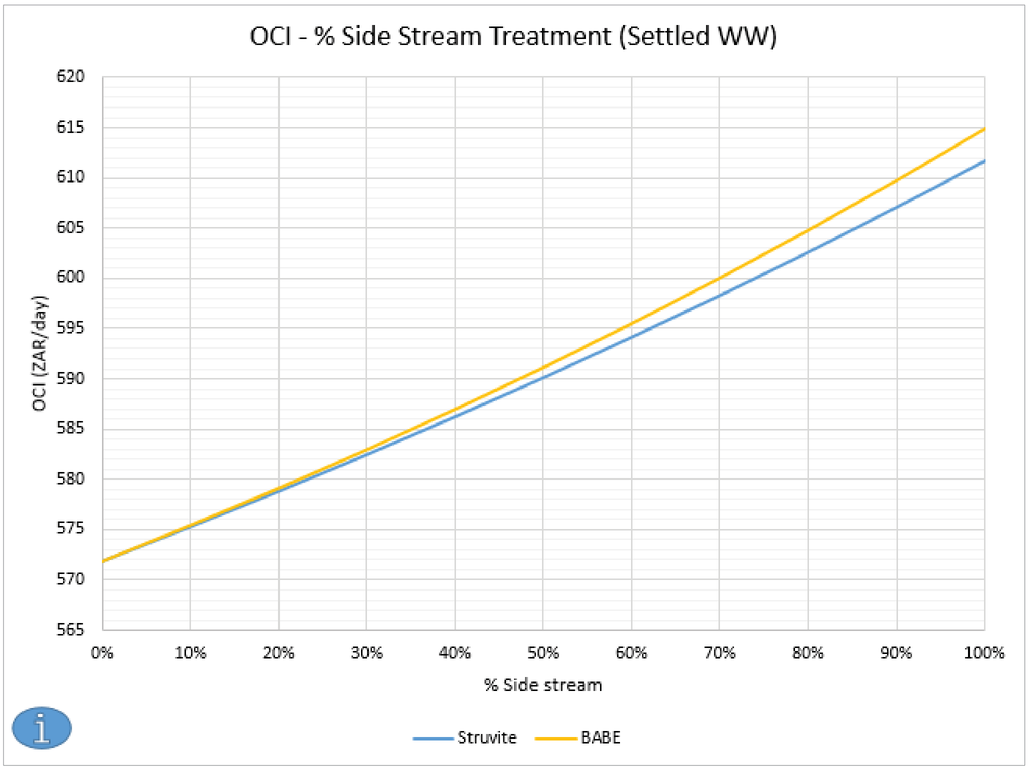

Figure 5-12: OCI variation with percentage treated dewatering liquor for plant C

5.6.5 Recommendations

The recommendation pertaining to the best side-stream treatment option for each plant configuration was made. The recommendation takes into account both the EQI and OCI using a weighted sum. For the purposes of the plant performance evaluation tool (PPET), it was the EQI was given a higher weight (60%) than the OCI (40%) because the primary objective of wastewater treatment plant is to achieve better effluent quality. The struvite precipitation process was recommended for the enhanced biological phosphorus removal (EBPR) layouts, namely UCT (plant A) and JHB (Plant C) layouts because they release higher concentration of phosphorus in the dewatering liquor. The BABE® process was recommended for the nitrification-denitrification layout, namely the 3-Stage Phoredox layout (plant B).

5.6.6 Conclusions

The dewatering liquor generated from AD systems treating PS usually have significantly less nutrient (N and P) content, than those treating WAS due to the low N and P bound in biodegradable particulate organics (BPO) from the influent waste, i.e. typical BPO PS composition for municipal waste is $CH_{1.6}O_{0.6}N_{0.03}P_{0.01}$, as shown by Ekama, 2017. However, this may vary depending on the source of the waste stream. The AS system biomass composition has usually higher N and P content than PS, i.e. OHOs have an elemental formula of $CH_{1.5}O_{0.4}N_{0.17}P_{0.02}$ and PAOs $CH_{1.5}O_{0.4}N_{0.17}P_{0.02} \cdot Mg_{0.31}K_{0.29}Ca_{0.05}PO_3$ shown by Ekama, 2017 & Ikumi et al., 2015. This allows for higher nutrient content in the dewatering liquor for AD of WAS, since the digestion of AS biomass, which is the source of BPO in AD of WAS, releases higher N, and significantly higher P and metals for cases where PAOS are present in the WAS. The extent to which the active biomass, OHO and PAOs, is present in the AD of WAS depends on the operation of the parent AS system. In South Africa, amongst other countries, the AS system sludge age is usually high enough to allow for sufficient time in degradation of influent sewage organics and nutrients and to promote the generation of effluent that meets the strict discharge regulations. However, the systems with high SRTs contain reduced active biomass concentration in the WAS, hence less quantities of BPO to be converted to biogas in AD – hence the AD of WAS from parent AS systems operated at high SRTs is generally not recommended (Ekama, 2017). If the sludge age of the parent AS system is lower, the active biomass fraction in WAS is higher and more methane could be generated. In this case, higher ammonia and phosphates concentrations are released in the process and find their way to the dewatering liquor. This is especially significant for AS systems with EBPR, whereby the P (and also metals – i.e. Mg, K and Ca that formed the polyphosphate inside the PAO biomass) are released in much higher quantities. Consequently, the WAS shall require thickening in DAF units before AD (to avoid struvite precipitation during the thickening process) and the AD will require careful operation that anticipates potential struvite precipitation, as the precipitation process would lower AD pH. Following the AD of EBPR WAS that contains high P and metals, the side-stream treatment process of struvite precipitation, rather than BABE would be preferred because the BABE process would not be able to remove the excess P that would end up being recycled back to the AS system and may eventually result in poor effluent quality (high P). The option of recycling the P back to the AS system may require dosage of acetate in the anaerobic zone of the AS system to remove the excess P that came with the dewatering liquor. This will be a significant operational cost and may result in increased sludge production (from growth of PAO biomass), which may in turn pose a threat to the capacity of the system (i.e. the design volume and secondary settling tank surface allowed to cater for a specified maximum total solid concentration). If struvite precipitation is used as the side-stream treatment process, then the maintenance of high pH and ensuring the presence of usually limiting components such as magnesium, would be necessary for maximum P recovery as struvite.

Apart from P recovery, the utilisation of struvite precipitation as the side-stream process, rather than recycling of the dewatering liquor, would result in lower nitrification oxygen demand in the parent AS system. This is due to some ammonia being used towards struvite ($MgNH_4PO_4 \cdot 6H_2O$) the precipitation process. However, ammonia is usually not the limiting component of the precipitation reaction – the precipitation of struvite usually gets limited by the quantity of magnesium present, with the acceptance of pH being maintained at a high value of above 7. Hence, the effluent from the struvite precipitation reaction may still have some ammonia while that from the BABE® process, which specifically removes large quantities of ammonia, is low.

Although side-stream processes would be recommended for treatment of dewatering liquor, the type of sludge digested, and the operation of the side-stream treatment process becomes a significant consideration. For dewatering liquor from an AD treating WAS that is not P rich, i.e. with low EBPR, then the recommended side-stream treatment operation would be the BABE® process rather than the struvite precipitation. This is unless the P released is significantly high to be recovered via dosage of magnesium towards struvite precipitation. Further, the benefits of side-stream treatment would depend on the selected unit process for implementation. It is notable that when the parent AS system is at capacity, the implementation of side-stream treatment processes is strongly recommended to ensure effluent quality compliance. If the AS treatment system is over capacity, then the tool may be used to determine whether the utilisation of side-stream treatment may result in further benefits such as lower oxygen consumption, where struvite recovery is implemented to remove ammonia and P, and better effluent quality, where the ammonia is too high in the influent and a side-stream process system such as BABE® would be useful towards augmented N removal. It is evident that the differences in treatment systems, i.e. variations in influent loads, system configurations and priority end products required – energy, water, phosphorus, etc., further investigations into strategies for the implementation of various side-stream treatment processes are required. The steady state model as a decision-making tool is not capable of predicting the actual cost value for the recovery of struvite through the dosage of magnesium because this depends on size of crystals and market demand, among other factors which require more complex models.

CHAPTER 6: GENERAL CONCLUSIONS AND RECOMMENDATIONS

The main goal of the research study was to improve the knowledge on the impact and mitigating measures of the sludge return liquors from anaerobic sludge digestion on the wastewater treatment process. The study commenced with an explorative review of existing innovative, sustainable and internationally-recognised technologies that have been successfully used to treat side-streams, and by doing so, creating reusable end-products. The study also entailed a review of existing models used for designing and optimising the operational performance of WWTWs. This review was aimed at understanding the technologies that may be applicable to South Africa plants, with focus on investment and operational costs, scalability, impact on final effluent compliance, sustainability and ease of retrofitting. Findings show that many technologies have been tested and commercialised for nutrient removal from sludge return side-streams and offer more significant benefits than conventional technologies. These technologies were categorised into N and P removal technologies. The N removal technologies identified include SHARON®, ANAMMOX®, CANON® and BABE®. These technologies are mostly based on ammonia oxidation over nitrite and/or nitrogen gas and occurring at high process temperatures (30-40°C). A comparative assessment of the technologies shows that, although SHARON® and ANAMMOX® may offer higher nitrogen removal efficiencies compared to CANON® and BABE®, they are however characterised by high investment costs. The review further shows that the BABE® technology may offer a cost-effective, less complex and improved nitrification process, and thus, could be easily implemented in South Africa. Phosphorus removal technologies reviewed include, but are not limited to, Ostara Pearl®, WASSTRIP®, AirPrex®, Crystalactor®, Calprex™, and Phospat™. These technologies provide a wide variety of struvite quality which ranges from low to premium grade. The review shows that South Africa has a potentially larger market for lower grade struvite, however there are currently no policies in place to position the South African organic market and consumers for the adoption of the end products of P recovery. It is recommended that policy formulation should centre on long-term P management as well as promotion of trade and use of wastewater products.

The project team embarked on a site investigation study aimed at understanding, from a local perspective, the impacts of sludge return liquors on operational performance and effluent quality compliance of WWTPs. The focus was to have an integrated overview and study of the relationship between the additional load from the sludge return liquors, rich in ammonia and phosphate, when recycled back to the main plant as well as their respective impact on the operation of the plants. Six South African WWTPs were used as case studies. It was observed that initial designs of the plants did not allow for additional loads from sludge return liquors. A few recent practices observed were more of a response to stringent legislations to protect surface water bodies with no standards or measures of quantifying the impacts of the additional streams. Most of the plants assessed were characterised by sub-optimal performance of anaerobic digesters, with highly varying nutrient loadings observed in the influent of plants with sludge liquor recycling steps. Furthermore, an increase in aeration demands of up to 10% was observed with recycled sludge liquors together with digesters operating at sub-optimal level. Higher aeration demands of up to 20% are expected when digesters are operated at optimal levels. Considering the findings from the site investigation study, it is imperative to initiate a comparative evaluation of side-stream treatment solutions against a full treatment solution in the main plant during preliminary design stages to ensure the selection of the most cost-effective and appropriate technical option. The development of a sludge return liquor impact simulation tool could assist in quantifying the effect of various return streams and in developing operational scenarios as a means of promoting sustainable planning and management. It is recommended that a separate research project could be done on the operational performance of digesters to identify the key challenges and the development of guidelines for operation and maintenance of anaerobic digesters.

Although, outside the scope of this study, it is important to note that majority of the plants assessed were plagued by poor solids capture in solid-liquid separation units such as thickeners, DAF units, though mostly belt presses. Continuous recycling of liquors with high TSS loadings to the main plant can impact negatively on effluent quality, sludge settleability, SRT, aeration demand and overall plant performance. A detailed study targeted on solids capture in the different sludge treatment units is highly recommended.

One of the key deliverables of this study was the development of a simple simulation tool to seamlessly assess the impact of sludge return liquors on plant performance in terms of effluent quality and operational cost. The impact tool was anchored on the foundational scientific principles of the Plant Wide Steady State Mass Balance Model (PWSSMBM) developed at the University of Cape Town. The most prominent BNR configurations in South Africa, i.e. UCT, JHB, MLE and 3-stage Phoredox, were incorporated into the simulation tool. Two side-stream technologies, struvite precipitation and BABE®, were also integrated into the tool to simulate the impact of treating a certain proportion of sludge return liquors. A fractionating module was required to help characterise the influent, particularly with the lack of information in most treatment plants. Standard performance evaluation indices – effluent quality index (EQI) and operational cost index (OCI) were employed in the model to assess varying design/control strategies implementable in treatment plants. Thus, the performance of plants can be assessed in terms of quantity of pollutants discharged per day, associated aeration energy costs and quantity of methane gas produced. The impact simulation tool was calibrated and validated against a reputable and dynamic simulation model – ASM2 which was implemented on the BIOWIN® simulation platform. The implementation was done for both AS and AD systems. Results show that PWSSMBM comprises explicit mass balanced equations, seen in the outputs that matched closely with the widely accepted ASM2 model, which has a good validation base. Results further show that recycling of sludge return liquors is significantly impacted by increase in influent flow rate and higher flux of ammonia and phosphates to the system. Ammonia was found to have a direct impact on aeration requirements of the AS system as aeration must be increased to accommodate higher influx of ammonia. Significant increase in influent phosphorus requires substantial substrate allocation towards PAO biomass growth, to allow for continuous removal of the excess phosphorus. Reduction in nitrate and orthophosphate effluent concentrations would necessitate regular dosing of biodegradable organics to the anoxic and anaerobic zones respectfully. This, coupled with the costs of increasing aeration capacity of the plant, will have a significant impact on the cost of operation.

The impact tool was tested using three of the six wastewater treatment plants earlier used as case studies. Recommendations pertaining to the best side-stream treatment option was made for each plant. The recommendations were based on a weighted sum of EQI and OCI, the weights of EQI and OCI assumed to be 60% and 40% respectively. Information on possible operating parameters that could be exploited to mitigate the negative impact of recycling the sludge return liquors were also provided.

The impact simulation tool developed in this study offers a simple and user-friendly interface to ensure ease-of-use by all stakeholders. The tool can be used for simulating different side-stream treatment scenarios, thereby facilitating the selection of the best sustainable solution for a new or upgraded wastewater treatment plants. The impact tool assumes a relevant role in decision making as well as contributing to educate and capacitate the wastewater treatment sector.

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APPENDIX 1

SITE RESEARCH REPORT

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CHAPTER 1: ‘Z’ Wastewater Treatment Plant

The ‘Z’ WWTP is located in Pretoria North. It lies north of Roodeplaat Dam (refer to Figure 1). The plant treats primarily domestic wastewater and some industrial wastewater. The works are owned and operated by the City of Tshwane Metropolitan Municipality (CoT).

In phase 1 of construction the plant (Module 1) was designed to treat 30 Mℓ/day using two biological nutrient removal (BNR) reactors, its’ start-up was made in June 1990. Due to the lower than initially expected raw sewage concentrations, the current maximum capacity of Module 1 is up to 45 Mℓ/day. In phase 2, an additional 40 Mℓ/day module (Module 2) was started-up in June 2014, to increase the overall capacity of the works to 85 Mℓ/day.

Phase 3 of construction was planned and designed, but the implementation is currently on-hold. This phase will implement a tertiary level of treatment with additional final settling tanks, chemical precipitation of phosphorous with metal salts and filtration.

Figure 1: Aerial view of ‘Z’ WWTP (Google Earth, 2016)

1.1 Process description

A description of the works is indicated below as per information collected from the Golder Associates Report (2007) and from the mechanical operation and maintenance manual available on site. The general process flow diagram of the treatment works is provided in Figure 2:

- **Inlet works** consists of:
  - Three mechanical front raked coarse screens (8 mm) and one manual screen on standby for the overflow.
  - Five vortex degritters.
  - Splitter box to divide the flow per two modules.

  - Fine rotary drum screens (3 mm) upstream of the PSTs (one screen for Module 1 and two (duty/standby) for Module 2).

- **Module 1** consists of:

  - Four PSTs (22 m diameter).
  - Primary sludge is not wasted in the PSTs, rather these units are operated as fermenters. The PSTs are on a 4-day retention cycle, where one of the 4 PSTs pumps the fermented sludge to the balancing tank. There is an option to pump the sludge directly to the biological reactors, digesters or fermenters.
  - Balancing tank (5 000 m^3).
  - Two biological reactors including nitrogen and phosphorus removal (19 575 m^3 each) including 18 compartments divided in 5 anaerobic, 5 anoxic and 8 aerobic zones. Nitrates are recycled with 6 duty a-recycled pumps. Reactors are aerated with fine bubble diffusion and there are 3 duty/1 standby blowers with VSD per reactor.
  - Four final settling tanks (FSTs) (32 m diameter) with two separated units per reactor.
  - Two rapid sand filters with continuous backwash. Each sand filter unit has 114 cells and is 166 m^2.

- **Module 2** consists of:

  - Three PSTs (25 m diameter).
  - PS is wasted in the northern most unit to the PS fermenters/thickeners.
  - The other two units are on a 4-day retention cycle, with one of the 2 PSTs pumps the fermented sludge to the balancing tank.
  - Balancing tank (12 000 m^3).
  - Two biological reactors including N and P removal (19 575 m^3 each) including 18 compartments divided in 5 anaerobic, 5 anoxic and 8 aerobic zones. Nitrates are recycled with 6 duty a-recycled pumps. Reactors are aerated with fine bubble diffusion and there are 3 duty/1 standby blowers with VSD per reactor.
  - Four FSTs (35 m diameter) with two separated units per reactor.

- **Disinfection** consists of:

  - The tertiary effluent and biological effluent from Modules 1 and 2 respectively feed into two chlorine contact tanks.
  - Treated effluent is stored in a maturation dam which has an overflow into the Roodeplaat Dam. If the effluent quality is substandard, there is a possibility to bypass the treated effluent and discharge it directly into the Roodeplaat Dam.

- **Sludge handling and disposal** consists of:

  - PS from one of the 3 PSTs in Module 2 is pumped to fermenters. The PS is then pumped to the ADs.
  - Biological sludge is pumped from the biological reactors to the dissolved air floatation (DAF) tanks in addition to Module 1's sand filter backwash.
  - Thickened biological sludge is pumped to the ADs.
  - Primary and biological sludge are digested in two mesophilic anaerobic digesters including mixing and heating (6 000 m^3 each).

  - Digested sludge is stored and mixed in a day tank and is subsequently dewatered in 7 belt presses, however, currently only 4 belt presses are operational.

- **Return liquors treatment** consists of:
  - Dewatering return liquors are taken to two precipitation tanks where a lime slurry is dosed to increase the pH and precipitate orthophosphate. The same precipitation tanks were designed to strip ammonia, but the aeration system was not installed.
  - The precipitate is settled out via two sedimentation/thickening tanks (10 m diameter each).
  - The thickened sludge is transported to the day tank and the treated return liquors are pumped to the beginning of Module 2 PSTs.

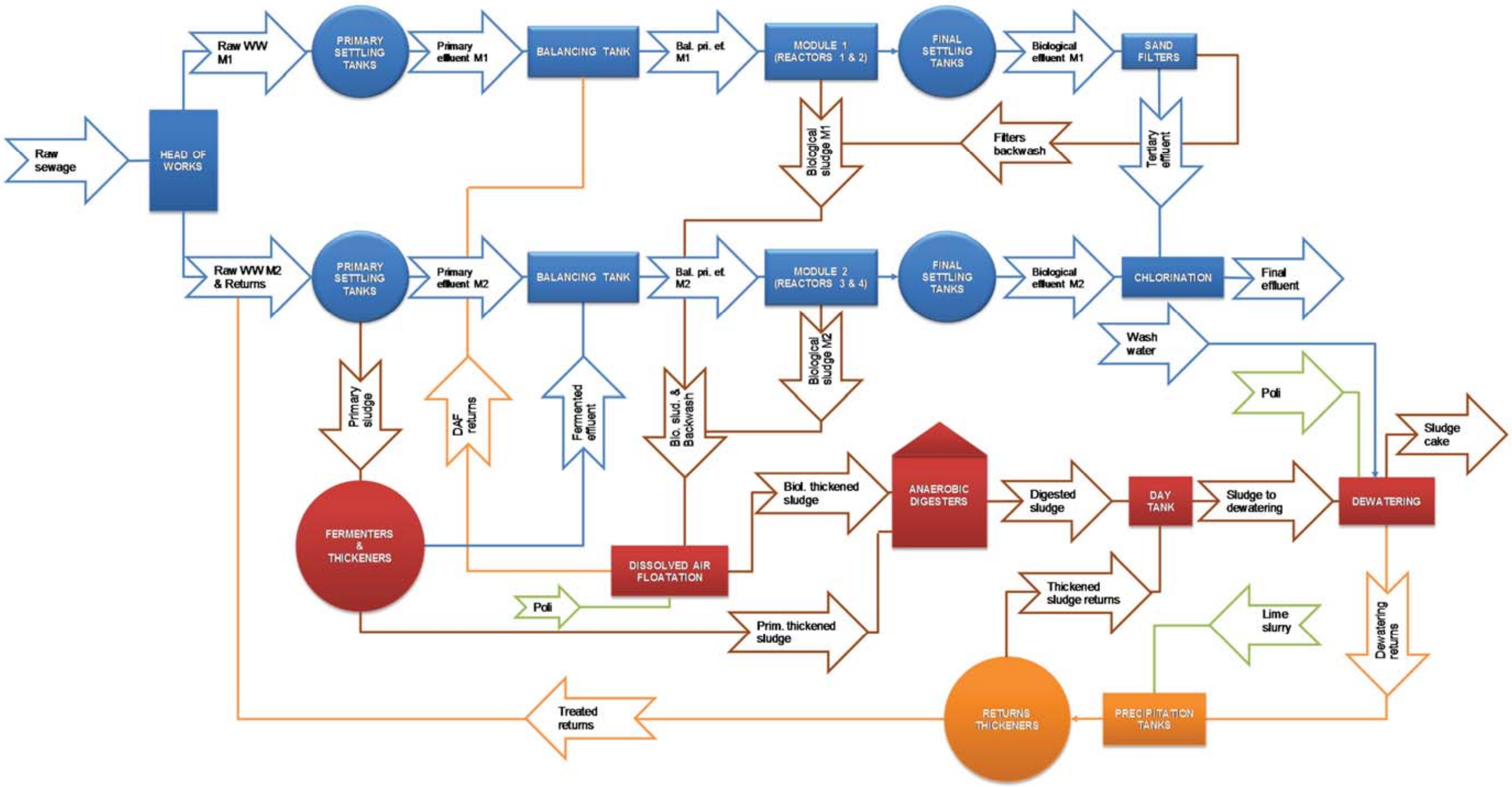

Figure 2: General process flow diagram of 'Z' WWTP

1.2 Design capacity

The total design capacity of the plant is indicated in Table 1. It is noted that the original designs of the two modules did not consider the additional load and flows from the sludge return liquors.

Table 1: Design flows and loads at 'Z' WWTP

Parameters	Module 1	Module 2	Total
Flow (Mℓ/d)	45	40	85
COD (kg/d)	22 500	20 000	42 500
TKN (kg/d)	2 100	1 867	3 967
TP (kg/d)	390	347	737

1.3 Effluent standard requirements

The latest water use license for 'Z' WWTP was granted to CoT in 2011 by the Department of Water Affairs. The water use license number is 27/2/2/A223/101/8. The final treated effluent requirements currently stipulated in the water use licence are as per Table 2.

Table 2: Effluent requirements for 'Z' WWTW

Parameter	Effluent standards	Method of compliance
COD (mg/ℓ)	50.0	90% compliance
TSS (mg/ℓ)	10.0	
NH_4 (mg N/ℓ)	1.0	
$NO_3 + NO_2$ (mg N/ℓ)	6.0	
PO_4 (mg P/ℓ)	0.1	

1.4 Technical performance

'Z' WWTP appears to be a well operated and maintained facility. The plant has a reasonable level of automation, including SCADA system. The operation team on site consists of only 4 process controllers divided by 3 shifts per day and a plant manager. Financial constraints have been affecting the appointment of additional process controllers as well as delaying the construction of phase 3.

On 20 September 2016, a site audit was held, and the following items were referred as the main points for beneficiation from the technical point of view:

- Waste activated sludge pumps were out of service. This was an isolated occurrence and currently already resolved.
- The new fermenters/thickeners for primary sludge are not helping to improve the quantity of volatile fatty acids that would allow a more efficient biological phosphorous removal. Per the experience of the operations team on site the biological phosphorous removal is optimised when using the PSTs as fermenters. Thus, the new fermenters/thickeners are no longer in operation.
- The anaerobic digesters are still not properly heated due to:
    - boilers and heating equipment were not operational, and the licensing process was to be finalised.
    - biogas storage in the double membrane gasholders is still not occurring since the gasholders were not installed yet.

- 3 out of 7 belt presses require to be serviced by the contractor (belt presses are still under the liability period).

- Critical struvite formation was constantly blocking the return liquors pumps and pipelines. As per the information from site, the struvite is only formed after the return liquors are precipitated with hydrated lime. To minimize the struvite formation, the operation team has been flushing the return liquors with final effluent daily.

1.5 Process performance

1.5.1 Influent characteristics

As indicated in the Figure 3 during the operational window selected (January 2015 to June 2016) 'Z' WWTP treated on average a total of 59 Mℓ/d (69% of the design capacity). The split between the two modules was on average 40% to Module 1 and 60% to Module 2, once during most of this period only one BNR reactor was operational in Module 1.

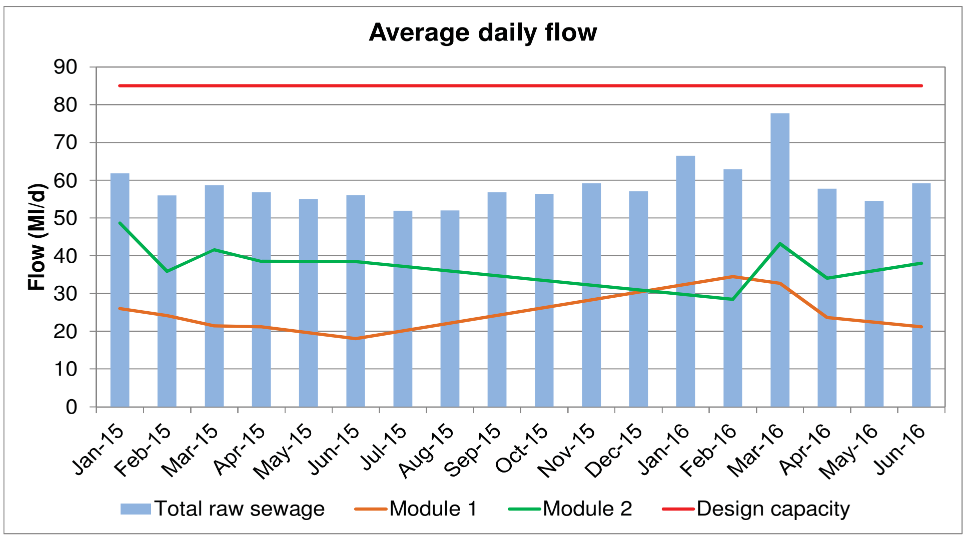

Figure 3: Average daily flow at 'Z' WWTP

The average influent concentrations and loads are indicated in Table 3 as well as the historical averages in Figure 4 and Figure 5. In general, the raw sewage shows a higher dilution rate than expected at the design stage. Currently the plant is treating 41% of the COD design load, 48% of the TKN design load and 30% of the TP design load.

Table 3: Average raw sewage concentrations and loads at 'Z' WWTP

Parameter	Average concentration (January 2015 to May 2016)		Average load (January 2015 to May 2016)	
COD	295	mg/ℓ	17 303	kg/d
TSS	136	mg/ℓ	7 971	kg/d
TKN	32	mg/ℓ	1 885	kg/d
NH_4	24	mgN/ℓ	1 435	kg/d
$NO_3 + NO_2$	0.07	mgN/ℓ	4.0	kg/d
PO_4	1.7	mgP/ℓ	101	kg/d
TP	3.7	mg/ℓ	217	kg/d

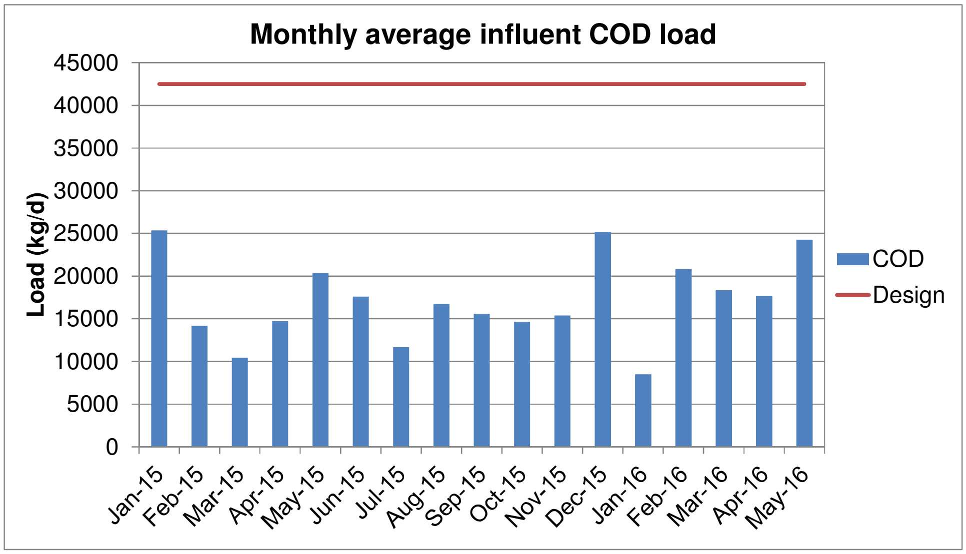

Figure 4: Average COD load at 'Z' WWTP

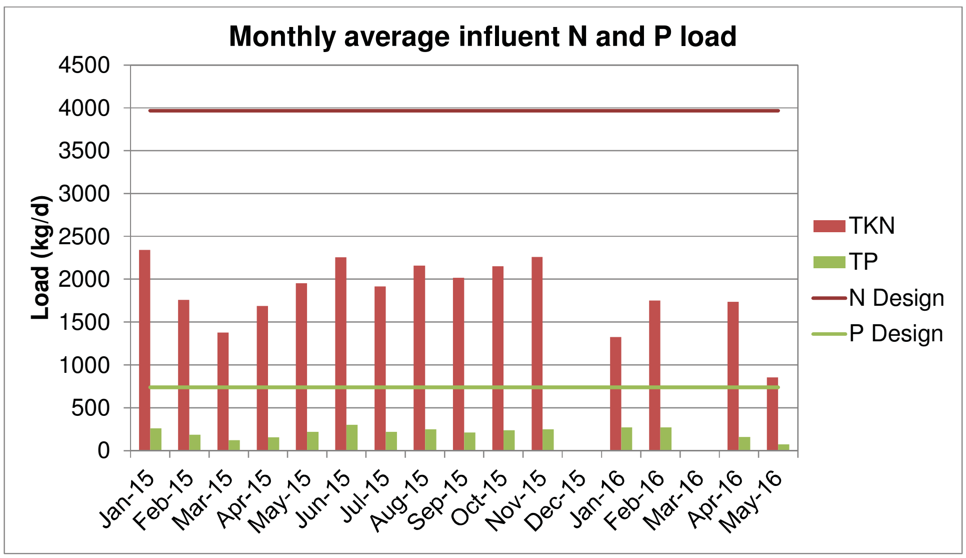

Figure 5: Average TKN and TP loads at 'Z' WWTP

1.5.2 Effluent quality

Considering the very stringent effluent standard requirements (Table 4) applicable at 'Z' WWTP, the plant shows an excellent performance regarding COD and TSS removal with 100% compliance in the research period (Table 4). However, with respect to nitrate plus nitrite and orthophosphate, the plant performance requires optimization as the average compliance rates were only 18% and 29% respectively (Table 4). Despite these non-compliances, the plant has a remarkably low average orthophosphate effluent quality (0.2 mgP/ℓ) considering only biological *P* removal is in place. The historical monthly average concentrations in the final effluent from January 2015 to May 2016 is in Figure 6 and Figure 7.

Table 4: Average final effluent quality and plant compliance at 'Z' WWTP

Parameter	Effluent quality standards	Average concentration (January 2015 to May 2016)	Average compliance (January 2015 to May 2016)
COD	50	30 mg/ℓ	100%
TSS	10	4.6 mg/ℓ	100%
NH_4	1.0	0.4 mgN/ℓ	88%
$NO_3 + NO_2$	6.0	7.6 mgN/ℓ	18%
PO_4	0.1	0.2 mgP/ℓ	29%

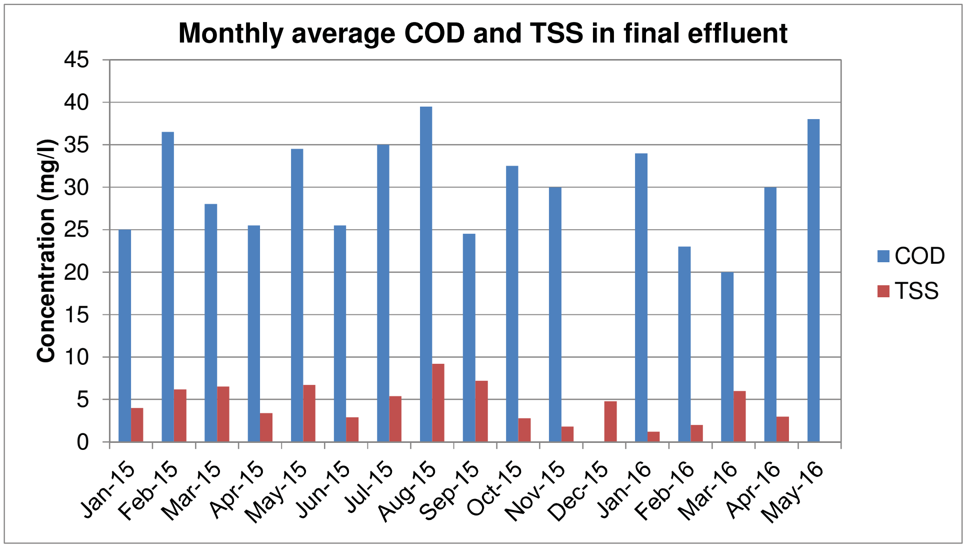

Figure 6: Monthly average COD and TSS in the final effluent at 'Z' WWTP

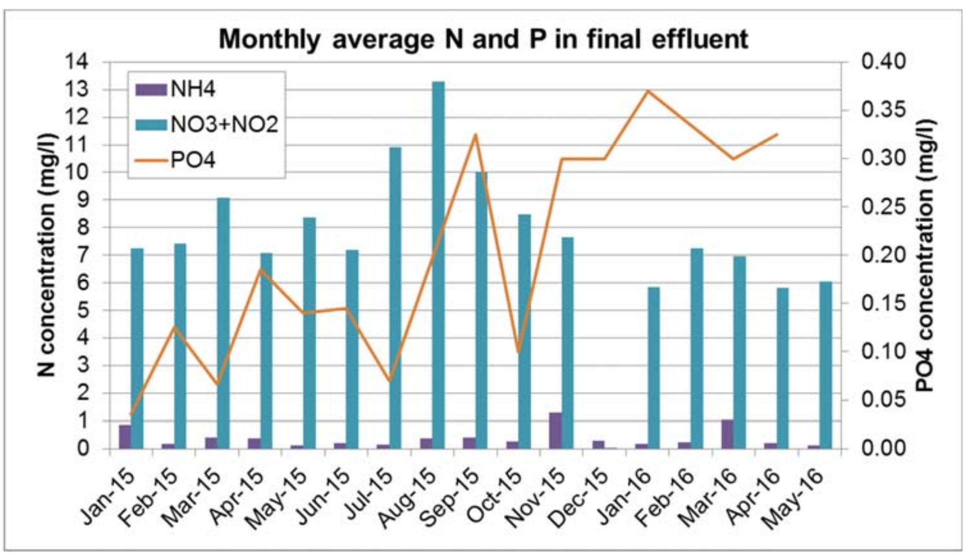

Figure 7: Monthly average ammonia, nitrate+nitrite and orthophosphate in the final effluent at 'Z' WWTP

1.5.3 Sludge treatment

1.5.3.1 Sludge characteristics

At 'Z' WWTP, PS is only extracted from one of three PSTs at Module 2. The remaining 6 PSTs (four on Module 1 and two on Module 2) are operated as fermenters to increase the hydrolysis processes and augment the quantity of VFAs which facilitates a more efficient biological P removal. Therefore, the biological system is essentially operated based on an extended aeration configuration. Consequently, the plant tends to have; a higher energy consumption, additional secondary sludge production, lower stabilisation of the secondary sludge and a lower biological capacity compared to the original design.

Table 5 indicates the characteristics of the PS and WAS prior floatation and AD. As the plant's analytical programme does not monitor the PS nor WAS (before floatation), the indicated values are only an estimate.

Table 5: Characteristics of the primary and biological sludge at 'Z' WWTP

Parameter	Primary sludge (from PST)	Biological sludge (*)	
		Before floatation	After floatation
Flow (m^3/d)	100	2 800	250
Dry solids (%)	1.2	0.33	3.5
Sludge mass (kg/d)	1 166	9 211	8 750

(*) Including the sludge in the backwash water from the rapid sand filters.

1.5.3.2 Sludge floatation

The floatation or thickening process is only applied to sludge wasted from the biological reactors and the backwash water from the rapid sand filters. The thickening occurs in 4 DAF units. Historical performance of the biological thickened sludge is presented in Figure 8. The dry solids content of the biological thickened sludge is between 3.0% and 4.5% (w/v), however, per the experience of the plant operational team it is extremely difficult to pump concentrations above 3.5%. Therefore, few of the analytical values may be over measured. The organic fraction is about 75%. The average operational solid load is about 3.7 $kg/m^2.h$, below the design sludge load (4.0 $kg/m^2.h$).

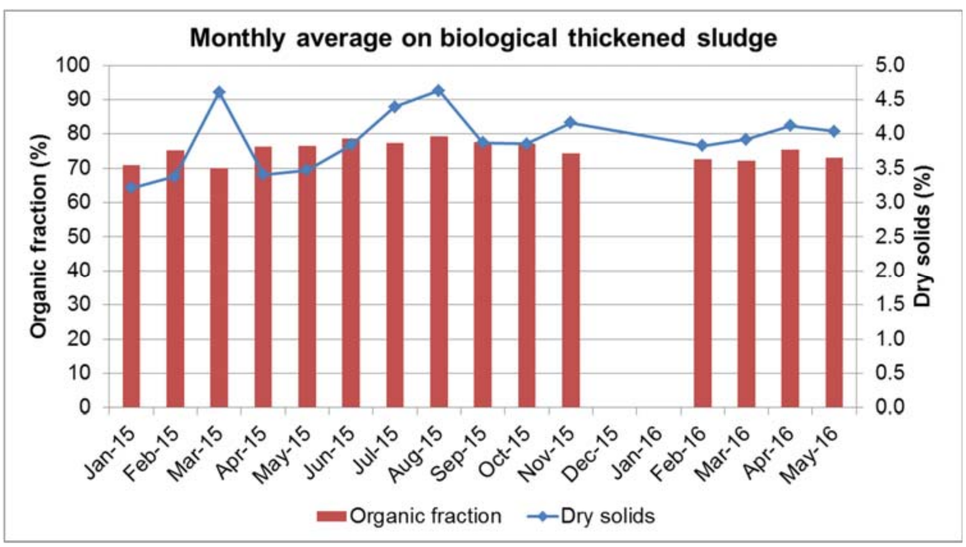

Figure 8: Monthly average organic fraction and dry solids content in the biological thickened sludge at 'Z' WWTP

1.5.3.3 Anaerobic sludge digestion

Primary and biological sludge are digested under mesophilic conditions in two ADs, pumped mixed and heated. The ADs have been in operation since January 2016, however several issues occurred during the commissioning of the gasholders and boilers, as well as with the licensing of the last units. These hurdles have been creating critical challenges to the heating system, thus the digesters are being operated with temperatures below the optimal temperature: 33ºC to 37ºC. The max temperature reached in the digesters was approximately 30ºC and only during a few weeks. Since the start-up, the digesters have been running at ambient temperature (15ºC to 30ºC) at most times. At this range of temperatures, the anaerobic stabilization of the sludge is slower and less efficient when compared with stable heated anaerobic digesters.

From February 2016 to May 2016, the dry solids content in the digested sludge was stable and approximately 2.5% (w/v) and the organic fraction was on average 68% (Figure 9). The average retention time in the anaerobic digesters was approximately 40 days. Typically for digesters in mesophilic conditions (35ºC), the minimum recommended retention time is 20 days. If the AD occurs at ambient temperatures around 20ºC, it is recommended that there is at least 60 days of retention time for reasonably mixed digesters. In fact, the destruction of VSS in the ADs was on average 32%, which appears reasonable considering that 90% of the sludge has a biological origin. In theory, the destruction rate could be slightly higher, varying from 34% to 37%, if the digestion temperature was about 35ºC.

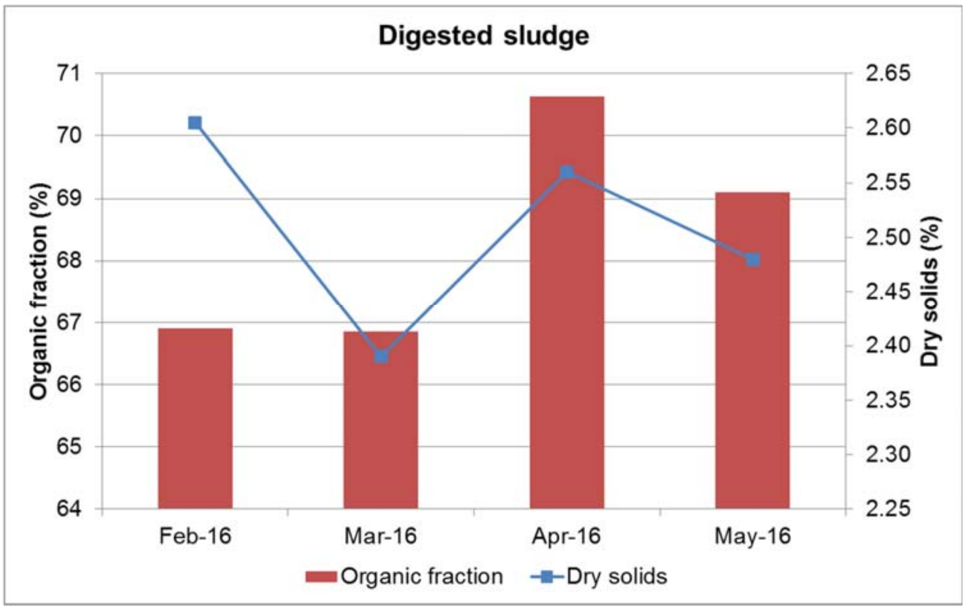

Figure 9: Monthly average organic fraction and dry solids content in the digested sludge at 'Z' WWTP

1.5.3.4 Sludge dewatering

During the monitoring period (February to May 2016), only 4 out of 7 belt presses were in operation. Typically, the belt presses have been running 8 hours per day and 7 days per week.

Per the few analytical results available, the average dry solids content in the sludge cake was approximately 13% (Figure 10) which is slightly lower than the typical range coming out of belt presses (15% to 18%). The dewatering facility has only been in operation since January 2016, therefore, further optimisations may be required to improve the dryness of the sludge cake.

On average these 4 belt presses have been running within the solids and hydraulic design loads capacities, i.e. approximately 240 kgDS/h/belt press (design capacity is 714 kgDS/h/belt press) and approximately 9 m³/h/belt press (design capacity is 35 m³/h/belt press).

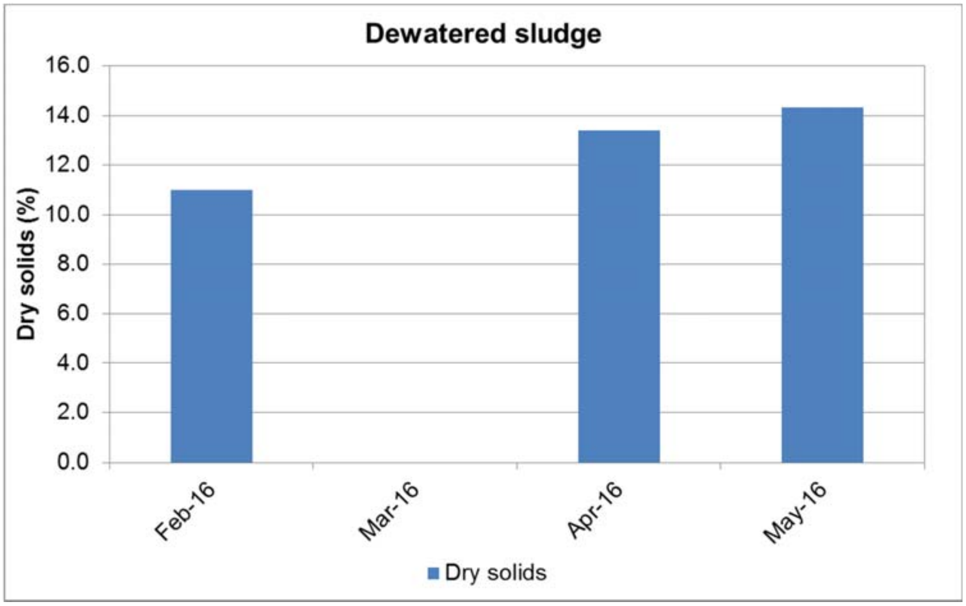

Figure 10: Monthly average dry solids content in the dewatered sludge at 'Z' WWTP

1.5.4 Treatment of dewatering sludge return liquors

The filtrate from the belt presses is routed to two precipitation channels where hydrated lime, in a slurry form, is dosed to promote the reduction of phosphate (through precipitation). Ammonia stripping is not possible as the reaction tank doesn't have an aeration system.

The recorded monthly average orthophosphate and ammonia concentrations in the dewatering return liquors from February to September 2016, are indicated in Figure 11. The average concentrations were approximately 323 mg NH_4-N/ℓ and 269 mg PO_4^--P/ℓ. The ratio of ammonia to orthophosphate in the return liquors appears unbalanced with very high orthophosphate concentrations compared to ammonia. It can be partly explained by the significant bio-P activity (high P content sludge), but the prepared mass balance shows a different ratio then observed and there is no clear reason to justify it. The ammonia concentration in the dewatering return flows is much lower than the ammonia concentration in the digested sludge. As there are no active processes for the removal of ammonia in the sludge return liquors line the most likely reason would be dilution. However, the dilution caused by the wash water pump is not sufficient to justify the difference. Further investigations would be required to identify this observation.

After precipitation, the treated dewatering returns showed concentrations about 215 mg NH_4 N/ℓ and 190 mg PO_4^-P/ℓ. The average removal efficiency of ammonia and orthophosphate has been poor and only about 28% and 32% respectively (Figure 12). Moreover, it appears that most of the reduction in orthophosphate and ammonia concentrations is due to dilution from the lime slurry dosed in the reaction tank.

From January to September 2016, the lime dosage was about 30 kg $Ca(OH)_2$/h on average, corresponding to 0.6 g $Ca(OH)_2$/ℓ. The design dosing rate was 70 kg $Ca(OH)_2$/h, corresponding to approximately 0.3 g $Ca(OH)_2$/ℓ. Although there are pH meters installed in the precipitation tanks, the sensors are out of service and therefore there is no indication if the optimum pH (± 9.5) has been achieved. Considering the low P removal efficiency, the lime dosage appears to be insufficient.

The lime dosing is causing a critical struvite formation which has been constantly blocking the return liquors pumps and pipelines. Struvite formation has not been detected in any processes upstream of the precipitation tanks.

Generally, the low efficiency of the current treatment facility for sludge return liquors indicates that the existing solution requires further optimisation and/or replacement.

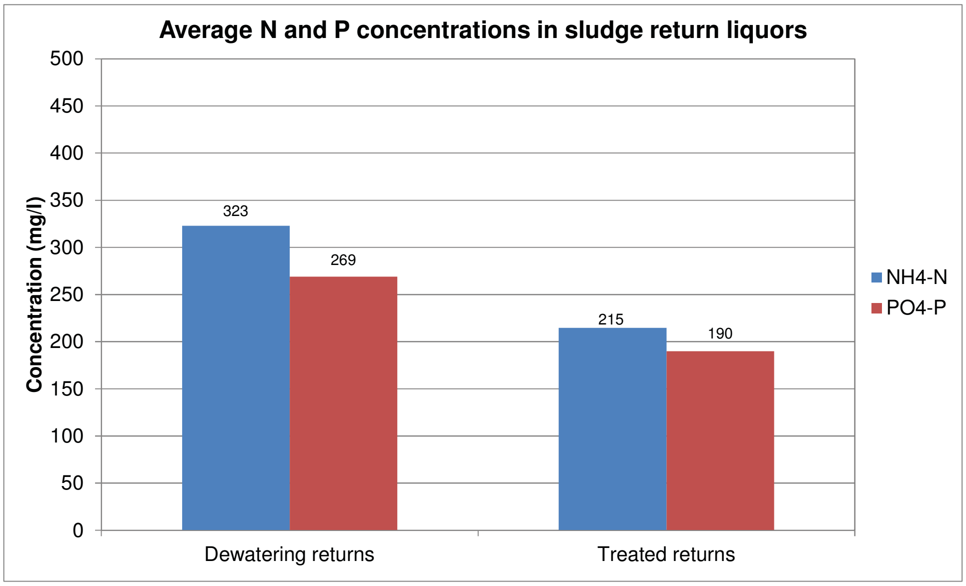

Figure 11: Average ammonia and orthophosphate concentrations in the sludge return liquors at 'Z' WWTP

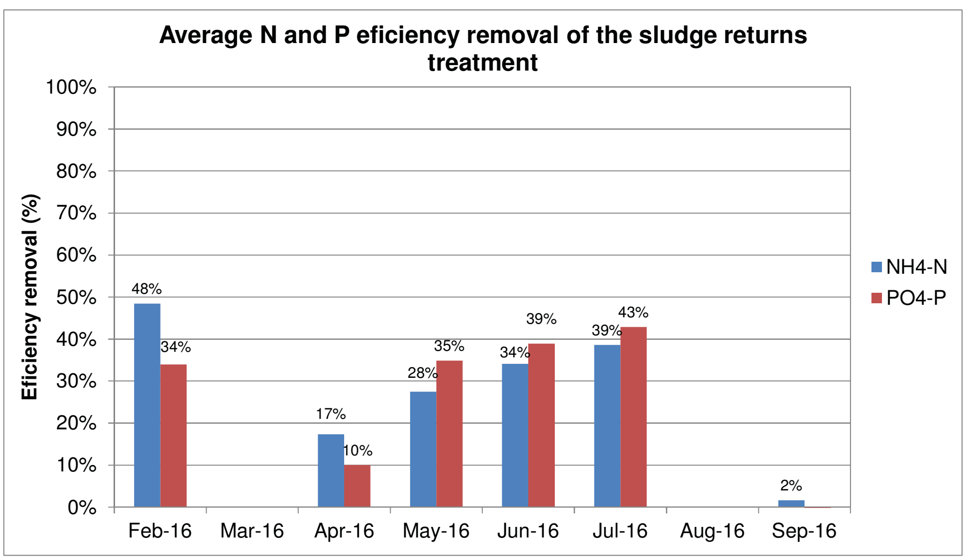

Figure 12: Average ammonia and orthophosphate efficiency removal in the SRL treatment facility at 'Z' WWTP

1.6 Impact of the sludge return liquors

1.6.1 Plant mass balance

A complete mass balance of the 'Z' WWTP was prepared to understand and evaluate the magnitude of the impacts of the sludge dewatering return liquors on the main treatment process addressed in the following sections. The result of the plant mass balance elaborated with the average data available from January 2015 to September 2016 is provided in Table 6. Once the analytical data available did not cover all streams and parameters, the following assumptions were required to complete the mass balance:

- Efficiency of COD removal in PSTs = 30%
- Efficiency of TSS removal in PSTs = 70%
- Efficiency of TKN removal in PSTs = 9%
- Efficiency of TP removal in PSTs = 11%
- COD in biological sludge: COD/MLVSS = 1.4
- Organic fraction in primary sludge = 80%
- TP removed with the biological sludge: TP/MLSS = 3%
- TKN removed with the biological sludge: TKN/MLSS = 8%
- Waste activated sludge = 5 100 mg/ℓ
- Efficiency of solids capture in belt press = 99%
- Wash water flow to clean the dewatering equipment = 0.18 Mℓ/d
- Water for lime slurry make-up = 0.075 Mℓ/d
- Back wash water for rapid sand filters = 1.0 Mℓ/d

To confirm the assumptions above and improve the accuracy of the mass balance it would be recommended to double-check the following parameters with an analytical programme during at least 3 days:

- Primary sludge:
  - COD, TSS, TKN and TP.
- Fermenters effluent:
  - pH, COD, TSS, TKN and TP.
- DAF units:
  - TSS in, TSS returned and DS sludge.
- Digested sludge:
  - COD, TKN, NH_4^-N, TP, PO_4^-P and DS.
- Dewatering returns:
  - COD, TKN, NH_4^-N, TP, PO_4^-P and TSS.
- Sludge cake (dewatered sludge):
  - COD, TKN, NH_4^-N, TP, PO_4^-P and DS.
- Outlet of reaction tank:
  - COD, TKN, NH_4^-N, TP, PO_4^-P and TSS.
- Thickened sludge from return clarifiers/thickeners:
  - COD, TKN, NH_4^-N, TP, PO_4^-P and DS.
- Return liquors after treatment:
  - COD, TKN, NH_4^-N, TP, PO_4^-P and TSS.

The following flows should be also confirmed:

- Primary sludge to digestion.
- Biological thickened sludge to digestion.
- Daily wash water to the dewatering facility.
- Water for lime slurry make-up.
- Dilution water added to the sludge return liquors sump.
- Return sludge liquors recycled to Module 2.

Table 6: Results of the mass balance at 'Z' WWTP

Water streams	Raw sewage	Raw WW M1	Raw WW M2	Raw WW M2 & Returns	Balanced primary effluent M1	Balanced primary effluent M2	Biological effluent M1	Biological effluent M2	Tertiary effluent M1	Final effluent
Flow (Ml/d)	58.7	23.6	35.4	36.0	26.2	35.9	24.8	34.5	24.8	59.0
COD (kg/d)	17303	6960	10440	11220	7430	10098	736	1050	715	1764
TKN (kg/d)	1885	758	1138	1262	804	1225	19.6	23.8	15.7	39
NH4 (kg/d)	1435	577	866	988	586	954	7.9	9.4	6.5	16
NO3+NO2 (kg/d)	4.0	1.6	2.4	2.4	1.6	2.4	199	268	166	434
TP (kg/d)	217	87	131	240	103	232	7.0	14	11	25
PO4 (kg/d)	101	40	61	169	41	163	2.0	7.8	6.6	14
TSS (kg/d)	7971	3206	4809	4839	3667	3673	146	180	115	295
COD (mg/l)	295	295	295	312	284	281	30	30	29	30
TKN (mgN/l)	32	32	32	35	31	34	0.8	0.7	0.6	0.7
NH4 (mgN/l)	24	24	24	27	22	27	0.3	0.3	0.3	0.3
NO3+NO2 (mgN/l)	0.1	0.1	0.1	0.1	0.1	0.1	8.0	7.8	6.7	7.3
TP (mgP/l)	3.7	3.7	3.7	6.7	3.9	6.4	0.3	0.4	0.4	0.4
PO4 (mgP/l)	1.7	1.7	1.7	4.7	1.6	4.5	0.1	0.2	0.3	0.2
TSS (mg/l)	136	136	136	135	140	102	5.9	5.2	4.6	5.0

Sludge streams	Primary sludge	Filters backwash	Biological sludge & backwash	Primary thickened sludge	Biological thickened sludge	Digested sludge	Thickened sludge returns	Sludge to dewatering	Sludge cake
Flow (Ml/d)	0.10	1.00	2.80	0.05	0.25	0.30	0.002	0.30	0.06
COD (kg/d)	1122	31	9686	1107	9216	7170	43	7213	7103
TKN (kg/d)	38	3.9	734	36	734	771	18	788	646
NH4 (kg/d)	34	1.5	1	33	0.9	199	14	214	77
NO3+NO2 (kg/d)	0.0	33	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TP (kg/d)	8.8	1.0	302	8.5	286	295	7	302	185
PO4 (kg/d)	6.2	0.3	0	6.0	0	265	5	271	157
TSS (kg/d)	1166	31	9211	1160	8750	7491	45	7536	7461
COD (mg/l)	11543	31	3459	22774	36863	24014	22658	24005	122887
TKN (mgN/l)	390	3.9	262	744	2937	2580	9298	2623	11170
NH4 (mgN/l)	351	1.5	0	674	3.4	668	7394	711	1332
NO3+NO2 (mgN/l)	0.0	33.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TP (mgP/l)	91	1.0	108	175	1145	987	3594	1004	3205
PO4 (mgP/l)	64	0.3	0	123	0	888	2766	900	2714
TSS (mg/l)	12000	31	3289	23865	35000	25088	23800	25079	129083

Sludge return liquors streams	Fermented effluent	DAF returns	Dewatering returns	Treated returns
Flow (Ml/d)	0.05	2.55	0.42	0.57
COD (kg/d)	15	471	823	780
TKN (kg/d)	1.7	45.6	143	125
NH4 (kg/d)	1.3	8.8	137	122
NO3+NO2 (kg/d)	0.0	0.0	0.0	0.0
TP (kg/d)	0.3	16	116	110
PO4 (kg/d)	0.2	0.4	114	108
TSS (kg/d)	7	461	75	30
COD (mg/l)	312	185	1948	1367
TKN (mgN/l)	35	17.9	337	219
NH4 (mgN/l)	27	3.4	323	215
NO3+NO2 (mgN/l)	0.1	0.0	0.0	0.0
TP (mgP/l)	6.7	6	275	192
PO4 (mgP/l)	4.7	0.2	269	190
TSS (mg/l)	135	181	178	53

1.6.2 Influent characteristics

The dewatering sludge return liquors, after chemical treatment, are combined with the raw sewage and both feed Module 2 at downstream of the inlet works. Since the anaerobic digesters have been in operation (from January 2016) and as indicated in Table 7 the current influent load of Module 2 increased due to the recirculation of the sludge return liquors. For example, the TKN load increased by approximately 11% and the PO_4^-P load increased by approximately 179% (Table 7). The phosphorous load returned from the sludge liquors appears to be extremely high and outside of the typical range for sludge liquors (5% to 30%) and therefore it should be further investigated.

None of the two modules were designed considering the additional loads returned from the sludge liquors. However, the plant is currently under loaded compared to the design capacity, it should be noted that the denitrification capacity is not sufficient to comply with the nitrate effluent quality required. In the future, should the plant reach its design capacity, the operation of Module 2 may be even more impacted.

Table 7: Impact of dewatering return liquors in the influent characteristics at 'Z' WWTP

Parameter	Raw sewage to the plant	Sludge returns	Module 2 raw ww (incl. returns)	Impact on Module 2 raw ww	Impact on total plant raw ww	Typical impact on raw ww (*)
Flow (Mℓ/d)	58.7	0.57	36.0	1.6%	1.0%	0.5% – 1.0%
COD (kg/d)	17 303	780	11 220	7.5%	4.5%	5% – 10%
TKN (kg/d)	1 885	125	1 262	11%	6.6%	9% – 13%
NH_4 (kg/d)	1 435	122	988	14%	8.5%	9% – 13%
TP (kgP/d)	217	110	240	84%	50%	5% - 30%
$PO_4^{-}P$ (kg/d)	101	108	169	179%	108%	5% - 30%
TSS (kg/d)	7 971	30	4 839	0.6%	0.4%	2% - 5%

(*) Based on Royal HaskoningDHV process design tool and excluding any dedicated treatment to the sludge return liquors

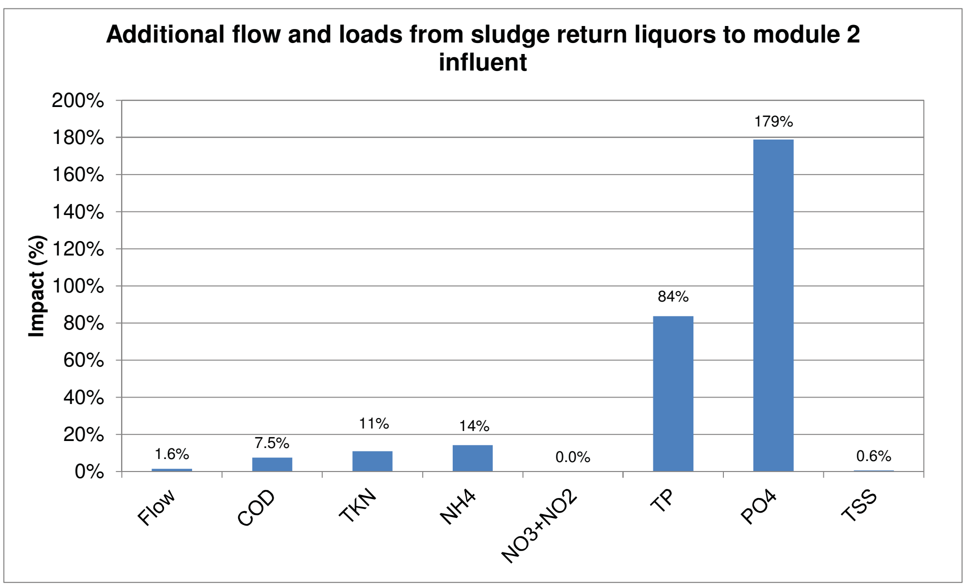

Figure 13: Additional flow and loads entering Module 2 from the SRLs treatment facility at 'Z' WWTP

Comparing the influent ratios from Module 1 (without return liquors) with a typical South African sewage (Table 8), generally the raw sewage at Plant 'Z' is slightly unbalanced, especially in terms of P characteristics (lower than usual). With respect to Module 2 (including return liquors), there is an unfavourable low COD/ PO_4 ratio for biological P removal, which has a significant influence from the return liquors with very high orthophosphate concentrations.

Table 8: Influent ratios with and without return liquors at 'Z' WWTP

Ratios	Module 1 influent (without return liquors)	Module 2 influent (with return liquors)	Typical values in South African ww (*)
COD / TSS	2.2	2.3	2.0
COD / TKN	9.2	8.9	8.2
COD / NH_4	12	11	14
COD / TP	80	47	54
COD / PO_4	172	66	117

(*) WRC Report TT389/09, Process Design Manual for Small Wastewater Treatment Works

1.6.3 Biological effluent quality

The average effluent quality of Modules 1 and 2 (biological effluent) is presented in Table 9. On average, both modules cannot meet the nitrate+nitrite effluent standard requirement and Module 2 cannot meet the orthophosphate standard requirement. It is important to note that the effluent quality requirements regarding orthophosphate is very stringent and it is a challenge to comply with this effluent requirement based only in biological phosphorous removal.

Nevertheless, assessing Figure 14 and Figure 15 from January 2015 to May 2016, it is noted that Module 1 kept a fairly stable orthophosphate effluent quality during the monitoring period, while in Module 2 the orthophosphate effluent quality appears to be in deterioration (since August 2015) and has been constantly high from January 2016 onwards. Especially from January 2016, this deterioration appears to coincide with the commissioning and start-up of the anaerobic digestion process and the recycling of the sludge liquors back to the beginning of Module 2.

Module 2 has been also responsible for 60% of the treatment of the incoming flow to the plant and it may also be a factor to add when considering possible reasons for the orthophosphate non-compliance. Considering that the orthophosphate concentrations were always very low (< 1.0 mgP/ℓ), it is difficult to judge if the recycling of the sludge liquors is the only factor affecting phosphorous compliance.

Table 9: Average effluent quality of the biological effluent from Modules 1 and 2 at 'Z' WWTP

Parameters	Module 1 (biological effluent)	Module 2 (biological effluent)
COD (mg/ℓ)	30	30
NH_4 (mg N/ℓ)	0.3	0.3
$NO_3 + NO_2$ (mg N/ℓ)	8.0	7.8
PO_4 (mg P/ℓ)	0.1	0.2
TSS (mg/ℓ)	5.9	5.2

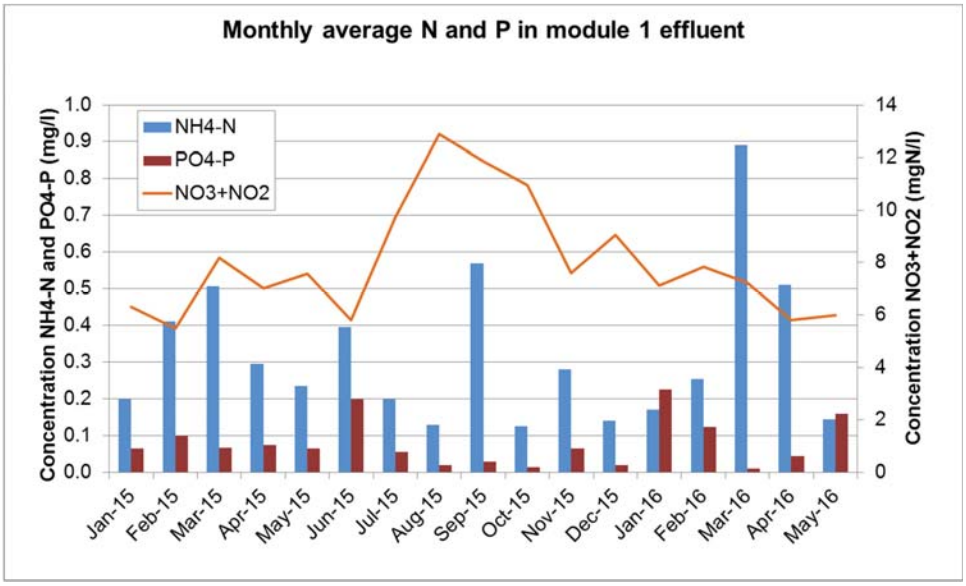

Figure 14: Monthly AV ammonia, nitrate+nitrite and orthophosphate effluent quality at 'Z' WWTP from Module 1

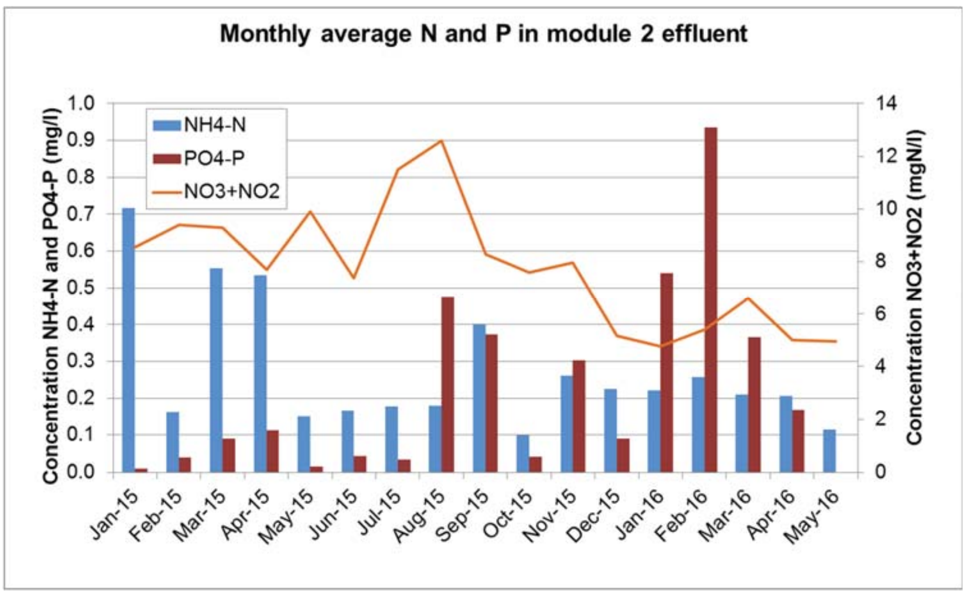

Figure 15: Monthly AV ammonia, nitrate+nitrite and orthophosphate effluent quality at 'Z' WWTP in Module 2

1.6.4 Aeration demand

At 'Z' WWTP the 4 BNR reactors are aerated through a fine bubble aeration system including disc diffusers and 3 duty/1 standby blowers per reactor. The oxygen supply to each reactor is controlled by a semi-automatic cascade method where the ammonia effluent concentration will define the best dissolved oxygen set points in the 4 oxygen sensors in different compartments.

The plant does not have individual energy meters in the aeration system, thus, historical consumption data is not available. However, from 9 to 10 February 2015 the operator measured the power per reactor in Module 2 (Figure 16). Sludge digestion and sludge return liquors were not available on site at the time and the impact of the sludge liquors was not included. Per these results, the average specific energy consumption in Module 2, without the contribution of the sludge return liquors and to keep an average O_2 setpoint of 1.9 mg O_2/ℓ, were 0.14 kW/m³ and 0.61 kW/kgCOD.

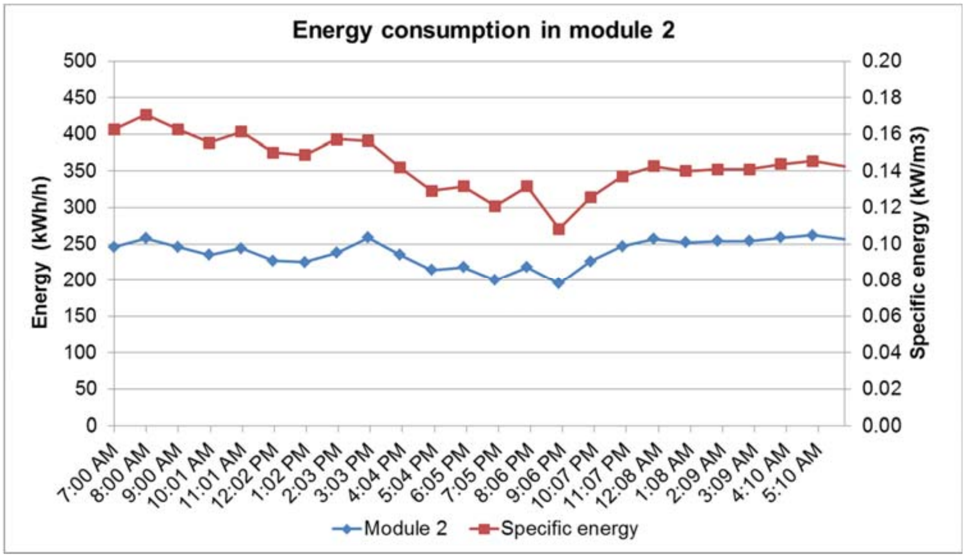

Figure 16: Aeration energy consumption in Module 2 at 'Z' WWTW without contribution of sludge return liquors

Since the additional ammonia load returned from the dewatering sludge liquors to the beginning of Module 2 is approximately 12% and the COD load has increased in 7.5% it is expected that the aeration requirements to improve the carbon removal and the nitrification capacity have increased from 7% to 10%.

1.6.5 Biological treatment capacity

Module 2 is currently treating 50% of the design COD load, 60% of the TKN design load and 62% of the TP design load. The specific biological sludge production is calculated in 0.56 kg MLSS/kgCOD removed and appears to be higher than usual for an extended aeration. On average, the sludge retention time have been around 36 days.

The additional loads from the sludge return liquors are still not over riding the capacity of Module 2, however, currently the biological treatment is not able to meet the nitrate standard. Therefore, the denitrification conditions (a-recycle capacity and anoxic volume) need to be assessed.

It should be noted that should the plant design capacity be reached in future, Module 2 may not be able to accommodate extra load from the return liquors since the plant was not designed to treat that e load.

1.7 Conclusions and recommendations

The site research conducted at 'Z' WWTP indicates the following conclusions regarding the impact of the sludge return liquors in the plant performance:

1. The return liquors are only recycled to Module 2 and therefore the influent ammonia and orthophosphate loads in this module have increased in 11% for TKN and 84% for TP. The phosphorous load appears to be extremely high and should be further investigated. Nevertheless, to minimize the impact of the sludge return liquors it should be considered an equal split between the two modules available.

2. Module 2 effluent quality is not complying with the nitrate+nitrite and orthophosphate quality standards. It is noted a deterioration in the Module 2 biological effluent quality since January 2016 and especially in the orthophosphate parameter. The overall plant performance regarding N and P compliance has been also negatively impacted since January 2016. This deterioration

appears to be coincident with the start-up of the ADs and the recycling of the sludge liquors to Module 2.

3. The efficiency of the sludge liquors treatment facility appears to be negligible and mostly influenced by a water dilution from the lime slurry and eventually others not quantified. The lime dosing is causing critical problems with struvite formation in the return flow pumps and pipelines, thus requires optimisation and/or replacement.

In addition, the following generic conclusions and recommendations should be noted:

4. The plant is generally well operated and shows a good level of maintenance.

5. The current hydraulic demand in the plant is 69% of the design capacity. The influent flow is split: 40% of the flow goes to Module 1 and 60% to Module 2.

6. The plant is currently under loaded compared to its design capacity. As an example, the current COD load is only 41%, TKN load is 48% and TP load is 30% compared to the design capacity.

7. It must be noted, that although the plant is under loaded, based on its original design, the effluent quality does not comply with the effluent requirements for N and P. Particularly for N, it implies that the plant cannot handle more N since the denitrification capacity is not sufficient or is not optimised. It is recommended to evaluate the denitrification process including the a-recycle capacity, the simultaneous denitrification rate and the readily biodegradable COD fraction available. Regarding the orthophosphate removal, it is important to bear in mind that currently this plant has a very stringent standard requirement (< 0.1 mg P/ℓ). Although only biological P removal is in place the plant has been able to meet on average a remarkable low orthophosphate concentration, i.e. 0.2 mgP/ℓ. Considering the stringent effluent requirements, a chemical precipitation step with metal salts to complement the biological P removal should be considered.

8. The AD process has been running since January 2016 and it is still not optimised. The digesters have been operated at ambient temperatures (20ºC to 25ºC). It is a matter of urgency to bring the boilers and gasholders into operation to increase the process temperature to at least 35ºC to improve the digestion stability and increase the volatile solids destruction. Please note that an optimised sludge digestion process will increase the N and P concentration in the sludge return liquors.

9. The dryness of the dewatered sludge could also be optimised since only 13% DS (w/v) has been reached. An optimisation of the polymer dosage and type shall be considered.

CHAPTER 2: ‘W’ Wastewater Treatment Plant

The ‘W’ WWTP is located in Klip River in Southern Johannesburg (refer to Figure 17). It lies north of Meyerton. The works is owned and operated by East Rand Water Care Association (ERWAT).

‘W’ WWTP has a total capacity of 170 Mℓ/d. Module 1 was commissioned in 1979 and has a capacity of 40 Mℓ/d. Modules 2 and 3 were commissioned in 1989 and 1993 respectively, each having a capacity of 40 Mℓ/d. The fourth module was completed in 2008 and its capacity is 50 Mℓ/d.

The plant currently treats influent from the Germiston and Alberton areas. The treated effluent is discharged into the Klip River.

Figure 17: Aerial view of ‘W’ WWTP (Google Earth, 2016)

2.1 Process Description

A description of the ‘W’ WWTP is indicated below as per information found in the operation and maintenance manuals for Modules 1, 2-3 and Module 4 (Mott MacDonald, 2016, Bradford, Conning and Partners, 1994 and Sintec, 2008 respectively). The general process flow diagram of the works in indicated in Figure 18.

- The **inlet works** consist of two parallel head of works which split flow between Modules 1-3 and Module 4:
  - Each module consists of:
    - Three screening chambers[1] which each have,
    - A stone trap and trash rack,
    - A fine screen.
  - Three vortex degritters,

[1] *The head of works for Module 4 has three screening chambers but currently only two of the three have screens*

- At each inlet, there is an overflow weir upstream of the screens which directs excessive inflow to a 19 000 m³ emergency dam.

- **Module 1** consists of:

  - Two PSTs:
    - The tanks are 25 m in diameter,
    - The total usable volume of each tank is 3 252 m³.
  - Two primary BNR reactors and two secondary BNR reactors:
    - Primary reactors have a total volume of 2 690 m³,
    - Secondary reactors have a total volume of 3 250 m³,
    - Primary reactors have 8 surface aerators and secondary reactors have 5 surface aerators.
  - FSTs:
    - Four primary clarifiers upstream of the secondary BNR reactors,
    - Four secondary clarifiers downstream of the secondary BNR reactors,
    - All clarifiers have a 30 m diameter,
    - The total usable volume of each tank is 1 767 m³.

- **Modules 2-3** consist of the following:

  - One balancing tank per module (7 350 m³ each),
  - Two 25 m diameter PSTs per module,
  - Primary sludge screening:
    - Module 2:
      - Single mechanical screen with one manually raked screen on standby.

- **Module 3** consists of:

  - Two identical mechanical fine screens which can each work on a standby or duty basis,
  - Two BNR reactors (one per module with 15 898 m³),
  - Each reactor has 3 aerated zones which have fine bubble diffused air aeration systems,
  - Air provided by five centrifugal blowers (4 duty, 1 standby),
  - Four 25 m diameter clarifiers.

- **Module 4** consists of:

  - Two adjacent balancing tanks (5 250 m³ each),
  - Two 34 m diameter PSTs,
  - A BNR reactor (21 688 m³),
  - Aerated zones equipped with fourteen surface aerators,
  - Four 34 m diameter clarifiers.

- **Disinfection** consists of the following:

  - Two identical 2 000 m³ chlorine contact tanks serve Modules 1-3 and 4 respectively,
  - Treated effluent is stored in maturation ponds, which discharge into the Klip River.

- **Sludge handling and disposal** consists of the following:

  - Primary sludge from the PSTs is pumped to anaerobic digesters,

- Biological sludge is pumped to five 10 m diameter DAF units with 424 m^3 each (1 unit per module except Module 4 which includes two units),
- Thickened biological sludge is pumped to anaerobic digesters,
- Primary sludge and biological thickened sludge are anaerobically digested in sixteen units:
  - Module 1: four digesters (not heated or mixed),
  - Module 2-3: six digesters (heated and biogas mixed),
  - Module 4: four digesters (heated and pump mixed),
- Sludge dewatering:
  - 60% of digested sludge is diverted to drying paddies,
  - 40% of digested sludge is mechanically dewatered in four belt presses:
    - Presses operate for 12 hrs per day, 7 days a week.

- **Sludge return liquors**:
  - Sludge return liquors from the DAF units of Modules 1-3 are recycled to the beginning of the biological reactors,
  - Sludge return liquors from the DAF units of Module 4 are recycled to upstream of the balancing tank,
  - Sludge dewatering returns (filtrate) and wash water (from belt press cleaning) split equally between Modules 1-3 and 4 and are recycled to downstream of the inlet works of the respective modules.

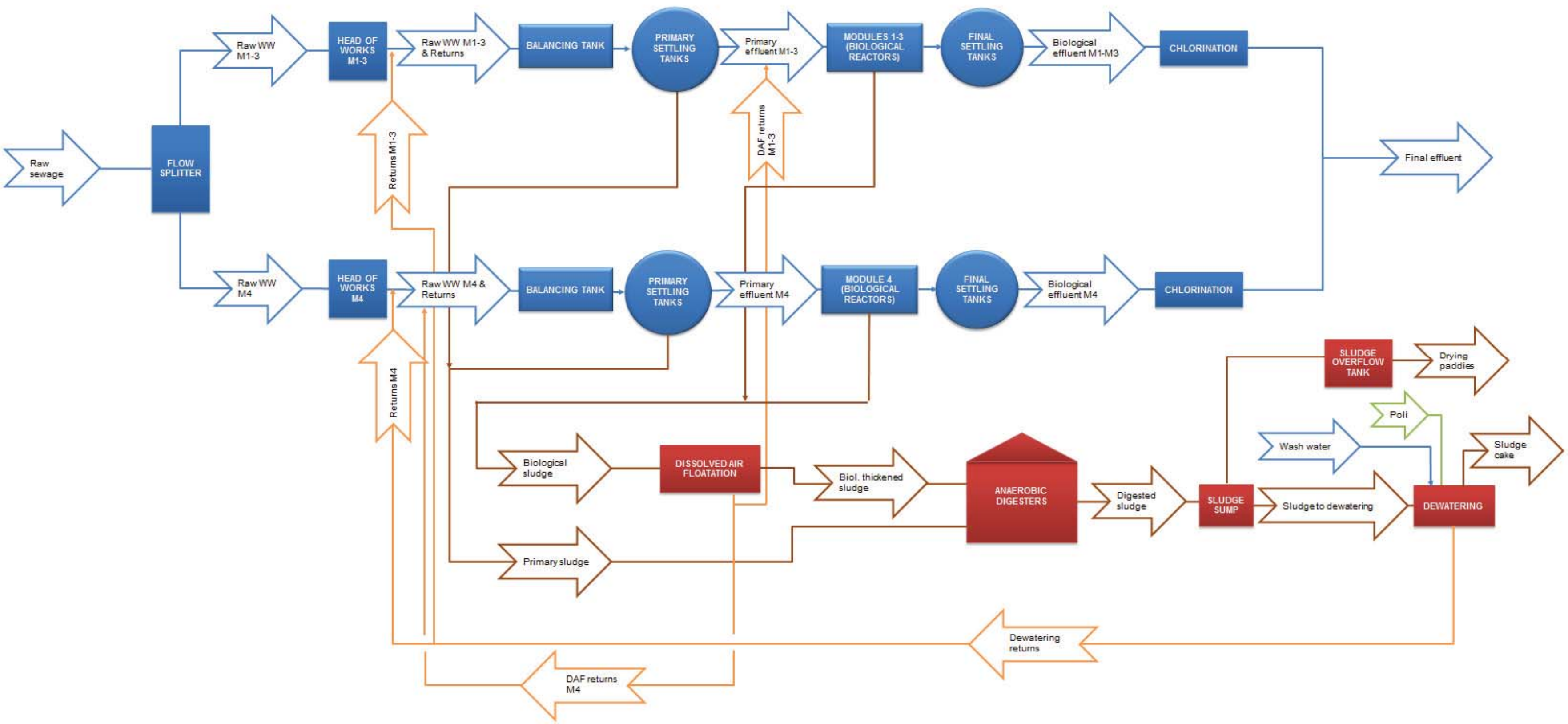

Figure 18: General Process Flow Diagram for 'W' WWTP

2.2 Design Capacity

The total capacity of the plant is indicated in Table 10.

Table 10: Design flows and loads at 'W' WWTP

Parameters	Module 1	Module 2-3	Module 4	Total
Flow (Mℓ/d)	40	80	50	170
COD (kg/d)	44 000	88 000	55 000	187 000
TSS (kg/d)	22 000	44 000	27 500	93 500
TKN (kg/d)	2 400	4 800	3 000	10 200
Ammonia (kg/d)	1 120	2 240	1 400	4 760
Total P (kg/d)	480	960	600	2 040
Ortho P (kg/d)	280	560	350	1 190

2.3 Effluent Standard Requirements

'W' WWTP current water use license number is 08/C22C/FG/646. The stipulated final effluent requirements are indicated in Table 11.

Table 11: Effluent requirements for 'W' WWTP

Parameter	Final Effluent Requirements
COD	70 mg/ℓ
TSS	20 mg/ℓ
Nitrate+Nitrite	9 mg/ℓ
Ammonia	4 mg/ℓ
Ortho P	0.7 mg/ℓ
E-Coli	500 CFU/100 mℓ

2.4 Technical Performance

'W' WWTP is a Class A plant. There are three shifts per day. Each shift is manned by one process controller (Class 4) and three assistant operators. There is one plant manager and a regional manager (Class 5). There is also a 24-hour standby plant manager for the plant.

The operating staff of 'W' WWTP highlighted the following issues at the plant:

- The DAF for Module 1 is old, has a poor efficiency and breaks down regularly. There are plans to replace/refurbish this unit.
- The pressurisation equipment used for the DAF units in Modules 1 & 3 regularly fails and requires replacement.
- Four surface aerators in Module 1 and three surface aerators in Module 4 are out of service for more than a year.
- The blowers for Modules 2-3 fail regularly.
- The primary sludge transfer pumps regularly undergo mechanical failure which, if not rectified quickly, can cause the overflow of solids in the PST's.
- The disinfectant used for Modules 1-3 causes regular blockages. The dosing pump for these modules also fails regularly. In Module 4 there is regular failure of the motive water pump.

2.5 Process performance

2.5.1 Influent Characteristics

As indicated in Figure 19, during the operational window selected (September 2015 to August 2016), 'W' WWTP treated on average a total of 252 Mℓ/d (148% of the design capacity). This indicates that the plant is currently operating above its design capacity. The split between Modules 1-3 and Module 4 is on average 78% and 22% respectively.

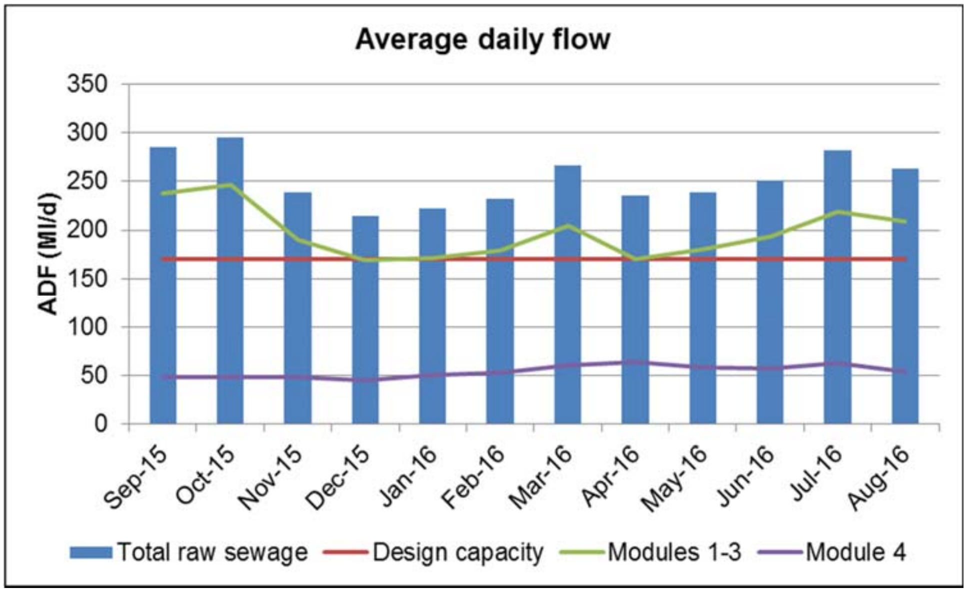

Figure 19: Average daily flow at 'W' WWTP

The average influent concentrations and loads are indicated in Table 12 as well as the historical averages in Figure 20 and Figure 21. Currently, the plant is treating 99% of the COD design load, 120% of the TKN design load and 75% of the TP design load.

Table 12: Average raw sewage concentrations at 'W' WWTP

Parameter	Average Concentration (September 2015 to August 2016)		Average Load (September 2015 to August 2016)	
COD	729	mg/ℓ	185 560	kg/d
TSS	195	mg/ℓ	49 265	kg/d
TKN	49	mg N/ℓ	12 285	kg/d
NH_4	24	mg N/ℓ	6 006	kg/d
PO_4	2.9	mg P/ℓ	733	kg/d
TP	6.1	mg P/ℓ	1 547	kg/d

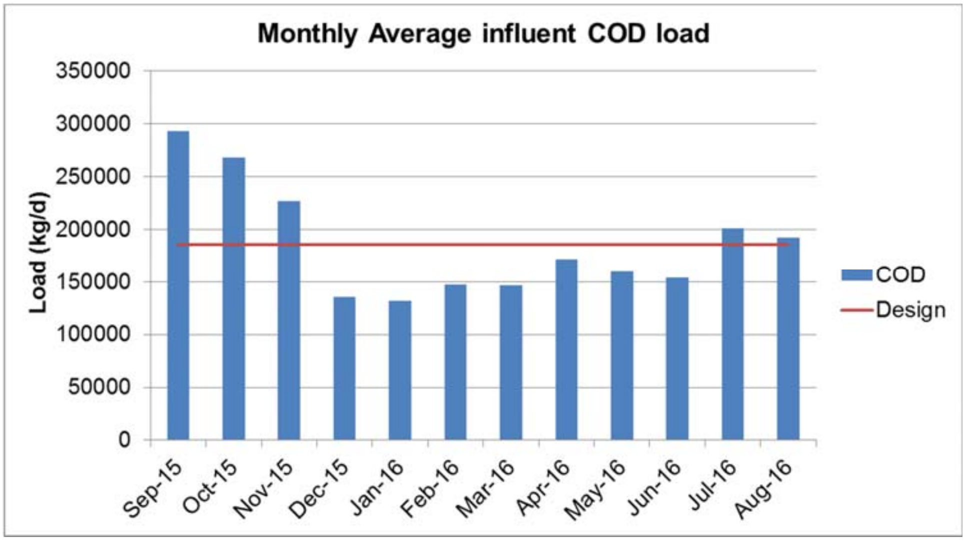

Figure 20: Average COD load at 'W' WWTP

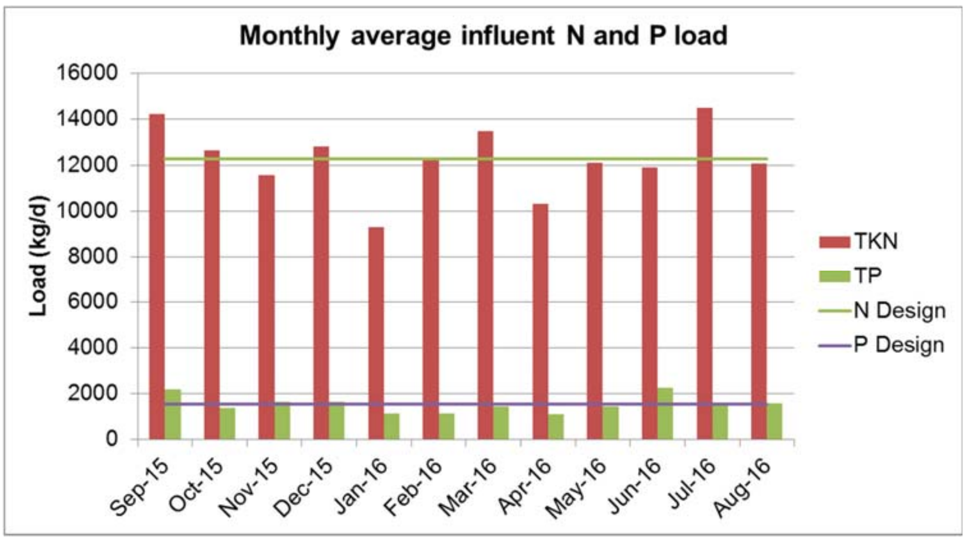

Figure 21: Average TKN and TP load at 'W' WWTP

2.5.2 *Effluent Quality*

This plant displays good performance, Table 13 indicates the average quality of treated effluent. For all parameters, compliance is 100% and above. This is surprising given that the plant, on average, treats influent flows that are higher than its capacity. The historical monthly average concentrations in the final effluent from September 2015 to August 2016 are indicated in Figure 22 and Figure 23.

Table 13: Average final effluent quality and plant compliance at 'W' WWTP

Parameter	Final Effluent Requirements	Average Concentration (September 2015 to August 2016)	Average compliance (September 2015 to August 2016)
COD	70 mg/ℓ	32 mg/ℓ	100%
TSS	20 mg/ℓ	11 mg/ℓ	100%
Nitrate+Nitrite	9 mg/ℓ	4.4 mg/ℓ	100%
Ammonia	4 mg/ℓ	0.9 mg/ℓ	100%
Ortho P	0.7 mg/ℓ	0.2 mg/ℓ	100%

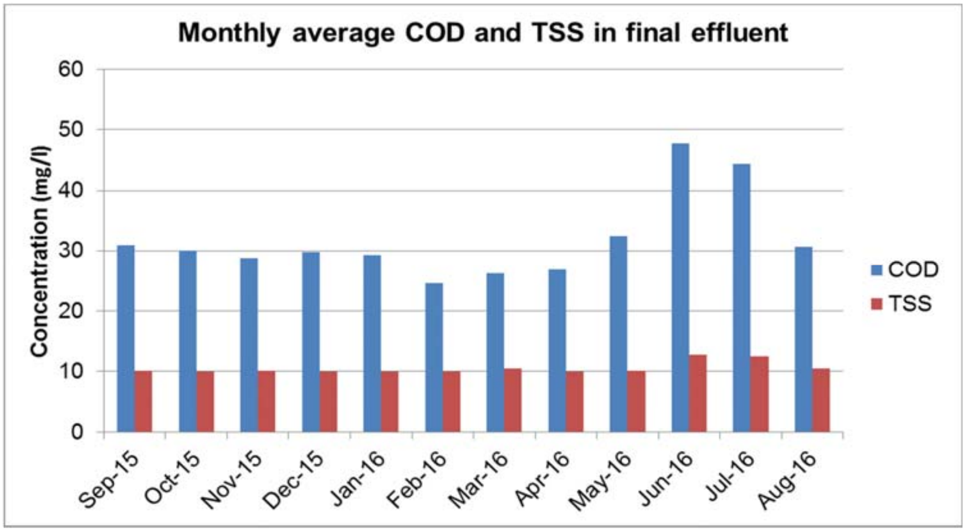

Figure 22: Monthly average COD and TSS in the final effluent at 'W' WWTP

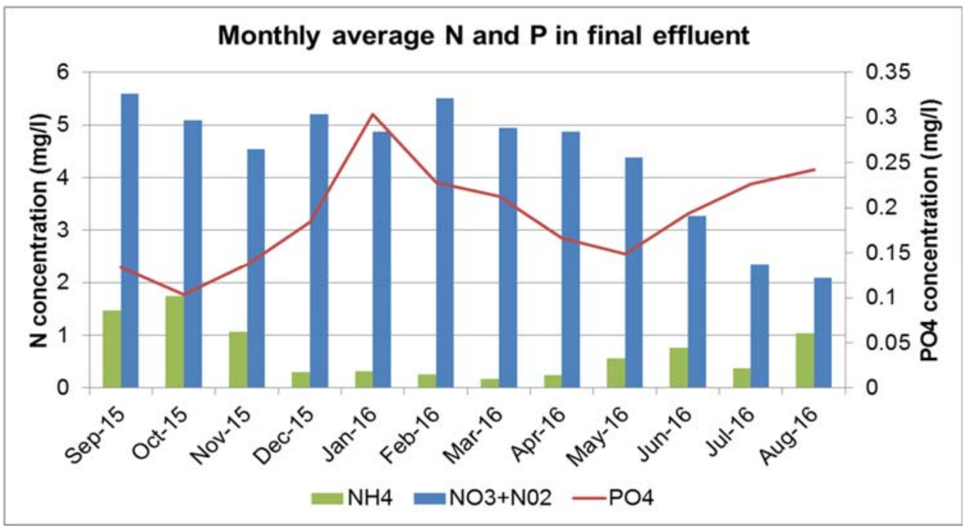

Figure 23: Monthly average ammonia, nitrate+nitrite and orthophosphate in the final effluent at 'W' WWTP

2.5.3 Sludge Treatment

2.5.3.1 Sludge Characteristics

At 'W' WWTP, PS is removed from all the settling tanks in all four modules and is sent to the ADs. The biological sludge is mostly wasted from the aeration tanks (except for Module 1, wasted from the RAS line), thickened in DAF units and finally sent to the ADs. Table 14 indicates the characteristics of the PS and WAS prior floatation and AD.

Table 14: Characteristics of the primary and biological sludge at 'W' WWTP

Parameter	Primary sludge (from PST)	Biological sludge (from BNR)	
		Before floatation	After floatation
Flow (m³/d)	844	5 150	413
Dry solids (%)	4.55	0.55 (*)	5.12
Sludge mass (kg/d)	38 380	28 323	21 126

(*) Average value considered for all four modules.

2.5.3.2 Sludge floatation

The thickening of sludge at 'W' WWTP occurs in five DAF tanks (one per module except Module 4 which has two units). The historical dry solids and organic fraction of the biological thickened sludge is presented in Figure 24. The average dry solids content of the biological thickened sludge is 5.1%. The average organic fraction is 73.9%. The solids capture in Modules 1-3 DAF units is poor and approximately 70%. Module 4 indicates higher solids capture, around 90%. The overall average solids capture of the units is approximately 75% which is significantly lower than the expected 90 to 95%.

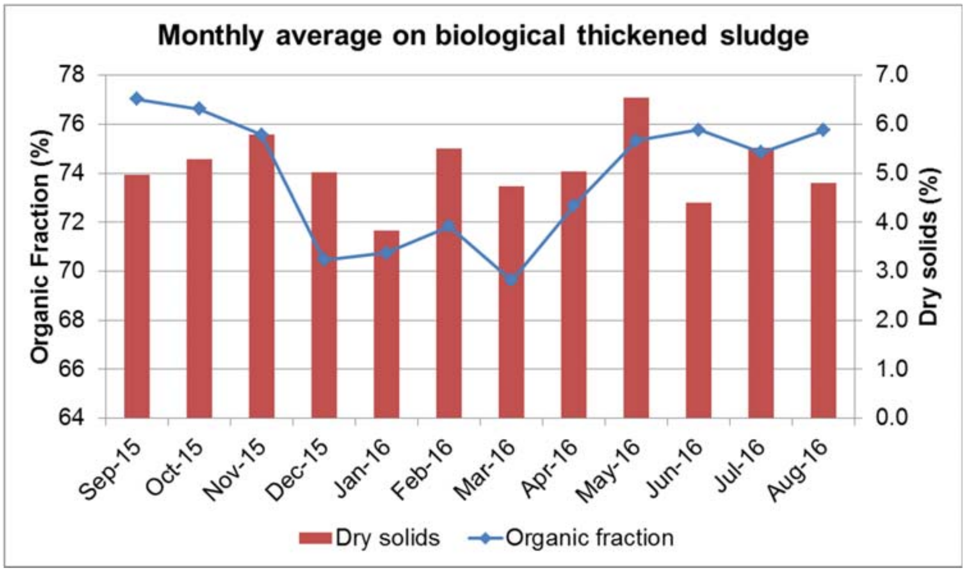

Figure 24: Monthly average organic fractions and dry solids content in the biological thickened sludge at 'W' WWTP

2.5.3.3 Anaerobic sludge digestion

Primary and biological sludge at 'W' WWTP are digested in 14 ADs. Table 15 indicates the digester arrangement at the works.

Table 15: Digester arrangement at 'W' WWTP

Module No.	Number of digesters	Digester conditions
1	4	Sludge not heated or mixed, high retention time
2-3	6	Sludge heated and mixed (using biogas)
4	4	Sludge heated and mixed (using pumps)

From September 2015 to August 2016, the average dry solids content was 3.3% and the organic fraction was 60.1% in the digested sludge (Figure 25).

The calculated HRT for the ADs is on average 102 days for Module 1 (cold digesters) and 31 days for Modules 2-4 (heated digesters). These times indicate proper retention capacity for cold digestion (usually 60 to 90 days) and for heated digestion at 35-37ºC (usually 15-20 days). The organic fraction of non-digested sludge is 71%. Per the long average retention time in the digesters, a higher destruction of VSS, about 60%, is expected. However, on average the calculated destruction of VSS is only 41%.

The operations staff at 'W' WWTP indicated that the average temperature in the heated digesters during winter is 29-32°C. On colder days, the minimum temperature drops to 25°C. These values are below the expected temperatures (35-37°C). During summer, the average temperature in the heated digesters is about

37°C. At the time of compilation of this document, the digesters for Module 1 were in the process of being refurbished with heating and pump mixing equipment.

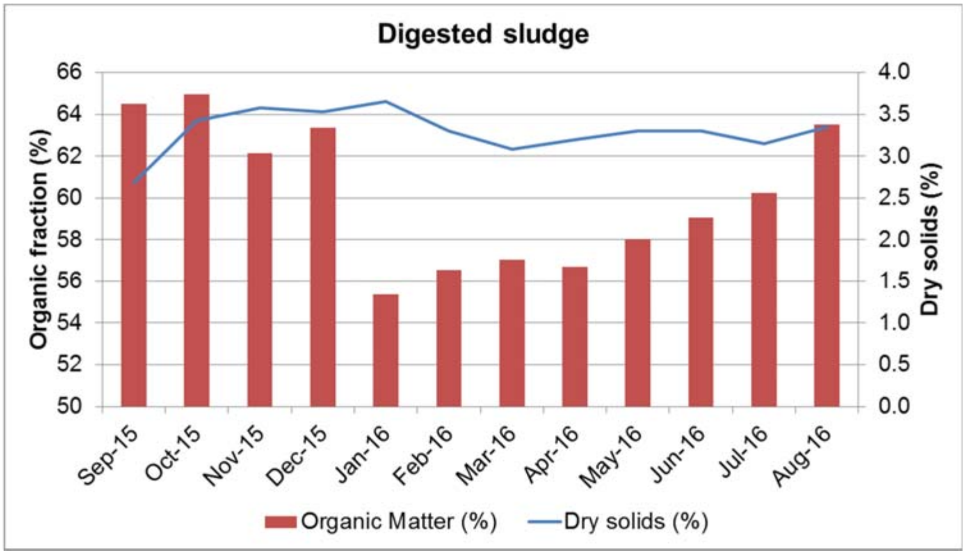

Figure 25: Monthly average organic matter and dry solids in the digested sludge at 'W' WWTP

2.5.3.4 Sludge dewatering

The digested sludge stream splits: 60% of the digested sludge is sent to drying paddies and 40% of the digested sludge goes to belt presses. There is a total of 4 belt presses at 'W' WWTP which operates 7 days a week for 12 hours. The drying paddies, on average, handle 28.7 tonnes/d of digested sludge and the belt presses, 18 tonnes/d of dewatered sludge.

The average dry solids content of the belt press sludge cake is 19%, which is slightly above the typical range coming out of belt presses (15-18%). Figure 26 indicates the dry solids content of the dewatered sludge in the belt presses between September 2015 and August 2016.

The calculated average solids capture in the mechanical dewatering is roughly 90% which is slightly lower than the optimal efficiency of 95%.

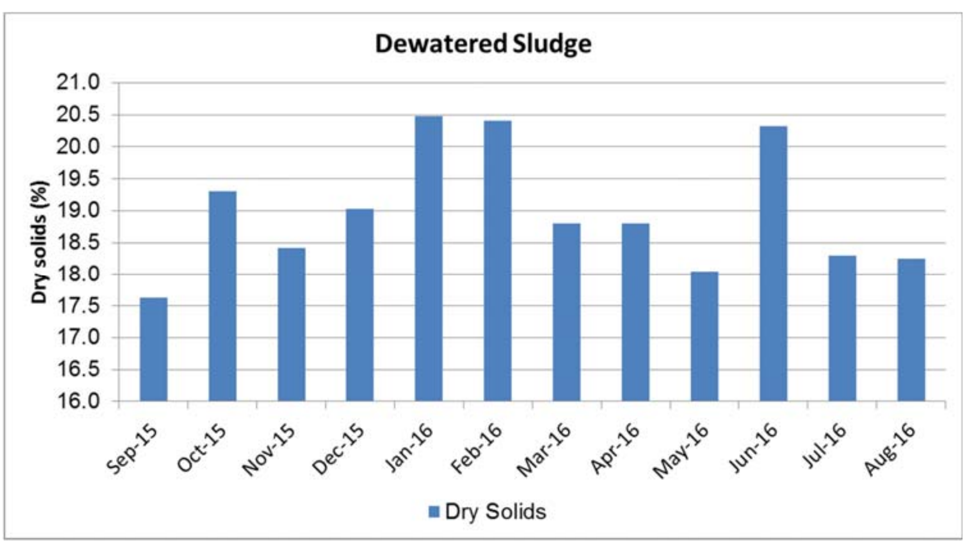

Figure 26: Average dry solids in the dewatered sludge at 'W' WWTP

2.5.3.5 *Quality of dewatering sludge and wash water return liquors*

There are two return liquor streams from the dewatering facility at ‘W’ WWTP, namely, sludge dewatering liquors (filtrate) and wash water liquors (from belt press washing). These streams combine and are split equally between Modules 1-3 and Module 4. At the plant, return liquors are not treated. Figure 27 indicates the average ammonia and orthophosphate concentrations in the combined return liquors.

The average ammonia and orthophosphate concentrations during the monitoring period (September 2015 to August 2016) were 431 mg N/ℓ and 52 mg P/ℓ respectively. The average TSS and COD concentrations during this period were 1 897mg/ℓ and 2 350mg/ℓ respectively.

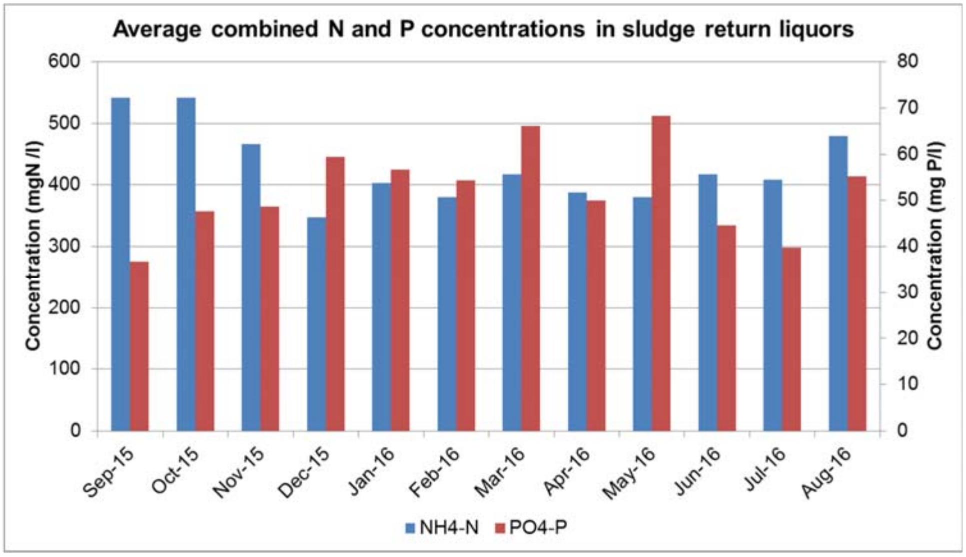

Figure 27: Average combined ammonia and orthophosphate concentrations in the SRLs at ‘W’ WWTP

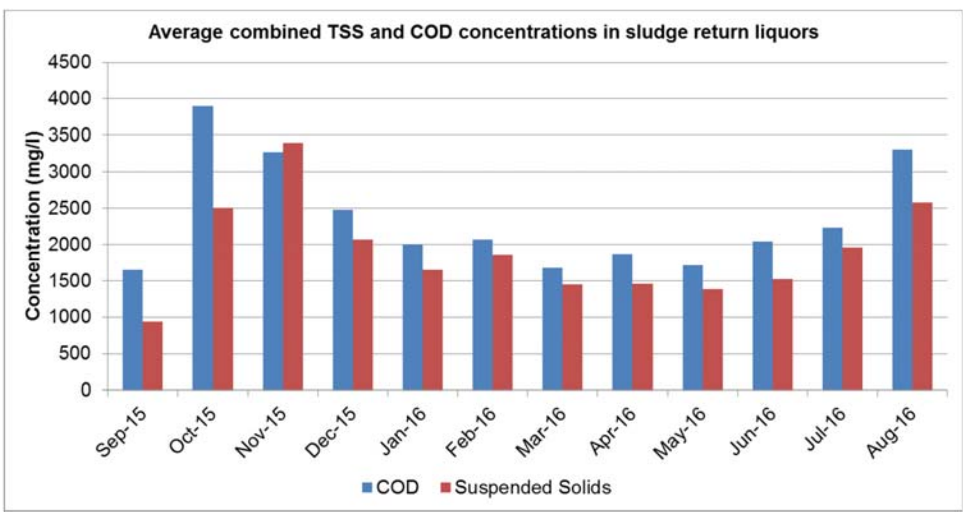

Figure 28: Average combined TSS and COD concentrations in the SRLs at ‘W’ WWTP

2.6 Impact of the sludge return liquors

2.6.1 Plant mass balance

A complete mass balance of the ‘W’ WWTP was prepared to understand and evaluate the magnitude of the impacts of the sludge dewatering return liquors on the main treatment process. The results, elaborated with the average data available from September 2015 to August 2016, is provided in Table 16. The analytical data available did not cover all streams and parameters, the following assumptions were required to complete the mass balance:

- COD in biological sludge: COD/MLVSS = 1.4
- Average WAS = 5 500 mg/ℓ
- Sludge to dewatering = 40%
- Sludge to paddies = 60%
- duty spent washwater pumps × 17 m³/h, 12 h/d
- Return liquors to Modules 1-3 = 50%
- Return liquors to Module 4 = 50%

To confirm the assumptions above and improve the accuracy of the mass balance it would be recommended to double-check the following parameters with an analytical programme during at least 3 days applicable to each module:

- Primary sludge:
  - COD, TSS, TKN and TP.

- DAF units:
  - TSS in and TSS returned.

- Digested sludge:
  - COD, TKN, NH_4^-N, TP and PO_4^-P.

- Dewatering returns:
  - TKN, NH_4^-N and TP.

- Sludge cake (dewatered sludge):
  - COD, TKN, NH_4^-N, TP and PO_4^-P.

The following flows should be also confirmed:

- Biological sludge to DAF units.
- Biological thickened sludge to digestion.
- Daily wash water to the dewatering facility.
- Return sludge liquors recycled to Modules 1-3 and Module 4.

Table 16: Results of the mass balance at 'W' WWTP

Water streams	Raw sewage	Raw WW M1-3	Raw WW M4	Raw WW M1-3 & Returns	Raw WW M4 & Returns	Primary effluent M1-3	Primary effluent M4	Biological effluent M1-3	Biological effluent M4	Final effluent
Flow (Ml/d)	252	198	55	198	56	201	56	197	55	252
COD (kg/d)	185560	144737	40823	145956	42621	122922	34025	6036	1445	7480
TKN (kg/d)	12285	9582	2703	9869	3030	9197	2695	613	134	747
NH4 (kg/d)	6006	4685	1321	4909	1546	4920	1546	265	27	292
NO3+NO2 (kg/d)	0	0	0	0	5.1	16	5	827	269	1096
TP (kg/d)	1547	1206	340	1256	413	1427	377	226	59	285
PO4 (kg/d)	733	571	161	599	189	607	189	53	7.1	59.9
TSS (kg/d)	49265	38427	10838	39331	12302	16592	3858	2093	548	2641
COD (mg/l)	736	733	748	737	759	611	608	31	26	30
TKN (mgN/l)	49	49	50	50	54	46	48	3.1	2.4	3.0
NH4 (mgN/l)	24	24	24	25	28	24	28	1.3	0.5	1.2
NO3+NO2 (mgN/l)	0	0	0	0	0.1	0	0.1	4.2	4.9	4.4
TP (mgP/l)	6.1	6.1	6.2	6.3	7.4	7.1	6.7	1.1	1.1	1.1
PO4 (mgP/l)	2.9	2.9	3.0	3.0	3.4	3.0	3.4	0.3	0.1	0.2
TSS (mg/l)	195	195	199	199	219	82	69	11	10	10

Sludge streams	Primary sludge	Biological sludge	Biological thickened sludge	Digested sludge	Sludge to dewatering	Sludge to paddies	Sludge cake
Flow (Ml/d)	0.844	5.150	0.413	1.26	0.50	0.75	0.08
COD (kg/d)	39073	29287	21844	34797	13919	20878	12542
TKN (kg/d)	1523	1983	1480	3003	1201	1802	628
NH4 (kg/d)	0	13	1.1	1118	447	671	0
NO3+NO2 (kg/d)	0	0	0	0	0	0	0
TP (kg/d)	160	1520	846	1006	712	294	613
PO4 (kg/d)	0	10	0.8	136	54	81	0
TSS (kg/d)	38380	28323	21126	41085	16434	24651	14626
COD (mg/l)	46312	5687	52938	27697	27697	27697	162605
TKN (mgN/l)	1806	385	3586	2390	2390	2390	8136
NH4 (mgN/l)	0	2.6	2.6	890	890	890	0
NO3+NO2 (mgN/l)	0	0	0	0	0	0	0
TP (mgP/l)	190	295	2050	801	1416	390	7951
PO4 (mgP/l)	0.0	1.9	1.9	108	108	108	0
TSS (mg/l)	45491	5500	51196	32702	32702	32702	189627

Sludge return liquors streams	DAF returns M1-3	DAF returns M4	Dewatering returns	Returns to M1-3	Returns to M4
Flow (Ml/d)	3.69	1.04	1.04	0.52	0.52
COD (kg/d)	7443	579	2438	1219	1219
TKN (kg/d)	516	40	574	287	287
NH4 (kg/d)	12	1.3	447	224	224
NO3+NO2 (kg/d)	16	5.1	0	0	0
TP (kg/d)	296	23	98	49	49
PO4 (kg/d)	8.5	0.8	54	27	27
TSS (kg/d)	7198	560	1808	904	904
COD (mg/l)	2014	555	2350	2350	2350
TKN (mgN/l)	140	39	553	553	553
NH4 (mgN/l)	3.2	1.2	431	431	431
NO3+NO2 (mgN/l)	4.2	4.9	0	0	0
TP (mgP/l)	80	22	95	95	95
PO4 (mgP/l)	2.3	0.8	52	52	52
TSS (mg/l)	1948	537	1897	1743	1743

2.6.2 Influent characteristics

The sludge return liquors include dewatering sludge liquors and DAFs supernatant. For Modules 1-3 dewatering sludge liquors are combined with the raw wastewater, while the DAFs supernatant is only discharged downstream of the primary treatment. For Module 4 all sludge liquors (DAF supernatant and dewatering liquors) are combined with the raw wastewater prior primary settling. DAF returns from each module are recycled to each respective module. Dewatering returns are split equally between Modules 1-3 and Module 4.

Table 17 indicates that the impact of dewatering sludge return liquors on raw wastewater from Modules 1-3 falls below typical range for most parameters. For Module 4, the effect of the return liquors is higher and is above the typical range for most parameters. The impact for Module 4 is more substantial because it treats a disproportionate amount of the return liquors compared to the treatment capacity of the module.

Figure 29 and Figure 30 indicate the impact of the dewatering return liquors for all relevant parameters.

Table 17: Impact of dewatering return liquors in the influent characteristics at 'W' WWTP

Parameters	Modules 1-3		Impact on Modules 1-3	Module 4		Impact on Module 4	Impact on total raw WW	Typical impact on Raw WW (*)
	Raw WW	Raw ww & Dewatering returns		Raw WW	Raw ww & Sludge returns			
Flow (Mℓ/d)	197.6	198.1	0.3%	54.6	55.1	1.0%	0.4%	0.5% – 1.0%
COD (kg/d)	144 737	145 956	0.8%	40 823	42 042	3.0%	1.3%	5% – 10%
TKN (kg/d)	9582	9 869	3.0%	2 703	2 990	10.6%	4.7%	9% – 13%
NH_4 (kg N/d)	4685	4 909	4.8%	1 321	1 545	16.9%	7.4%	9% – 13%
TP (kg/d)	1206	0	4.1%	340	0	14.5%	6.4%	5% – 30%
PO_4 (kg P/d)	571	1 256	4.7%	161	389	16.8%	7.4%	5% – 30%
TSS (kg/d)	38427	599	2.4%	10 838	188	8.3%	3.7%	2% – 5%

(*) Based on Royal HaskoningDHV process design tool and excluding any dedicated treatment to the sludge return liquor

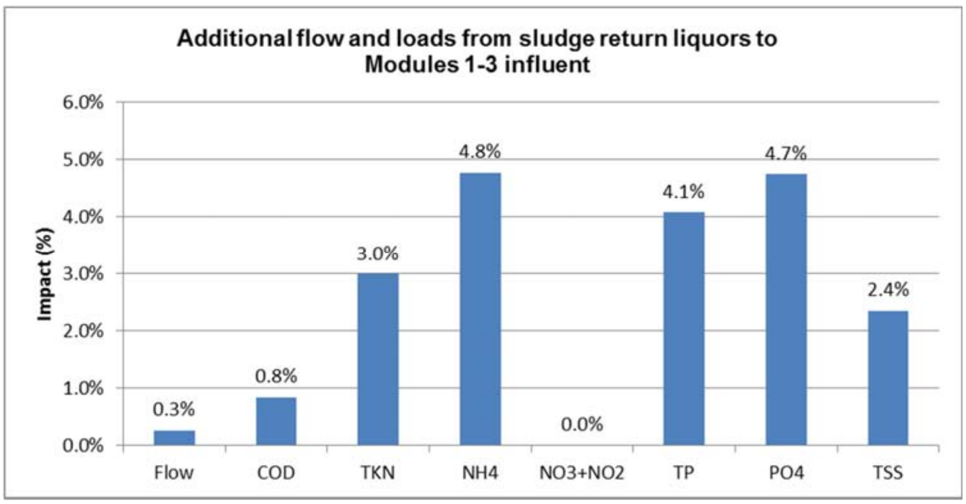

Figure 29: Additional flow and loads entering Module 1-3 from the sludge return liquors treatment at 'W' WWTP

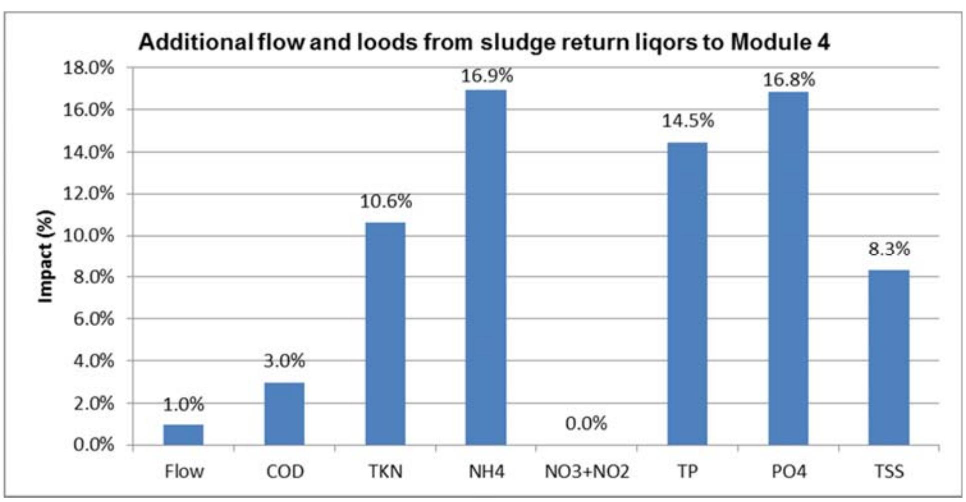

Figure 30: Additional flow and loads entering Module 4 from the dewatering sludge return liquors at 'W' WWTP

Currently, 40% of the digested sludge is dewatered using belt presses, with the other 60% being dried on drying beds/paddies. If in future all the digested sludge was dewatered using belt presses and the return liquors were split evenly between Modules 1-3 and Module 4, there would be a slight additional impact on the influent load on Modules 1-3 and a more significant impact in Module 4. In this scenario, Module 4 would see an increment of load due to the dewatering return liquors in of 27% for NH_4^-N, 23% for TP, 27% for PO_4^-P and 13% for TSS.

Comparing the influent ratios for Modules 1-3 and Module 4 (including dewatering returns) with a typical South African sewage (Table 18), it is noted that all ratios lie above the typical ranges. The reason behind that is the unusual low influent solids and nutrients (N and P) concentrations compared to the influent COD concentration. In practice, this does not have an impact in the plant's performance.

Table 18: Influent ratios with and without return liquors at 'W' WWTP

Ratios	Modules 1-3	Module 4	Typical SA Raw WW*
	Raw WW & Returns	Raw WW & Returns	
COD/TSS	3.6	3.6	2.0
COD/TKN	15	14	8.2
COD/ NH_4	30	27	14
COD/TP	116	108	54
COD/ PO_4	244	223	117

(*) WRC Report TT389/09, Process Design Manual for Small Wastewater Treatment Works

2.6.3 Biological effluent quality

The average effluent quality of Modules 1-3 and Module 4 (biological effluent) is presented in Table 19. On average, all parameters in the biological effluent meet the effluent standard requirements.

Assessing Figure 31 from September 2015 to August 2016, it is noted that Modules 1-3 have a lower ammonia concentration between December 2015 and April 2016. This could be due to the higher summer temperatures helping facilitate nitrification. This also accounts for why there is a higher nitrate and nitrite concentration during this period resulting from higher nitrification capacity with more NO_x production. Apparently, the denitrification capacity does not exactly follow the improved nitrification capacity in summer period. For Module 4 Figure 32 indicates that ammonia concentrations are stable through the year seasons and lie below 1.0 mg N/ ℓ (with an exception in Jun 2016).

Table 19: Average effluent quality of the biological effluent at 'W' WWTP

Parameters	Modules 1-3 (biological effluent)	Module 4 (biological effluent)
COD (mg/ℓ)	31	26
NH_4 (mg N/ℓ)	1.3	0.5
NO_3 + NO_2 (mg N/ℓ)	4.2	4.9
PO_4 (mg P/ℓ)	0.3	0.1
TSS (mg/ℓ)	11	10

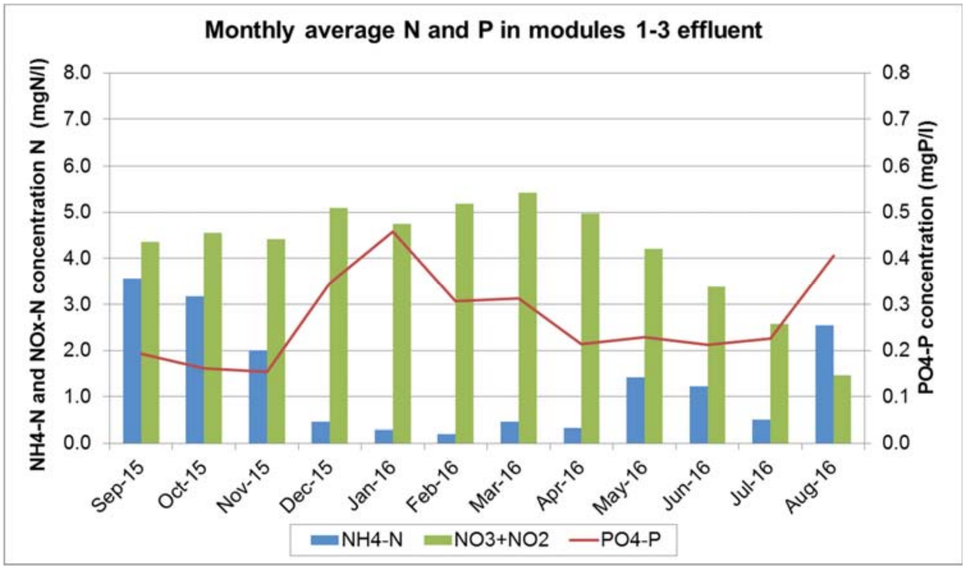

Figure 31: Monthly AV ammonia, nitrate+nitrite and orthophosphate effluent quality from Modules 1-3 at 'W' WWTP

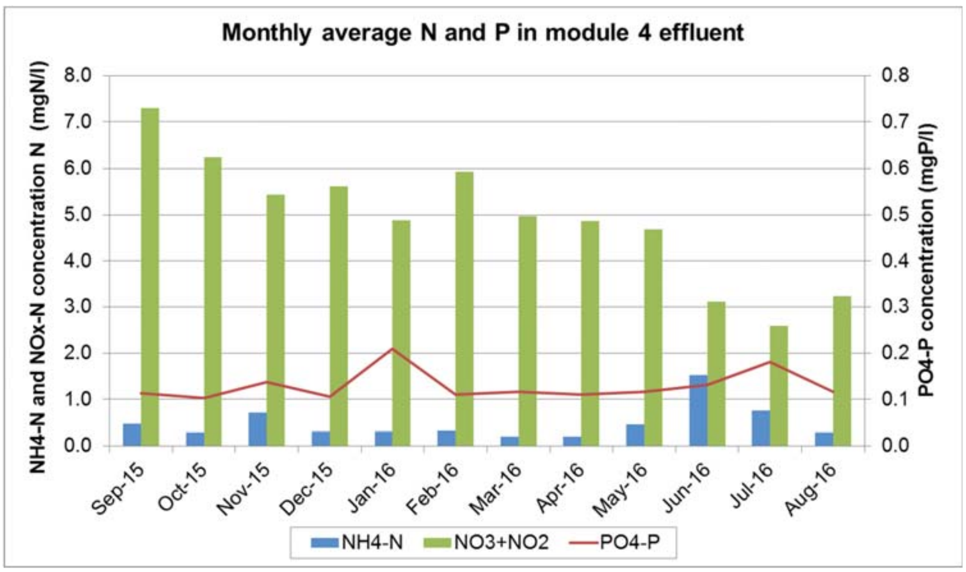

Figure 32: Monthly AV ammonia, nitrate+nitrite and orthophosphate effluent quality from Module 4 at 'W' WWTP

2.6.4 Aeration demand

At Waterval, the four modules include surface aerators and fine bubble diffusers with blowers. The aeration equipment installed is as following:

- Module 1:
    - o 16 × 37 kW stage 1 surface aerators running 24 hours/day.
    - o 10 × 37 kW 2 stage surface aerators running 24 hours/day.
    - o Currently, four stage 1 surface aerators are out of service.
- Modules 2-3:

- o 5 × fixed speed 375 kW centrifugal blowers (4 duty, 1 standby) provide air for fine bubble aeration system. Duty blowers run 24 hours/day.

- Module 4:
  - o × 75 kW surface aerators running 24 hours/day.
  - o 10 × 55 kW surface aerators running 24 hours/day.
  - o Currently, three surface aerators are out of service.

The plant does not have individual energy meters in the aeration system and therefore historical consumption records are not available. However, for the current operating conditions, i.e. only 40% of the digested sludge is dewatered and respective sludge liquors returned to treatment, it is estimated that about 72 000 kW/d are spent in aeration in the biological reactors (55 500 kW/d in Modules 1-3 and 16 500 kW/d in Module 4).

If in future 100% of the digested sludge is dewatered, the flow and load of the sludge liquors will increase, and it is expected that the total aeration consumption also increases in at least 5% (as per current split 3% in Modules 1-3 and 10% in Module 4).

If side stream treatment for the current returns is considered, it should be possible to decrease the total aeration capacity in the biological treatment by 8% and if in the future 100% of the sludge is dewatered, the reduction in the aeration demand should be at least 12%.

2.6.5 Biological treatment capacity

The current inflow to all modules is above the plant design flow. Modules 1-3 are treating 165% and Module 4 receiving 112% of their design flows. For Modules 1-3 COD, TKN and ammonia loads are greater than the design loads. For Module 4 only TKN and ammonia loads are slightly greater than the design loads (refer to Table 20).

For the current high flow/load treated in Modules 1-3, it is surprising that its effluent requirements are still mostly compliant as referred in section 2.6.3. This may be justified by a reasonable sludge retention time in Modules 1-3, approximately 9 days, when the minimum SRT to nitrify at 14ºC is only 6 days. Module 4 shows a much higher SRT (19 days on average) and since it is much less overloaded, its performance is always excellent and not affected by variation of process temperature.

Table 20: Current biological treatment capacity at Waterval WWTW

Parameters	Modules 1-3			Module 4		
	Design	Actual		Design	Actual	
Flow (Mℓ/d)	120	198	165%	50	56	112%
COD (kg/d)	132 000	145 956	111%	55 000	42 621	77%
TSS (kg/d)	66 000	39 331	60%	27 500	12 302	45%
TKN (kg/d)	7 200	9 869	137%	3 000	3 030	101%
NH_4^-N (kg/d)	3 360	4 909	146%	1 400	1 546	110%
TP (kg/d)	1 440	1 256	87%	600	413	69%
PO_4^-P (kg/d)	840	599	71%	350	189	54%

2.7 Conclusions and recommendations

The site research conducted at 'W' WWTP indicates the following conclusions regarding the impact of the sludge return liquors in the plant:

1. The dewatering return liquors, rich in ammonia and ortho-phosphate, are recycled to the beginning of the treatment process, before primary treatment, and the flow is split: 50% to Modules 1-3 and 50% to Module 4. Considering that Module 4 corresponds to only 35% of the total biological capacity available, the current split of the returns is not proportional and therefore increases the impact of the return liquors on this module, i.e. an additional 17% of ammonia and ortho-phosphate to be treated as well as additional 8% in TSS. At the moment, this is not critical and not affecting the effluent quality of Module 4. In comparison, Modules 1-3, with 65% of the biological capacity available, shows an almost negligible impact in the increase of the inflow and influent load. Despite the current minimal impact on these modules, it would be recommended to make a proportional split of the dewatering returns per the capacity of the modules.

2. Currently only 40% of the digested sludge is mechanically dewatered and only the corresponding fraction of dewatering return liquors is recycled to the beginning of the treatment works. If, in the near future, 100% of the digested sludge is dewatered, an additional 60% of the dewatering returns will be added to the current influent. In that case the impact on Module 4 will be even higher (estimated in 27% increase on NH_4^-N and PO_4^-P each).

3. The DAF returns are also a point of concern and especially on Module 1 due to the age of the installation and continuous breakdowns in equipment. In general, the high TSS concentration returned from the DAF's supernatant indicates a non-optimal efficiency of the floatation units. Therefore, the hydraulic and solids loads should be properly checked as well as the pressurization systems.

4. Although Plant 'W' is overloaded the plant's performance is still compliant with the current standard effluent requirements. However, it should be noted that the plant has a relatively lenient requirement for ammonia and if more stringent effluent limits are applied (for example ammonia < 1 mgN/ℓ), Modules 1-3 would not be able to continuously comply (refer mainly to the winter season).

In addition, the following generic conclusions and recommendations shall be noted:

5. The plant is generally well operated and shows a good level of maintenance.

6. The current hydraulic demand in the plant is 150% of the total design capacity. Modules 1-3 have a current capacity of 165% of the design flow and Module 4 has 112% of its design flow. Also, the ammonia load coming in to Modules 1-3 is already at 146% of the design load. ERWAT is already planning the extension of the plant. This will be extremely helpful to alleviate the extra flow currently reaching Modules 1-3.

7. The anaerobic digestion process has been running smoothly and no critical issues were encountered. The long sludge retention time in the digesters (> 100 days in the cold digesters and > 30 days in heated digesters) is allowing 40% of VSS destruction. A slightly higher VSS destruction rate, close to 50-60%, was expected. It is recommended to double check the digestion temperature in the heated digesters and mixing conditions as well.

CHAPTER 3: 'K' Wastewater Treatment Plant

The 'K' WWTWP is located in the KwaZulu-Natal Phoenix industrial/residential area and is owned and operated by eThekwini Municipality. The plant treats mainly domestic sewage from these two areas, and only 10 to 15% of the influent is from industries. The 'K' WWTP has a treatment capacity of 80 Mℓ/d; consisting of a 15 Mℓ/d trickling filter module and a 65 Mℓ/d activated sludge module. The current ADWF is about 57 Mℓ/d. An overview of the 'K' WWTP site is presented in Figure 33.

The plant's key unit operations consist of primary sedimentation, trickling filters, AS treatment and AD. The biological effluent is clarified in secondary clarifiers and humus tanks and then discharged into the environment after chlorination. The WAS from the aerobic process is thickened and dewatered using mechanical presses. A portion of the PS (30%) is dewatered and incinerated in a fluidised bed reactor (FBR).

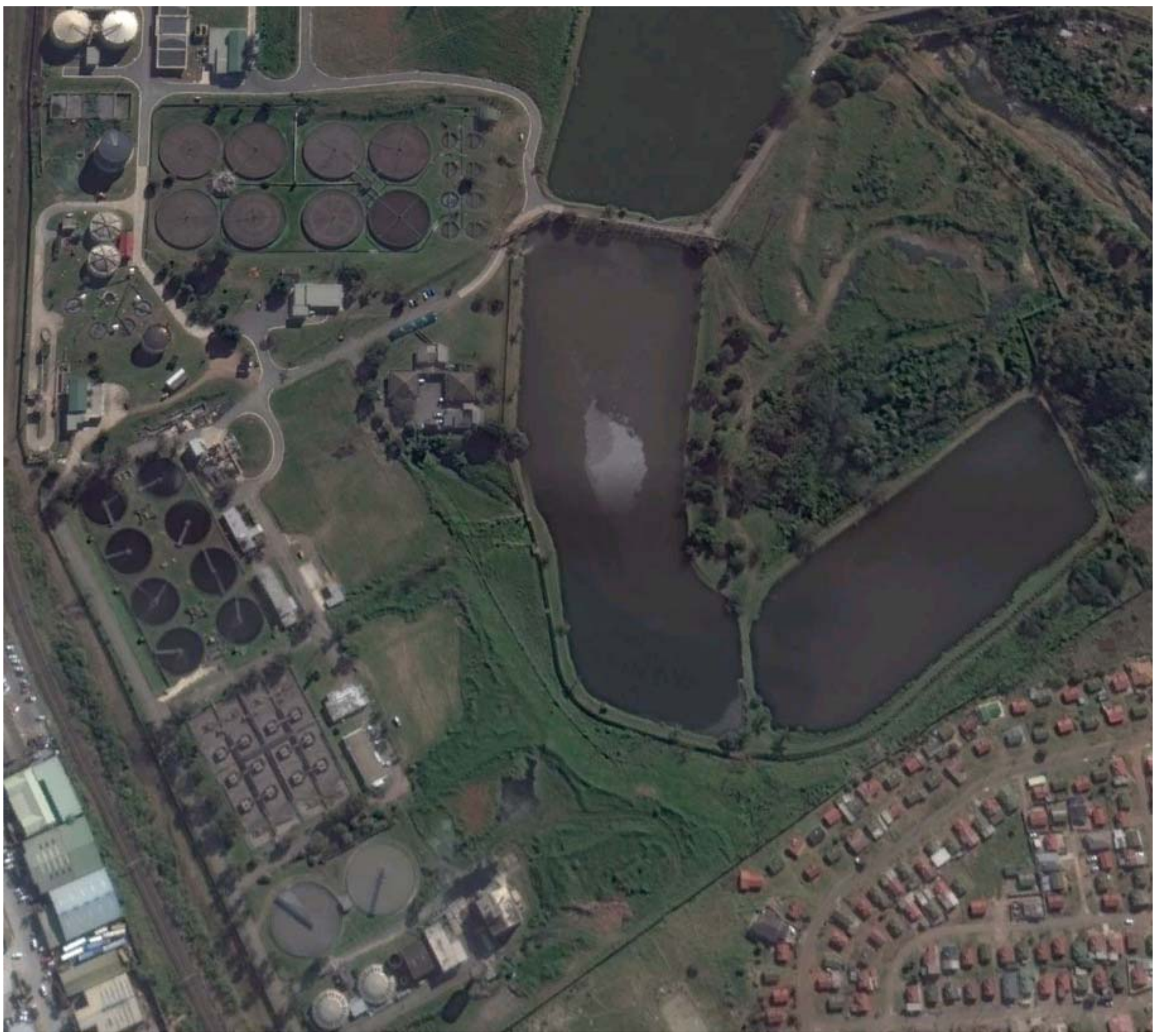

Figure 33: Aerial view of 'K' WWTP (Google Earth)

3.1 Process description

A description of the works is indicated below as per information retrieved from the plant's as-built drawings. The general process flow diagram of the treatment works is provided in Figure 34.

- **Inlet works** consists of:
  - Two mechanical stone traps,
  - Three mechanical inlet screens (new works),
  - Two aerated degritters.

- **Wastewater treatment** consists of:
  - 15 Mℓ trickling filter module:
    - Six PSTs
    - trickling filters
    - humus tanks
  - 65 Mℓ fully aerobic activated sludge module,
  - An aerobic process consisting of 16 aerators arranged in 4 lanes with 4 aerators per lane,
  - Eight SSTs.

- **Disinfection** consists of:
  - Final effluent from the SSTs is discharged into two maturation ponds which overflow via a third maturation pond into the uMhlangane River.

- **Sludge handling and disposal** consists of:
  - A portion of the PS (30%) is dewatered and incinerated in a fluidised bed reactor (FBR). The remaining primary sludge from the two PSTs is thickened and anaerobically digested. The FBR unit, however, is currently not in operation due to a planned upgrade to maximise its operations. This has been the situation for over 2 years. Thus, all the PS now undergoes thickening and is pumped to the anaerobic digesters,
  - WAS is pumped from the SSTs to the DAF unit while return activated sludge (RAS) is recycled to the AS system,
  - Thickened primary sludge is digested in four mesophilic anaerobic digesters including mixing and heating (2 000 m³ each).
  - Digested sludge undergoes further digestion in two secondary digesters (2 310 m³ each)
  - Digested sludge is stored in a digested sludge sump which subsequently feeds the dewatering plant. The digested sludge is fed to mechanical screw (Huber) presses via four sludge-feed lines.
  - Biological thickened sludge from the DAF unit is pumped to a secondary sludge feed sump from where it is fed to the dewatering plant and thereafter incinerated or beneficially applied to agricultural land.

- **Return liquors treatment** consists of:
  - All sludge return liquors from gravity thickeners, DAF, secondary digester and mechanical dewatering are returned upstream of the PSTs included in the AS module.

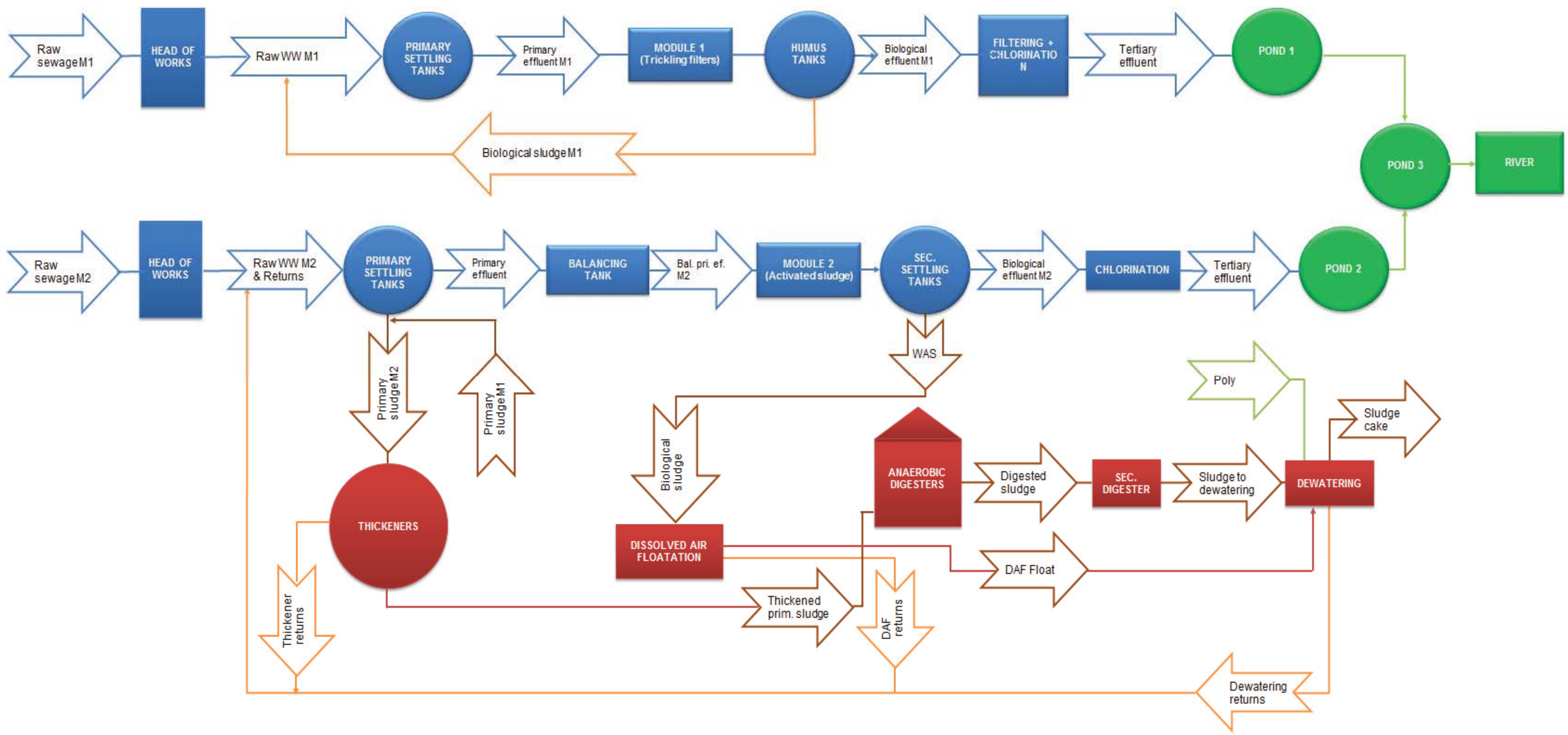

Figure 34: 'K' WWTP block diagram

3.2 Design capacity

The total design capacity of the plant is indicated in Table 21.

Table 21: Design flows and loads at 'K' WWTP

Parameters	Old works	New works	Total
Flow (Mℓ/d)	15	65	80
COD (kg/d)	12 000	50 000	62 000
TKN (kg/d)	520	3 600	4 120
TP (kg/d)	90	765	855

3.3 Effluent standard requirements

Currently, the 'K' WWTP does not have water use licence in place; implying that there are no existing wastewater limit values that specifically governs the discharge of effluent generated at the works. An application has been made in this respect. Table 22 presents general wastewater limit values applicable to discharge of wastewater into a water resource as gazetted in the Revision of General Authorisations in terms of Section 39 of the National Water Act, 1998 (Act No. 36 of 1998) – Gazette No. 36820 (6 September 2013). Considering the non-existence of a water use licence, it is assumed that the general standards will be applicable to the works.

Table 22: General requirements for effluent discharge applicable to 'K' WWTP

Parameter	Effluent standards	Method of compliance
COD (mg/ℓ)	75	90% compliance
TSS (mg/ℓ)	25	
NH_4 (mg N/ℓ)	6	
$NO_3 + NO_2$ (mg N/ℓ)	15	
PO_4 (mg P/ℓ)	10	

3.4 Technical performance

The Royal HaskoningDHV team conducted a site visit to the works on 28 November 2016. The 'K' WWTP appears to be a well operated and maintained facility with reasonable level of automation and optimization measures including SCADA system, VSDs and DO sensors.

However, the old works has been offline for about six months due to a fault to the inlet screens at the old works. The screens are currently being replaced by mechanical raked screens removed from the new works as a result of an upgrade. Consequently, all wastewater is currently being treated at the new works.

3.5 Process performance

3.5.1 Influent characteristics

Figure 35, the average daily flow of wastewater treated at 'K' WWTP between January 2014 and June 2016 is presented. On average, a total of 60 Mℓ/d of wastewater was treated at the works; implying 75% of the plant's design capacity. The new works treats approximately 90% of the flows (54 Mℓ/d) while the old works treats the remaining 10% (6 Mℓ/d); representing 83% and 40% of the design capacity of the new and old works respectively.

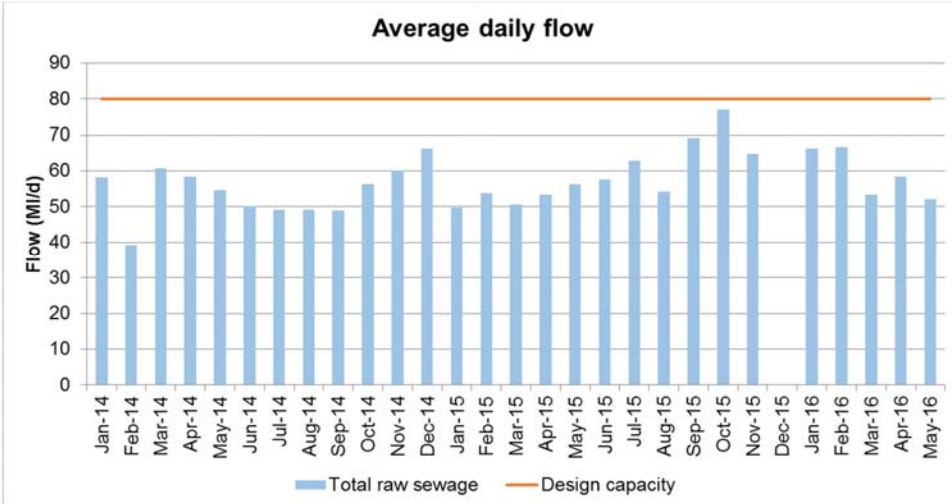

Figure 35: Average daily flow at 'K' WWTP

The average influent concentrations and loads are indicated in Table 23 and historical averages in Figure 36 and Figure 37. In general, the raw sewage shows a high loading rate but remains within the plant's design specification. Currently the plant is treating 67% of the COD design load, 72% of the TKN design load and 62% of the TP design load.

Table 23: Average raw sewage concentrations and loads at 'K' WWTP

Parameter	Average concentration (January 2014 to June 2016)		Average load (January 2014 to June 2016)	
COD	727.3	mg/ℓ	41 456	kg/d
TSS	612.8	mg/ℓ	34 930	kg/d
TKN	52.3	mg/ℓ	2 983	kg/d
NH_4	21.7	mgN/ℓ	1 234	kg/d
PO_4	3.2	mgP/ℓ	182	kg/d
TP	9.3	mg/ℓ	532	kg/d

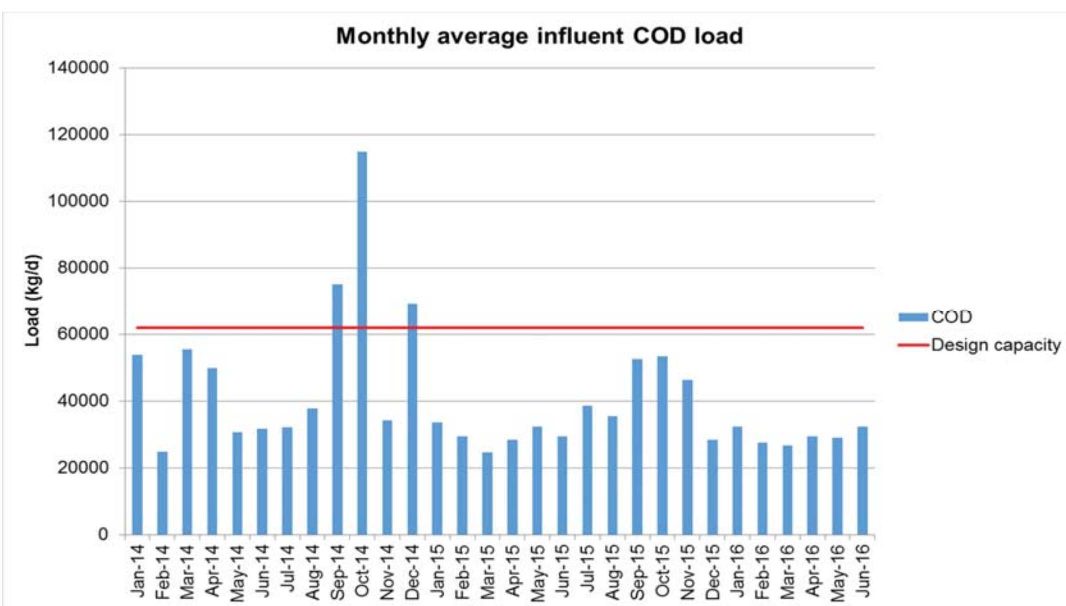

Figure 36: Average COD load at 'K' WWTP

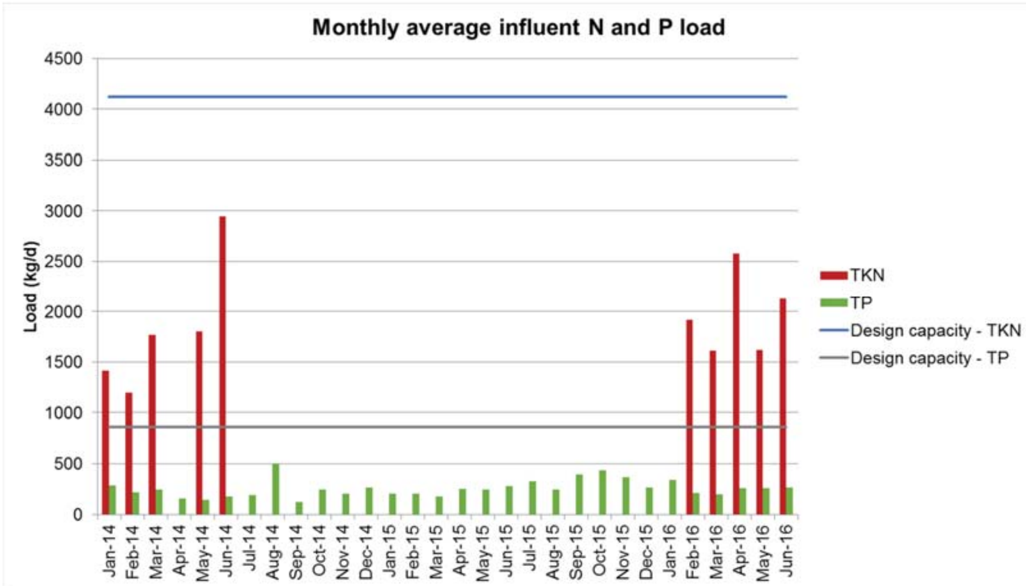

Figure 37: Average TKN and TP loads at 'K' WWTP

*Missing values were observed in TKN data between July 2014 and January 2016

3.5.2 Effluent quality

Benchmarking the final effluent discharged at 'K' WWTP (Table 24) against the effluent general wastewater discharge limits (refer to Section 3.3), excellent phosphorous removal is achieved at the plant as 100% compliance was observed during the period under review. However, the average concentrations of COD, TSS and NH_4 were beyond allowable limits in many instances or samples; representing 89%, 90% and 69% compliance respectively. Institution of process optimization measures is advised to ensure full compliance with specified limits.

Table 24: Average final effluent quality and plant compliance at 'K' WWTP

Parameter	Effluent standards	Average concentration (January 2015 to June 2016)	Average compliance (January 2015 to June 2016)
COD	75	48,4 mg/ℓ	89%
TSS	25	12,1 mg/ℓ	90%
NH_4	6	5,1 mgN/ℓ	69%
$NO_3 + NO_2$	15	3,8 mgN/ℓ	100%
PO_4	10	2,4 mgP/ℓ	100%

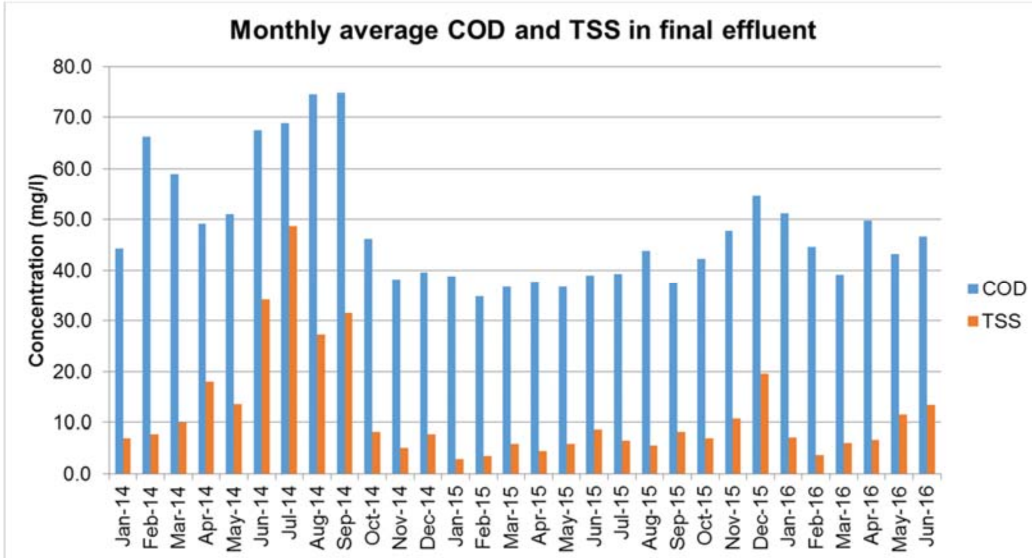

Figure 38: Monthly average COD and TSS in the final effluent at 'K' WWTP

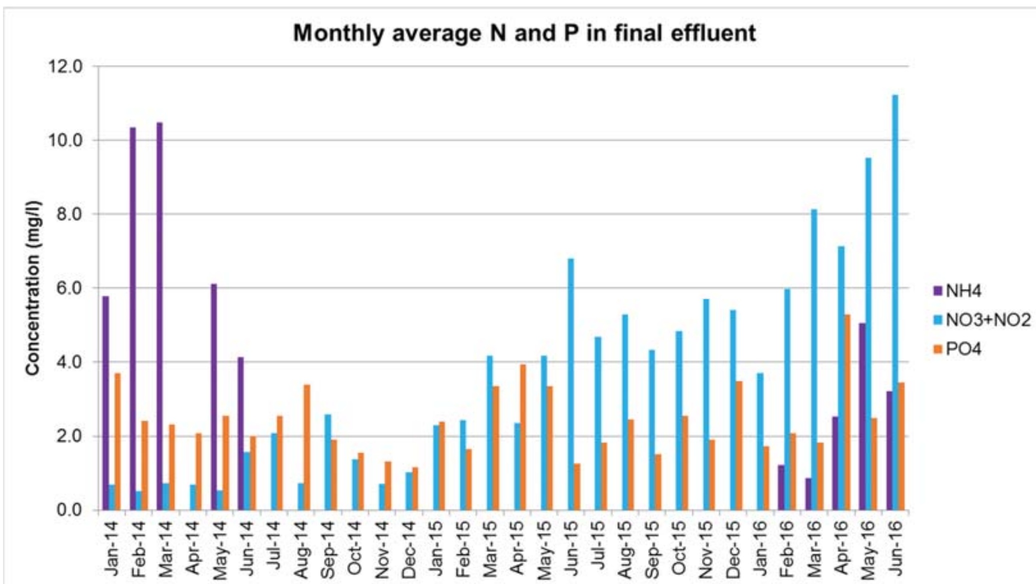

Figure 39: Monthly average ammonia, nitrate+nitrite and orthophosphate in the final effluent at 'K' WWTP

3.5.3 Sludge treatment

3.5.3.1 Sludge characteristics

At 'K' WWTP, PS from the PSTs at the old and new works is extracted and sent to two thickeners. Sludge from the humus tank is recycled to the incoming flow into the PSTs at the old works. Sludge production at the humus tanks is approximately 300 m³/day at 1-2% dry solids. Biological sludge is wasted from the SSTs and fed into the DAF unit. The design capacity of the plant with regards to sludge handling and treatment is 125 ton sludge per day; comprising approximately 65-ton digested sludge per day at 25% total solids and 60 ton WAS per day at 22% TS.

Table 25 indicates the characteristics of the PS prior and after thickening and WAS before and after floatation.

Table 25: Characteristics of primary and biological sludge at the new and old plants in 'K' WWTP

Parameter	Primary sludge		Biological sludge	
	Before thickening	After thickening	Before floatation	After floatation
Flow (m³/d)	1 300	650	665	186
Dry solids (%)	1.8	3.2	1.2	4.1
Sludge mass (kg/d)	22 967	20 670	8 279	7 626

3.5.3.2 *Sludge thickening*

Primary and biological sludge from the old works is combined with PS from the new works and all together are gravity thickened to 3.2% DS. The thickeners show a reasonable solids capture at 90%.

The historical performance of primary and biological thickened sludge is presented in Figure 40. The average dry solids content of the primary and biological thickened sludge is approximately 3.2% and 4.1 % (w/v) respectively, and it is aligned with the plant's design values. The organic fraction of the sludge is about 62% and 66% respectively. Also, the DAF units indicate a solids capture around 92%.

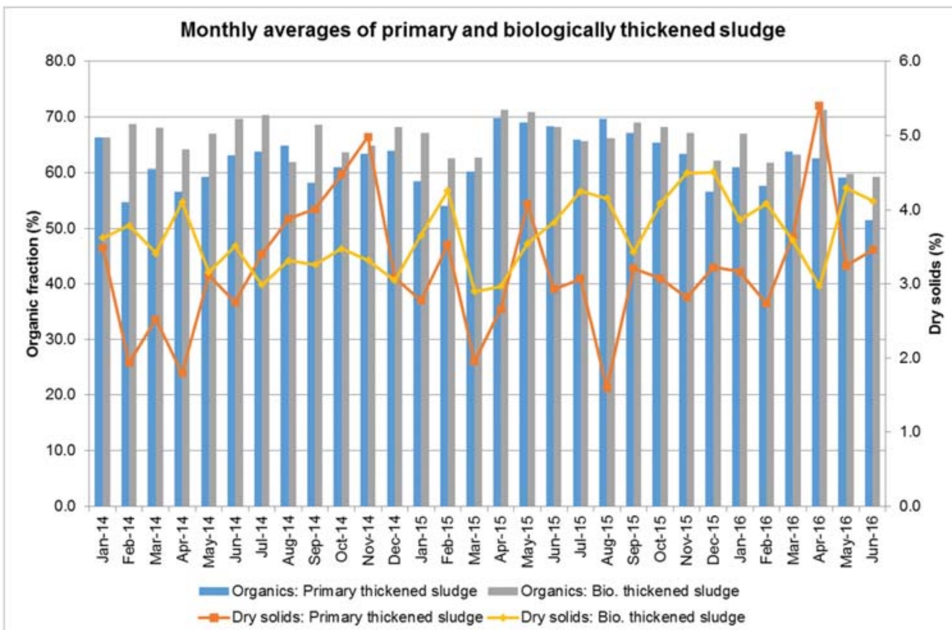

Figure 40: Monthly averages of organic fraction and DS content in the PS and WAS thickened sludge at 'K' WWTP

3.5.3.3 *Anaerobic sludge digestion*

PS is anaerobically digested in 4 digesters. The digesters were operated at between 30-35°C using heat produced from about 40% of biogas. The remaining biogas, comprising of approximately 65% methane and 35% CO_2 is flared to atmosphere. At this range of temperatures, the anaerobic stabilization of the sludge is considered efficient due to stability in the heating process of the ADs. Further stabilization of the sludge is achieved in two secondary digesters; allowing for the supernatant liquor separation and decantation.

The DS content of sludge digested during the period January 2014 to June 2016 ranged between 1.2% and 4.3%; averaging 2.7% (w/v), and the organic fraction was on average 60% (Figure 41). The average retention time in the ADs was approximately 15 days, which is just within the range (i.e. 15-20 days recommended retention time) for digesters operated under mesophilic conditions (35ºC). The destruction of VSS in the digesters is calculated to be 23%. This is less than the typical range (50% to 460%) of VSS destruction in PS anaerobically digested. It is recommended to thoroughly check the temperature as well as mixing conditions in the ADs.

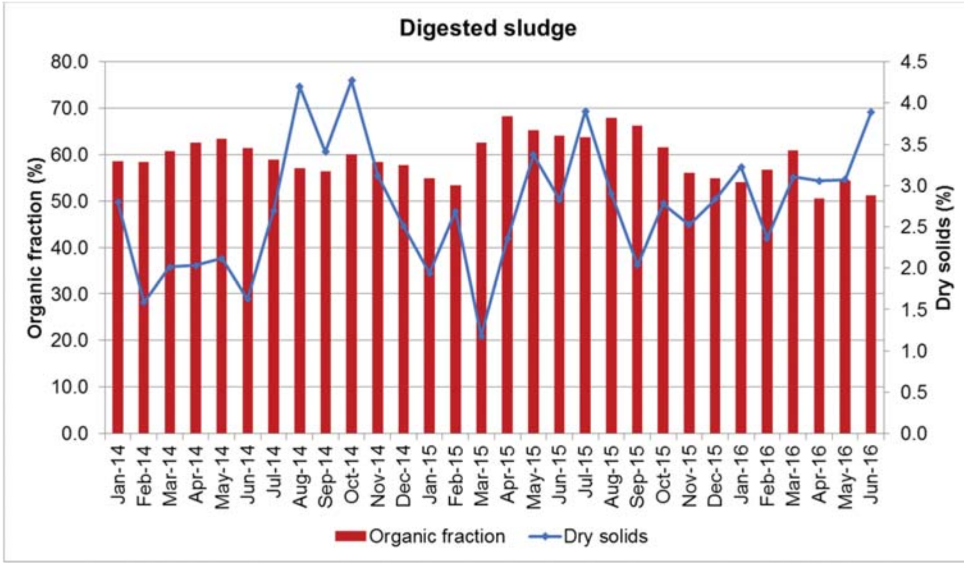

Figure 41: Monthly average organic fraction and dry solids content in the digested sludge at 'K' WWTW

3.5.3.4 Sludge dewatering

The combination of primary digested sludge and biological thickened sludge are mechanical dewatered using a centrifuge system; comprising 8 Huber units. Upon analysis of data received, the average DS content in the sludge cake was approximately 24% (Figure 42), which is within the typical operating range of mechanical screw presses (20-30%).

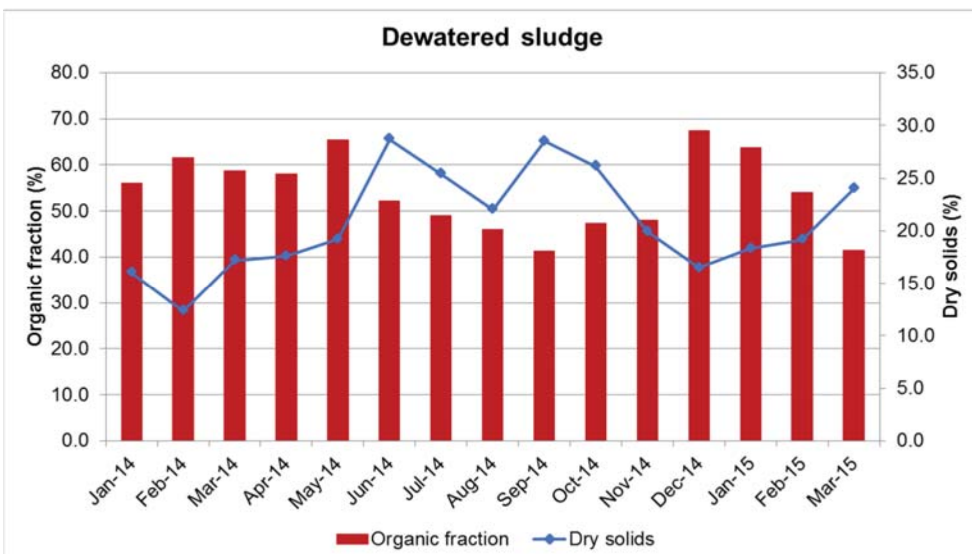

Figure 42: Monthly average organic fraction and dry solids content in the dewatered sludge at 'K' WWTP

3.5.4 Treatment of sludge return liquors

Per information received from process engineers at the works, no treatment is given to the sludge return liquors at the plant.

The recorded monthly average orthophosphate and ammonia concentrations in the return liquors from January 2014 to June 2016 are indicated in Figure 43. The average concentrations were approximately 18 mg NH_4 N/ℓ and 5 mg PO_4^-P /ℓ which appear to be very low and another indication that the anaerobic digestion process is not optimised.

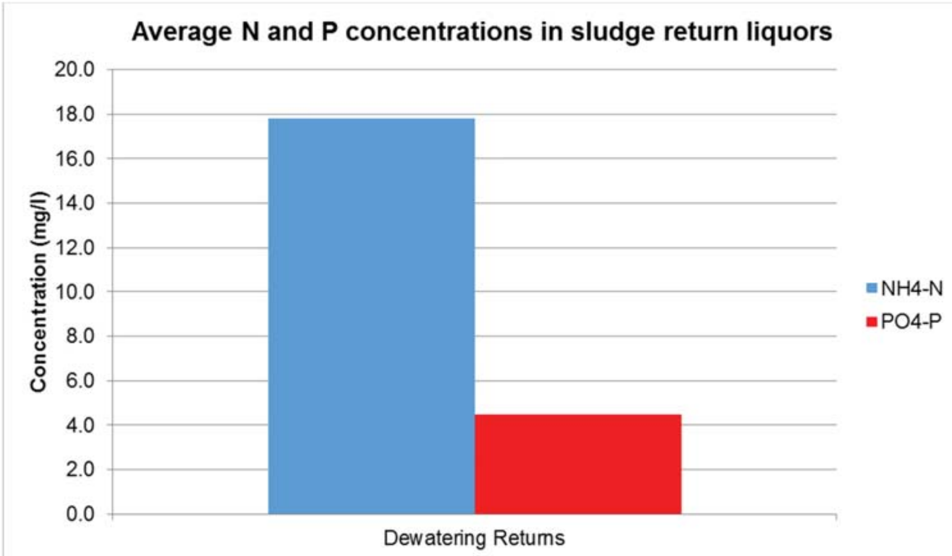

Figure 43: Average ammonia and orthophosphate concentrations in the sludge return liquors at 'K' WWTP

3.6 Impact of sludge returns liquors

3.6.1 Plant mass balance

A complete mass balance of the 'K' WWTP was prepared to understand and evaluate the magnitude of the impacts of the sludge dewatering return liquors on the main treatment process addressed in the following sections. The result of the plant mass balance, elaborated with the average data available from January 2014 to June 2016, is provided in Table 26. Once the analytical data available did not cover all streams and parameters, the following assumptions were required to complete the mass balance:

- COD in biological sludge: COD/MLVSS = 1.4
- TKN/SS ratio = 7%
- TP/SS ratio = 5%
- Washwater to dewatering plant = 20% of feed

To confirm the assumptions above and improve the accuracy of the mass balance it would be recommended to double-check the following parameters with an analytical programme during at least 3 days:

- Primary sludge (old and new):
  - COD, TSS, TKN and TP.
- Biological sludge:
  - COD, TSS, NH_4^-N, TKN, PO_4^-P and TP.
- Primary thickened sludge:
  - TSS in, TSS returned and DS sludge.
- DAF units:

- o TSS in, TSS returned and DS sludge.

- Digested sludge:
  - o COD, TKN, NH_4^-N, TP, $P0_4^-$P and DS.

- Thickeners returns:
  - o COD, TKN, NH_4^-N, TP, $P0_4^-$P and TSS.

- DAF returns:
  - o COD, TKN, NH_4^-N, TP, $P0_4^-$P and TSS.

- Digester returns:
  - o COD, TKN, NH_4^-N, TP, $P0_4^-$P and TSS.

- Dewatering returns:
  - o COD, TKN, NH_4^-N, TP, $P0_4^-$P and TSS.

- Sludge cake (dewatered sludge):
  - o COD, TKN, NH_4^-N, TP, $P0_4^-$P and DS.

The following flows should be also confirmed:

- Primary sludge to thickener, and to digestion.
- Biological thickened sludge
- Dewatered sludge.
- Return sludge liquors recycled to new works.
- Washwater to dewatering.

Table 26: Results of the mass balance at 'K' WWTP

Water streams	Raw WW - Old works	Raw WW - New works	Raw WW - New works & Returns	Balanced primary effluent - Old works	Balanced primary effluent - New works	Secondary effluent - Old works	Secondary effluent - New works	Final effluent
Flow (Ml/d)	6.0	54.0	56.0	6.0	55.0	5.7	54.3	60.0
COD (kg/d)	2010.0	41191.2	46765.7	1218.0	32950.4	988.2	1757.9	2905.7
TKN (kg/d)	153.0	2106.0	2454.7	133.2	2233.8	22.2	211.9	459.3
NH4 (kg/d)	102.0	1404.0	1439.6	88.8	1439.6	14.8	141.3	306.2
NO3+NO2 (kg/d)	0.0	0.0	3.0	0.0	3.0	7.8	239.1	228.1
TP (kg/d)	23.9	374.2	589.5	25.3	524.6	28.7	273.8	302.6
PO4 (kg/d)	11.4	178.2	187.1	12.0	187.1	13.7	130.4	144.1
TSS (kg/d)	1008.0	30515.4	36779.6	414.0	17676.9	208.1	869.4	726.4
COD (mg/l)	335.0	762.8	835.1	203.0	599.1	173.4	32.4	48.4
TKN (mgN/l)	25.5	39.0	43.8	22.2	40.6	3.9	3.9	7.7
NH4 (mgN/l)	17.0	26.0	25.7	14.8	26.2	2.6	2.6	5.1
NO3+NO2 (mgN/l)	0.0	0.0	0.1	0.0	0.1	1.4	4.4	3.8
TP (mgP/l)	4.0	6.9	10.5	4.2	9.5	5.0	5.0	5.0
PO4 (mgP/l)	1.9	3.3	3.3	2.0	3.4	2.4	2.4	2.4
TSS (mg/l)	168.0	565.1	656.8	69.0	321.4	36.5	16.0	12.1

Sludge streams	Primary sludge - Old works	Primary sludge - New works	Total primary sludge	Primary thickened sludge	Biological sludge - Old works	Biological sludge - New works to DAF	DAF sludge to dewatering	Digested sludge to dewatering	Total feed to dewatering	Sludge cake
Flow (Ml/d)	0.3	1.0	1.3	0.7	0.3	0.7	0.2	0.5	0.7	0.1
COD (kg/d)	1107.0	13815.3	14922.3	13430.0	315.0	8692.5	7062.8	12849.6	19912.4	17816.6
TKN (kg/d)	42.2	220.9	354.1	318.7	22.4	581.4	534.4	285.1	819.4	669.2
NH4 (kg/d)	14.6	0.0	14.6	14.6	1.4	1.9	0.5	0.0	0.5	0.0
NO3+NO2 (kg/d)	0.0	0.0	0.0	0.0	0.0	2.9	0.8	0.0	0.8	0.0
TP (kg/d)	14.3	64.8	79.1	71.2	15.6	415.5	381.7	63.9	445.6	338.3
PO4 (kg/d)	0.0	0.0	0.0	0.0	0.6	1.6	0.4	0.0	0.4	0.0
TSS (kg/d)	894.0	19102.7	22966.7	20670.0	300.0	8278.6	7626.0	15995.2	23621.2	21482.6
COD (mg/l)	3690.0	13815.3	11478.7	20661.6	1050.0	13071.5	37972.0	27281.6	30308.1	197961.9
TKN (mgN/l)	140.8	220.9	272.4	490.3	74.8	874.3	2872.9	605.2	1247.2	0.0
NH4 (mgN/l)	48.8	0.0	11.3	22.5	4.8	2.9	2.9	0.0	0.8	0.0
NO3+NO2 (mgN/l)	0.0	0.0	0.0	0.0	0.0	4.4	4.4	0.0	1.2	0.0
TP (mgP/l)	47.7	64.8	60.9	109.6	52.1	624.9	2052.4	135.6	678.3	0.0
PO4 (mgP/l)	0.0	0.0	0.0	0.0	2.1	2.4	2.4	0.0	0.7	0.0
TSS (mg/l)	2980.0	19102.7	17666.7	31800.0	1000.0	12449.0	41000.0	33960.1	35953.1	238695.7

Sludge return liquor streams	Thickener Supernatant	DAF returns	Secondary digester SNL	Dewatering returns	Total return liquor streams
Flow (Ml/d)	0.7	0.5	0.2	0.7	2.0
COD (kg/d)	1929.2	604.4	945.0	2095.8	5574.5
TKN (kg/d)	35.4	47.1	116.0	150.2	348.7
NH4 (kg/d)	0.0	1.4	33.6	0.5	35.6
NO3+NO2 (kg/d)	0.0	2.1	0.0	0.9	3.0
TP (kg/d)	7.9	33.8	66.2	107.4	215.2
PO4 (kg/d)	0.0	1.1	7.3	0.4	8.9
TSS (kg/d)	2296.7	652.6	1176.4	2138.6	6264.2
COD (mg/l)	2968.0	1261.8	27281.6	3029.4	2787.5
TKN (mgN/l)	54.5	98.3	605.2	217.2	174.4
NH4 (mgN/l)	0.0	2.9	0.0	0.8	17.8
NO3+NO2 (mgN/l)	0.0	4.4	0.0	1.2	1.5
TP (mgP/l)	12.2	70.5	135.6	155.2	107.6
PO4 (mgP/l)	0.0	2.4	0.0	0.6	4.5
TSS (mg/l)	3533.3	1362.4	33960.1	3091.2	3132.4

3.6.2 Influent characteristics

The sludge return liquors are combined with the incoming raw sewage at the new works. As a result of only PS being digested at the plant, the concentration of return liquors is normal; with no significant impacts on the influent load to the new works, except for TP which increased by 36.4% (Table 27). The increase in TP loads is relatively higher than that of other parameters, but the ortho-P load coming from the sludge returns is low. Therefore, most of the TP load is from solids.

Although the concentration of other parameters appears to be insignificant on the plant, it is important to note that, if the management of the works decides to digest all the sludge produced at the works (i.e. subject WAS to anaerobic digestion) in the near future, it is expected that the return liquor concentration will increase 10 folds. This will, in turn, impact of the carbon and nutrients concentration in the aeration basin, necessitating higher aeration capacity.

Table 27: Impact of dewatering return liquors in the influent characteristics at 'K' WWTP

Parameter	Raw sewage to the plant	Sludge returns	New works raw ww (incl. returns)	Impact on new works raw ww	Impact on total plant raw ww	Typical impact on raw ww (*)
Flow (Mℓ/d)	60	2	56	3.6%	3.3%	0.5% – 1,0%
COD (kg/d)	41 456	5 575	46 766	11.9%	13.4%	5% – 10%
TKN (kg/d)	2 983	349	2 455	14.2%	11.7%	9% – 13%
NH_4 (kg/d)	1 237	36	1 440	2.5%	2.9%	9% – 13%
TP (kgP/d)	532	215	590	36.4%	40.4%	5% – 30%
PO_4^-P (kg/d)	182	9	187	4.8%	4.9%	5% – 30%
TSS (kg/d)	34 930	6 264	36 780	17.0%	17.9%	2% – 5%

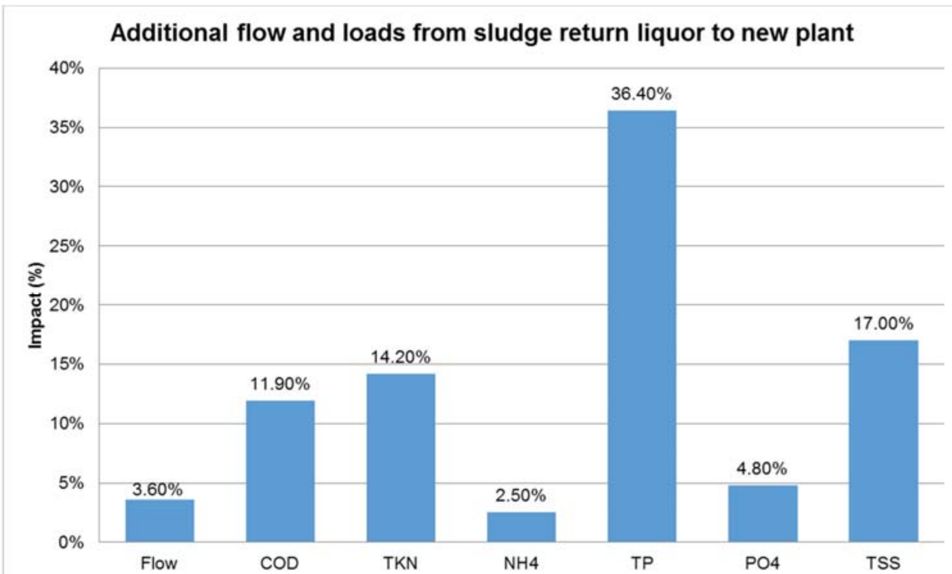

Figure 44: Additional flow and loads entering in Module 2 from the sludge return liquors treatment at 'K' WWTP

Comparing the influent ratios from the old works (without return liquors) with a typical South African sewage (Table 28), generally the raw sewage at 'K' WWTP is slightly unbalanced, especially in terms of P characteristics (lower than usual). With respect to the new works (including return liquors) it is noted that there is an unfavourable low COD/ PO_4 ratio for P biological removal, which has a significant influence from the return liquors with very high orthophosphate concentrations.

Table 28: Influent ratios with and without return liquors at 'K' WWTP

Ratios	Old works influent (without return liquors)	New works influent (with return liquors)	Typical values in South African ww
COD/TSS	2	1.3	2.0
COD/TKN	13.2	19.1	8.2
COD/ NH_4	19.7	32.5	14
COD/TP	84	79.3	54
COD/ PO_4	176.3	250	117

3.6.3 Biological effluent quality

The average biological effluent quality figures for the plant are presented in Table 29. As indicated, the plant can meet the effluent standard requirement for all the parameters. It is important to note that the general effluent quality requirements were used as benchmark in this case, as the plant, currently, does not have a water use licence. Application in this regard is however in progress, hence the assumption that the general limits apply.

Upon analysis of biological effluent data over the period January 2014 to June 2016, a gradual increase in average concentration of nitrate + nitrite in the biological effluent was observed at both old and new works (Figure 45). Orthophosphate levels were however not measured in the biological effluent at both works. In addition, only a few samplings were done/reported for ammonia.

Table 29: Average effluent quality of the biological effluent from old and new works at 'K' WWTP

Parameters	Old works biological effluent	New works biological effluent
COD (mg/ℓ)	57	64.1
NH_4 (mg N/ℓ)	4.8	2.9
$NO_3 + NO_2$ (mg N/ℓ)	2.5	4.4
PO_4 (mg P/ℓ)	2.1	2.4
TSS (mg/ℓ)	12	31.7

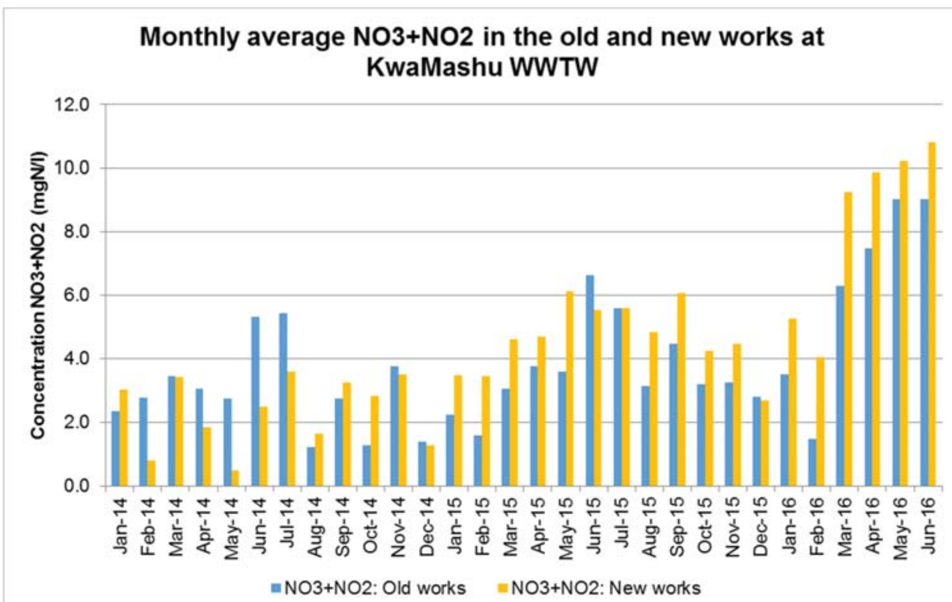

Figure 45: Monthly average nitrate + nitrite biological effluent quality at 'K' WWTP

3.6.4 Aeration demand

'K' WWTP currently has a conventional AS module arranged in 4 lanes. Each lane has 4 aerators installed on it; totalling 16 aerators. The power consumed per aerator is not measured at the plant and can therefore only be calculated. However, DO sensors and VSDs are installed to ensure adequate aeration and power optimization. Eight of the 16 aerators each have a motor size of 90 kW, while the motor size of each of the remaining eight is 45 kW. All aerators are run for 24 hours a day. Currently, the estimated energy requirements for aeration is about 19 000 kWh/d. If the current returns were treated the energy saving in aeration would be about 10%.

3.6.5 Biological treatment capacity

The new works currently treats 94% of the design COD load, 68% of the TKN design load and 77% of the TP design load. The specific biological sludge production is calculated in 0.28 kg MLSS/kgCOD removed and appears reasonable for a conventional AS system. On average the sludge retention time have been around 15 days.

The additional loads from the sludge return liquors are still within the capacity of the new works, however, optimization measures are necessary to avoid overshooting the plant's COD design capacity. It should be noted that if in the future WAS is digested, the new works may not be able to accommodate the extra load from the return liquors as additional aeration will be required.

3.7 Conclusions and recommendations

The site research conducted at 'K' WWTP indicates the following conclusions regarding the impact of the sludge return liquors on plant performance:

1. The new works receives 100% of the flow and loads from the sludge return liquors. With the sludge return liquors, the influent characteristics increased by 11.9% for COD, 14.2% for TKN, 36.4% for TP and 17% for TSS. The sludge return liquors at the plant appears to have little or minor impact on the plant as there is no significant increase in influent characteristics, especially on ammonia (2.5%) and orthophosphate (4.8%). The exception is in the case of TP which increased by 57.5%, showing an important TSS contribution (20.5%). Low ammonia and orthophosphate in the returns can be attributed to the non-digestion of WAS (only PS is digested) and the poor performance of the AD process.

2. Although the concentration of other parameters appears to be insignificant on the plant, it is important to note that, if WAS from the new plant is to be anaerobically digested in the future, the return liquor concentration is expected to increase significantly, thereby impacting on the concentration in the aeration basin; requiring higher aeration capacity.

3. The final effluent from the plant follows general discharge standards. However, at the old works, an increased TSS levels were observed in the effluent from the maturation pond. It suggests that the pond may require cleaning.

In addition, the following generic conclusions and recommendations shall be noted:

4. The plant is generally well operated and shows a good level of maintenance.

5. The plant is approaching its design capacity. Changes in the process configuration and increased loads due to return of sludge liquors may necessitate an upgrade of the plant soon.

6. For an AS plant that has not reached its design, an ammonia concentration of below 1 mg/ℓ is manageable. Considering the concentration from the AS plant is higher than 1 mg/ℓ, this indicates that there are challenges with the sludge retention time, aeration capacity or potentially toxicity.

7. High TSS coming from the return liquors indicates that the dewatering can be optimized. It is recommended to further investigate optimization. The high TSS in the return liquors lower the SRT in AS plant. The reduced SRT can impact the nitrification process.

8. The digester is performing poorly, with only 23% destruction of VSS while a performance of 40 till 60% can be expected.

CHAPTER 4: ‘P’ Wastewater Treatment Plant

The ‘P’ WWTP is situated approximately 1 km east of the MR102, Phoenix/Ottawa intersection and approximately 6.5 km from the Gateway Shopping Complex. The plant is owned and operated by the eThekwini Water and Sanitation Department and treats only domestic sewage. The plant, designed for a treatment capacity of 50 Mℓ/d, was constructed in 1987 with a design capacity of 12.5 Mℓ/d, and upgraded to 25 Mℓ/d in 1997. The existing works was designed based on a BNR AS principle, but now operates based on the AS principle with an installed capacity of 25 Mℓ/d. The current average flow into the plant is 24.5 Mℓ/d. With commissioning of an additional 25 Mℓ/d unit underway, the capacity of the works will increase to 50 Mℓ/d.

’P’ WWTPs key unit operations consist of a head of works, primary sedimentation, AS treatment, and anaerobic digestion systems. Currently the works has two PSTs, one activated sludge reactor and three clarifiers. A two-fold increase of these units is expected after the planned commissioning as the new module is a mirror image of the existing plant. Primary sludge is anaerobically digested in two anaerobic digesters, and digested sludge and biological sludge are dewatered before beneficially applied to land.

Figure 46: Aerial view of ‘P’ WWTP (Google Earth)

4.1 Process description

A description of the works is indicated below per information retrieved from the plant's as-built drawings and design manual of. The general process flow diagram of the treatment works is provided in Figure 47:

- Head of works consists of:
  - Two inlet channels,
  - One hand raked screen,
  - One mechanical screen fitted with screenings washer/compactor unit,
  - Two aerated grit removal chambers,
  - Two screw lift pumps for conveyance of raw sewage to the PSTs.

- Wastewater treatment consists of:
  - Four PSTs,
  - A 25 Mℓ conventional activated sludge process, with nutrient removal capacities,
  - Six SSTs.

- Disinfection consists of:
  - Final effluent from the SSTs is discharged into three maturation ponds which overflow into the river via the third maturation pond.

- Sludge handling and disposal consists of:
  - Primary sludge is anaerobically digested in two mesophilic digesters (2 600 m^3 each) including mixing and heating. Primary digested sludge is mechanically dewatered before beneficial application to agricultural land.
  - Three secondary digesters (510 m^3 each).
  - WAS is stored in a sludge sump from where it is pumped to a belt press for dewatering.
  - Primary digested sludge and biological sludge are fed to the dewatering plant consisting of a belt press via two sludge-feed lines.
  - Dewatered sludge is stored in silos before being applied to agricultural land.

- Return liquors treatment consists of:
  - Dewatering sludge return liquors are recycled upstream of the PSTs.

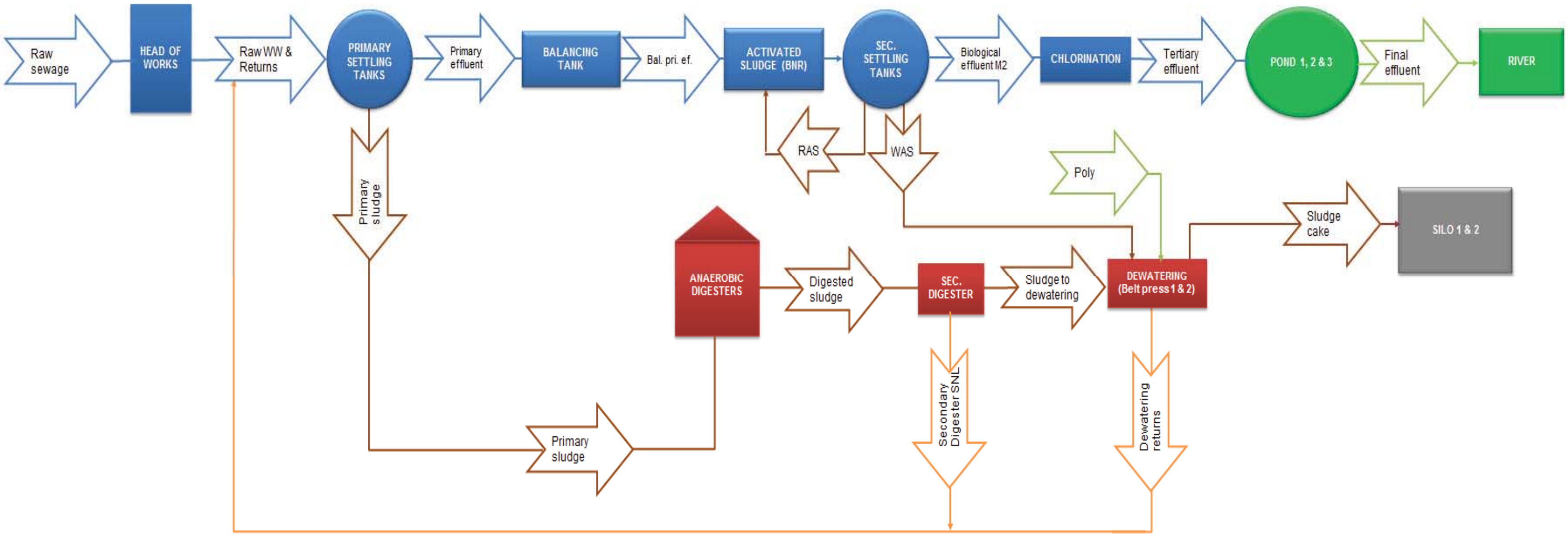

Figure 47: 'P' WWTP block diagram

4.2 Design capacity

The total design capacity of the plant is indicated in Table 30.

Table 30: Design flows and loads at 'P' WWTP

Parameters	Total
Flow (Mℓ/d)	25
COD (kg/d)	17 500
TKN (kg/d)	1 225
TP (kg/d)	675

4.3 Effluent standard requirements

Table 31 presents the standard effluent requirements applicable to the 'P' WWTP as obtained in the plant's water use licence (Licence No. 11/U20M/F/1177). It is important to note that an application for review of the limits is currently in progress; considering the ongoing upgrade to the works.

Table 31: Effluent discharge requirements applicable to 'P' WWTP

Parameter	Effluent standards	Method of compliance
COD (mg/ℓ)	75	
TSS (mg/ℓ)	25	
NH_4 (mg N/ℓ)	6	90% compliance
$NO_3 + NO_2$ (mg N/ℓ)	10	
PO_4 (mg P/ℓ)	10	

4.4 Technical performance

The Royal HaskoningDHV team conducted a site visit to the works on 28 November 2016. The 'P' WWTP appears to be a well operated and maintained facility. The operation team on site consists of 4 senior process controllers and 2 process controllers; operating 3 shifts per day and a plant manager.

However, the following observations were made regarding the technical performance of the plant. The dewatering plant comprising two belt presses were not in operation during the site visit. Hence secondary digested sludge as well as the WAS is recycled to the PSTs; resulting to high solids carry over in the PSTs. Per the plant superintendent, this has been the situation in the past two weeks. The construction of a new dewatering plant comprising two belt presses is on-going, and it is expected that sludge dewatering will be decommissioned upon start-up of the new belt presses. In addition, desludging of the PSTs is done manually. Automated desludging of the PSTs is recommended for investigation.

Sludge is currently stockpiled onsite as there is no contract in place for sludge disposal or off-take at the works. Generally, it is expected that the performance of the works will improve upon commissioning of the new works next year.

4.5 Process performance

4.5.1 Influent characteristics

In Figure 48, the average daily flow of wastewater treated at 'P' WWTP between January 2014 and September 2015 is presented. On average, a total of 24.5 Mℓ/d of wastewater was treated at the works; implying 98% of the plant's design capacity is reached, and therefore, the on-going upgrade is urgent.

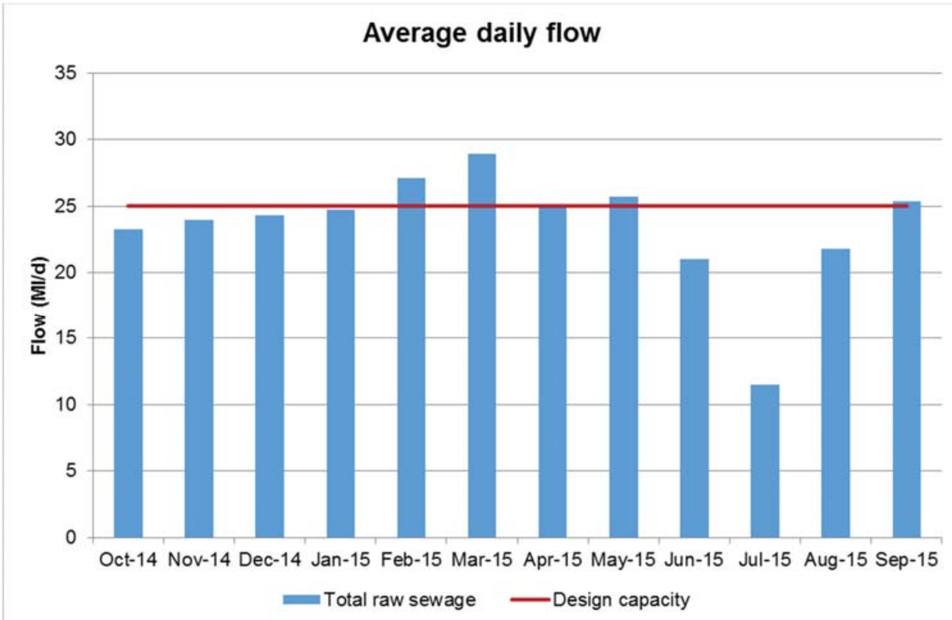

Figure 48: Average daily flow at 'P' WWTP

The average influent concentrations and loads are indicated in Table 32 as well as the historical averages in Figure 49 and Figure 50. In general, the raw sewage shows a high loading rate. Although the inflow to the plant and TP load are within the plant's design capacity (98% and 81% respectively), the COD and TKN influent characteristics (101% and 117% respectively), are slightly above the design load of the plant; implying that the plant is overloaded.

Table 32: Average raw sewage concentrations and loads at 'P' WWTP

Parameter	Average concentration (January 2014 to June 2016)		Average load (January 2014 to June 2016)	
COD	722	mg/ℓ	17 687	kg/d
TSS	373	mg/ℓ	9 141	kg/d
TKN	58.8	mg/ℓ	1 441	kg/d
NH_4	40.1	mgN/ℓ	982.5	kg/d
$NO_3 + NO_2$	18.7	mgN/ℓ	458.2	kg/d
PO_4	3.6	mgP/ℓ	88.2	kg/d
TP	22.2	mg/ℓ	545.2	kg/d

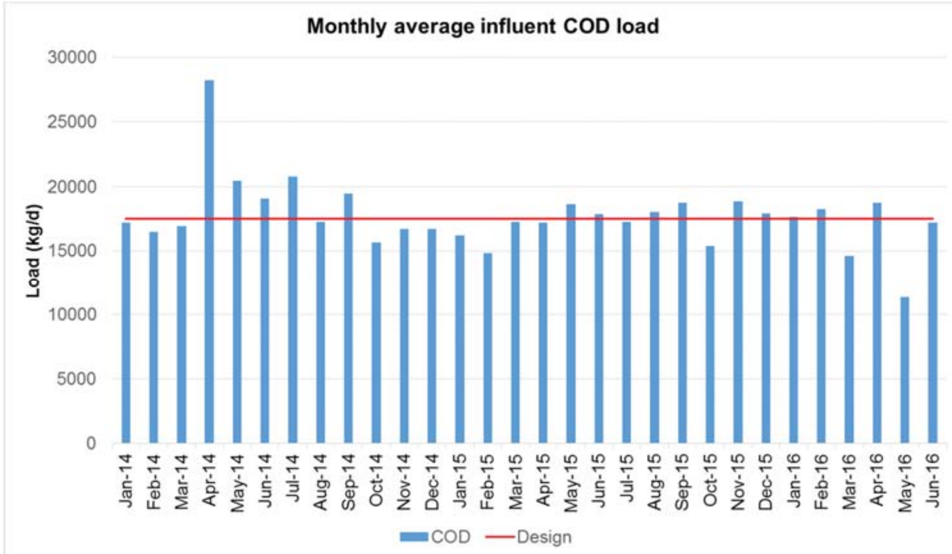

Figure 49: Average COD load at 'P' WWTP

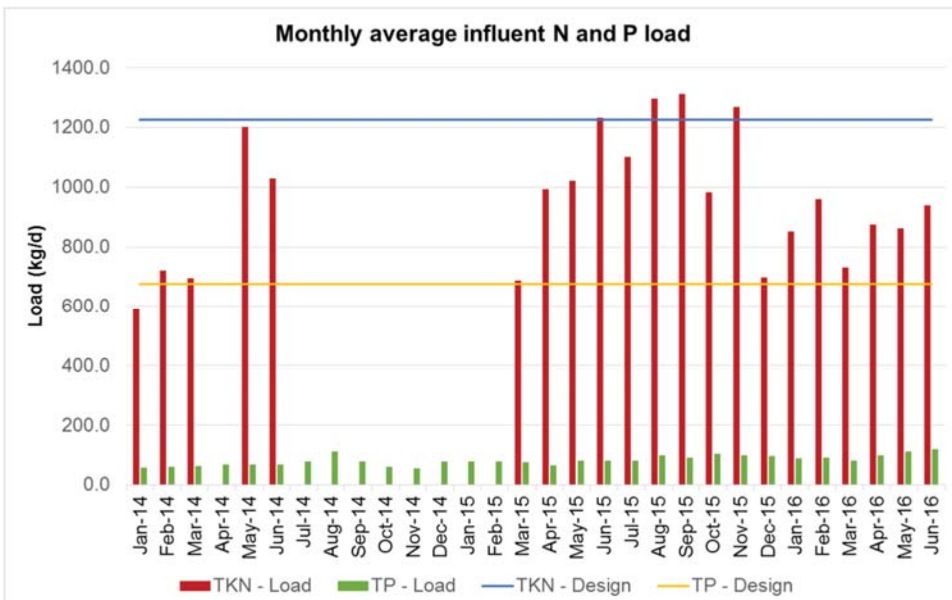

Figure 50: Average N and P loads at 'P' WWTP

*Missing values were observed in N data between July 2014 and February 2015

4.5.2 Effluent quality

In Table 33, performance of the works with respect to final effluent discharged is presented. Final effluent discharged at the works was benchmarked against the works' effluent discharge limits as specified in the plant water use licence. The results show significant compliance with the limits considering 88% and 95% compliance for COD and TSS respectively. Although, good P-removal is achieved at the plant (97% for ortho-P), poor ammonia removal (only 17% compliance) was noted during the period under review and constantly from August 2015 onwards.

Table 33: Average final effluent quality and plant compliance at 'P' WWTP

Parameter	Average concentration (January 2015 to June 2016)	Average compliance (January 2015 to June 2016)
COD	48.5 mg/ℓ	88%
TSS	9.8 mg/ℓ	95%
NH_4	17.7 mgN/ℓ	17%
$NO_3 + NO_2$	1.1 mgN/ℓ	100%
PO_4	3.5 mgP/ℓ	97%

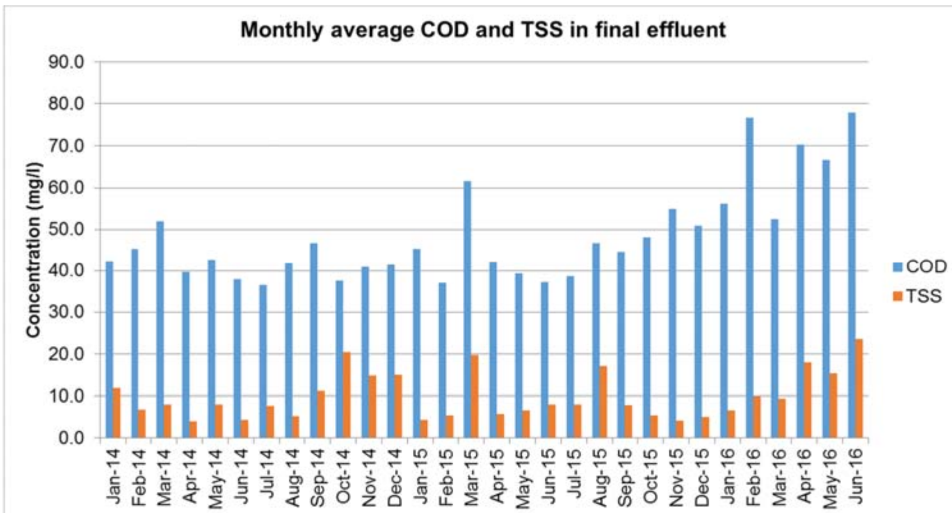

Figure 51: Monthly average COD and TSS in the final effluent at 'P' WWTP

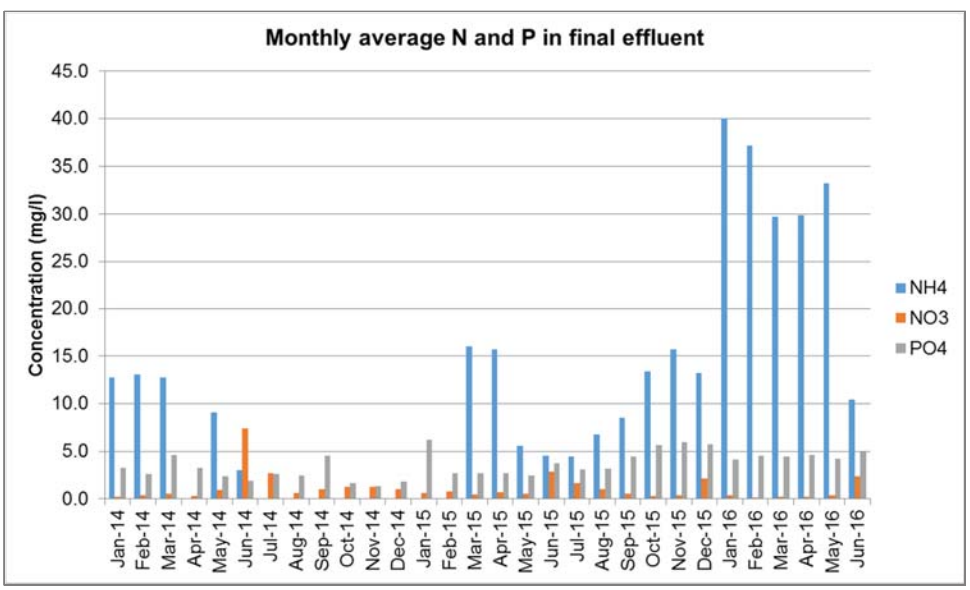

Figure 52: Monthly average ammonia, nitrate and orthophosphate in the final effluent at 'P' WWTP

4.5.3 Sludge treatment

4.5.3.1 Sludge characteristics

At ‘P’ WWTP, PS from the PSTs is sent directly to the ADs, as currently, there are no thickeners in operation. However, two new thickeners are to be commissioned in 2017 as part of the upgrade to the works. WAS is discharged from the SSTs and thereafter dewatered using a belt press.

Table 34 indicates the characteristics of the PS and WAS before and after dewatering.

Table 34: Characteristics of the primary and biological sludge at ‘P’ WWTP

Parameter	Primary sludge	Biological sludge
Flow (m^3/d)	185	147
Dry solids (%)	3.5	0.9
Sludge mass (kg/d)	5 732	1 377

4.5.3.2 Sludge thickening

No thickening is done to the PS at the works; however, two new 14 m diameter circular mechanically-scraped gravity sludge thickeners are currently being put in place as part of the upgrade to the works. Each thickener is designed to handle 200 m^3/day of sludge.

4.5.3.3 Anaerobic sludge digestion

At ‘P’ WWTP, only PS is anaerobically digested in 2 × 2 600m^3 heated and mixed (pumped mixing) digesters. The digesters are heated to mesophilic temperature (35°C) using about 40% of biogas. The primary digested sludge is allowed to stabilize in a secondary digester which comprises 3 cells. The dry solids content of primary sludge digested during the period January 2014 to June 2016 averaged 2% (w/v), and the organic fraction was on average 69%. The digesters are being operated under a temperature range of 30ℓ C to 35ℓ C which is within the optimal temperature range of 33ℓ C to 37ℓ C for mesophilic digesters, although further optimization of the process is advised. The average retention time in the ADs was approximately 36 days, which is higher than the minimum recommended retention time (20 days) for mesophilic digesters. The destruction of VSS in the ADs was on average 52% which is reasonable under mesophilic conditions, considering that only PS is digested.

Two new 18.3 m diameter primary digesters will be constructed as part of the on-going upgrade to the plant. The two new primary digesters are designed for thermophilic digestion with a retention period of 25 days but will however be operated under mesophilic conditions of 37ℓ C.

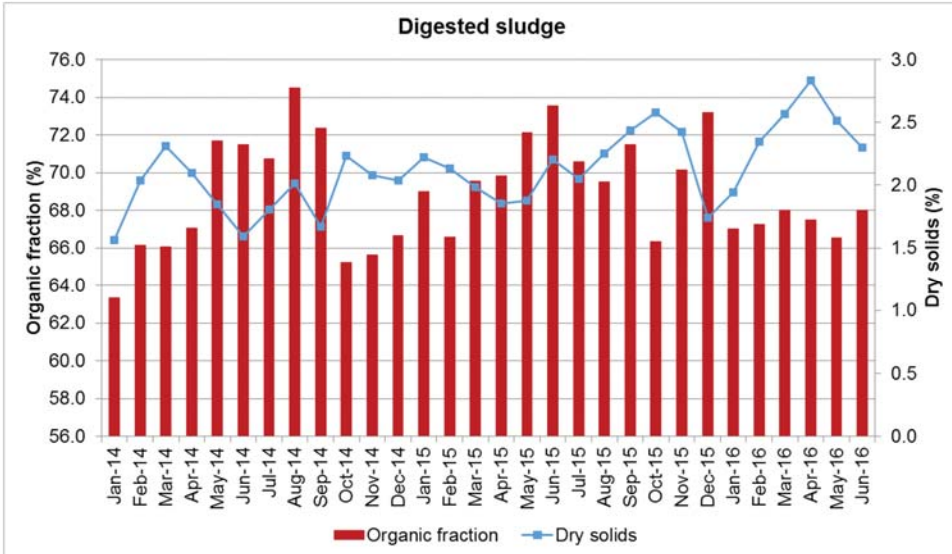

Figure 53: Monthly average organic fraction and dry solids content in digested sludge at 'P' WWTP

4.5.3.4 Sludge dewatering

Primary digested sludge and WAS are mechanically dewatered in two separate belt presses (belt press 1 and 2). The average DS content of sludge cake from the belt press (dewatered WAS) is 12.3%. Upon analysis of data made available, the average DS content in the sludge cake from the digested sludge is approximately 23%. The performance of the belt presses is satisfactory as their DS content are within the typical operating range of mechanical belt presses (10-15% for WAS and 20-30% for digested sludge). The historical performance of the dewatering plant is presented in Figure 54.

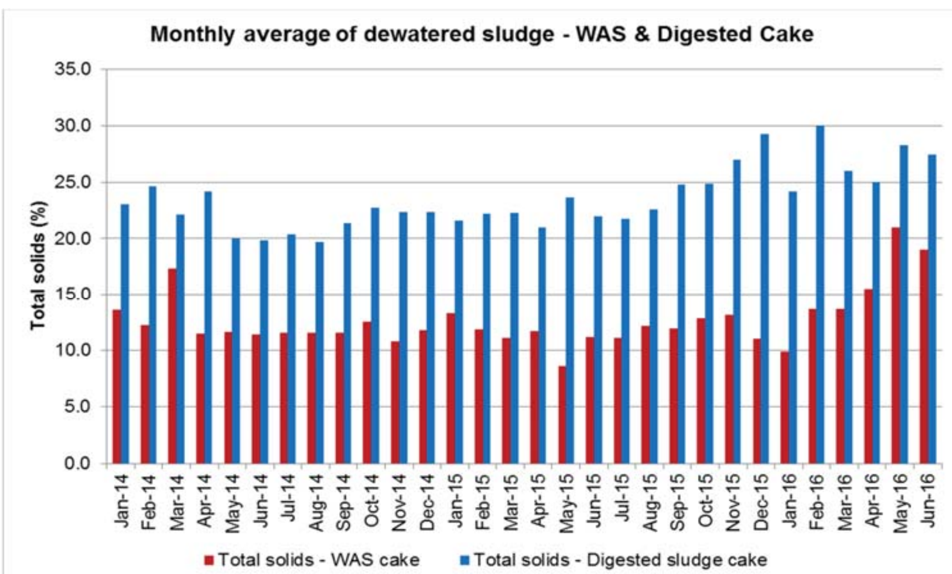

Figure 54: Monthly average of dry solids content in the dewatered sludge at 'P' WWTP

4.5.3.5 Treatment of sludge return liquors

Per information received from the process engineers, no treatment is given to the sludge return liquors at the plant. Analysis of the wastewater concentrations in the return liquors is presented in Figure 55. The average concentrations for ammonia and orthophosphate were approximately 111 mg/ℓ and 22.4 mg/ℓ respectively.

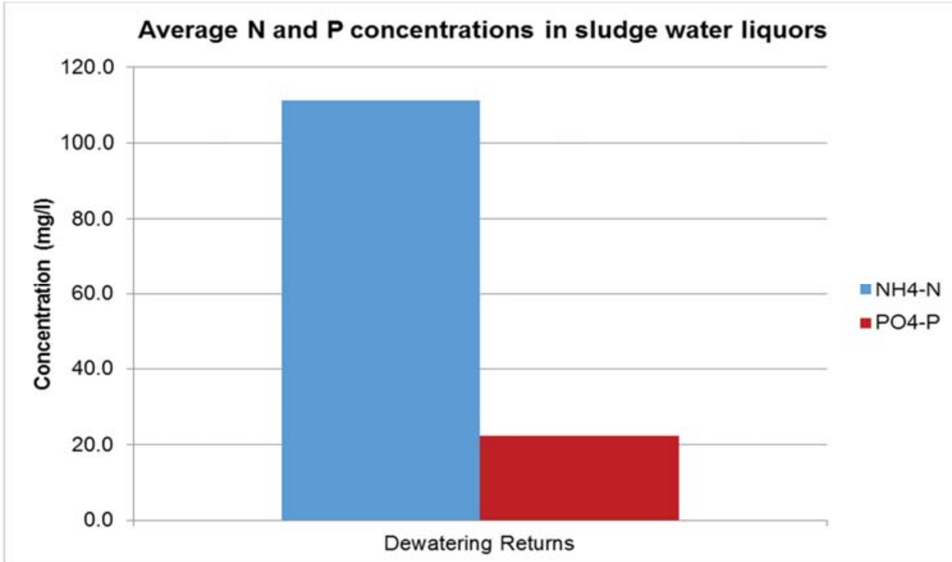

Figure 55: Ammonia and orthophosphate concentrations in the sludge return liquors at 'P' WWTP

4.6 Impact of sludge returns liquors

4.6.1 Plant mass balance

A complete mass balance of the 'P' WWTP was prepared to understand and evaluate the magnitude of the impacts of the sludge dewatering return liquors on the main treatment process addressed in the following sections. The result of the plant mass balance elaborated with the average data available from January 2014 to June 2016 is provided in Table 35. Once the analytical data available did not cover all streams and parameters, the following assumptions were required to complete the mass balance:

- Determination of TKN in primary influent = 150% of ammonia concentration
- COD in biological sludge: COD/MLVSS = 1.4
- TKN/MLSS = 7%
- TP/MLSS = 5%
- TP/ PO_4 ratio ~ 2.1
- VSS/TSS ratio = 75%

Table 35:Results of the mass balance at 'P' WWTP

Water streams	Raw WW	Raw WW & Returns	Primary effluent	Biological/Tertiary effluent	Final effluent
Flow (Ml/d)	24.5	24.8	24.6	24.4	24.4
COD (kg/d)	17687	18085	10816	1200	1186
TKN (kg/d)	1467	1591	1447	249	449
NH4 (kg/d)	978	1041	1041	188	433
NO3+NO2 (kg/d)	0	0	0	81	27
TP (kg/d)	184	244	217	70	98
PO4 (kg/d)	87	105	105	27	86
TSS (kg/d)	9141	10002	3447	865	240
COD (mg/l)	722	730.0	440	49.1	48.5
TKN (mgN/l)	60	64	58.9	10.2	18.4
NH4 (mgN/l)	40	42	42.4	7.7	17.7
NO3+NO2 (mgN/l)	0.0	0.0	0.0	3.3	1.1
TP (mgP/l)	7.5	9.8	8.8	2.9	4.0
PO4 (mgP/l)	3.6	4	4.3	1.1	3.5
TSS (mg/l)	373	404	140	35.4	9.8

Sludge streams	Primary sludge	Biological sludge to belt press	Primary Dig. sludge to belt press	Primary Dewatered Sludge	Biological Dewatered Sludge	Total Sludge Cake
Flow (Ml/d)	0.185	0.147	0.035	0.02	0.07	0.09
COD (kg/d)	7269	1446	864	5506	1273	6779
TKN (kg/d)	143	97.5	33.9	31.5	85.2	117
NH4 (kg/d)	0.0	1.1	0.0	0.0	0.3	0.3
NO3+NO2 (kg/d)	0.1	0.5	0.0	0.0	0.4	0.4
TP (kg/d)	26.8	147	10.2	8.3	138	147
PO4 (kg/d)	0.0	0.2	0.0	0.0	0.0	0.0
TSS (kg/d)	5693	1377	937	5244	1212	6456
COD (mg/l)	39293	18186	24676	239400	18186	72895
TKN (mgN/l)	774	1217	969	1370	1217	1255
NH4 (mgN/l)	0.0	4.5	0.0	0	4	3
NO3+NO2 (mgN/l)	0.4	6.1	0.0	0	6	4
TP (mgP/l)	145	1978	291	363	1978	1579
PO4 (mgP/l)	0.0	0.6	0.0	0	1	0
TSS (mg/l)	30773	17320	26773	228000	17320	69423

Sludge return liquor streams	Primary Sludge Returns (SNL)	Belt Press 1 Filtrate	Belt Press 2 Filtrate	Total return liquor streams
Flow (Ml/d)	0.15	0.019	0.11	0.27
COD (kg/d)	195	29.9	173	398
TKN (kg/d)	109	2.4	12.3	124
NH4 (kg/d)	62.4	0.4	0.8	63.7
NO3+NO2 (kg/d)	0.0	0.02	0.1	0.1
TP (kg/d)	50.1	1.8	8.4	60.3
PO4 (kg/d)	16.6	0.4	0.1	17.2
TSS (kg/d)	669	28.5	165	862
COD (mg/l)	1301	1574	1635	1448
TKN (mgN/l)	728	126	117	451
NH4 (mgN/l)	416	21.6	7.7	232
NO3+NO2 (mgN/l)	0.0	1.1	0.6	0.3
TP (mgP/l)	334	97.4	78.9	219
PO4 (mgP/l)	111	22.4	1.1	62.5
TSS (mg/l)	4457.6	1499	1557	3136

4.6.2 Influent characteristics

The dewatered sludge return liquors are combined with the incoming screened sewage and channelled into the PSTs. Table 36 presents analysis of sludge return liquors in relation to its impacts on influent characteristics. The NH_4^-N and PO_4^-P loads increased by approximately 6.5% and 20% respectively. The ammonia load is slightly below the typical range for sludge liquors. However, orthophosphate loads in the return liquors are high and well outside the typical range.

Table 36: Impact of dewatering return liquors in the influent characteristics at 'P' WWTP

Parameter	Raw sewage to the plant	Sludge returns	Raw ww (incl. returns)	Impact on total plant raw ww	Typical impact on raw ww (*)
Flow (Mℓ/d)	24.5	0.27	24.8	1.1%	0,5% – 1,0%
COD (kg/d)	17 687	398	18 085	2.3%	5% – 10%
TKN (kg/d)	1 467	124	1 591	8.5%	9% – 13%
NH_4 (kg/d)	978	64	1 041	6.5%	9% – 13%
TP (kg/d)	184	60	244	33%	5% - 30%
PO_4 (kg/d)	87	17	105	20%	5% - 30%
TSS (kg/d)	9 141	862	10 002	9.4%	2% - 5%

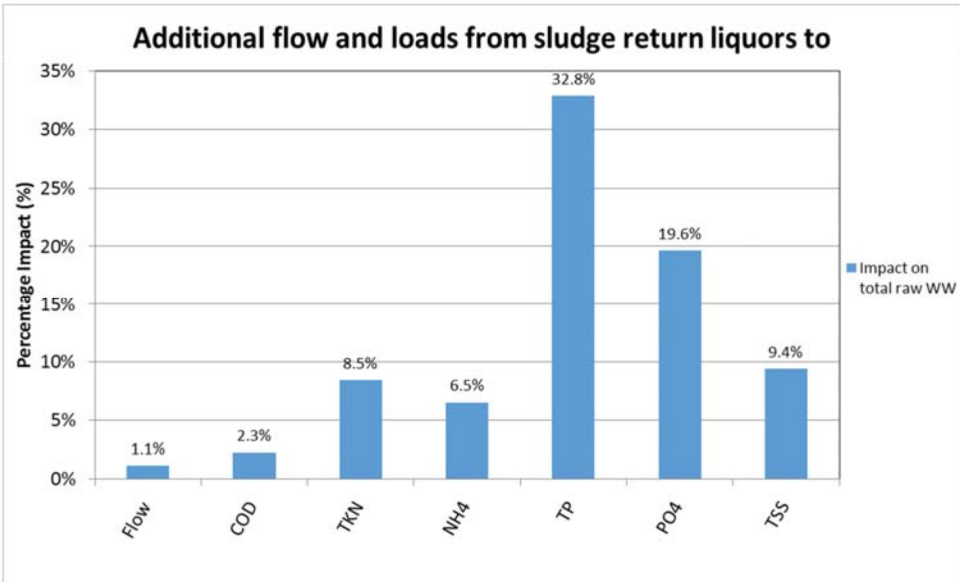

Figure 56: Additional flow and loads from sludge return liquors at 'P' WWTP

Comparative analysis between the influent ratios for the plant, (with and without return liquors), and typical South African sewage (Table 37), show minor variations for TSS; however significant imbalance is observed for COD: nutrients (N and P) ratios.

Table 37: Influent ratios with and without return liquors at 'P' WWTP

Ratios	Plant influent (without return liquors)	Plant influent (with return liquors)	Typical values in South African ww
COD/TSS	1.9	1.8	2.0
COD/TKN	12.1	11	8.2
COD/ NH_4	18	17	14
COD/TP	96	74	54
COD/ PO_4	202	173	117

4.6.3 Biological effluent quality

The average biological effluent quality figures for the plant are presented in Table 38. As indicated, the biological treatment meets the effluent standard requirement for all the parameters.

Table 38: Biological effluent at 'P' WWTP

Parameters	Biological effluent
COD (mg/ℓ)	49.1
NH_4 (mg N/ℓ)	7.7
$NO_3 + NO_2$ (mg N/ℓ)	3.3
PO_4 (mg P/ℓ)	1.1
TSS (mg/ ℓ)	35.4

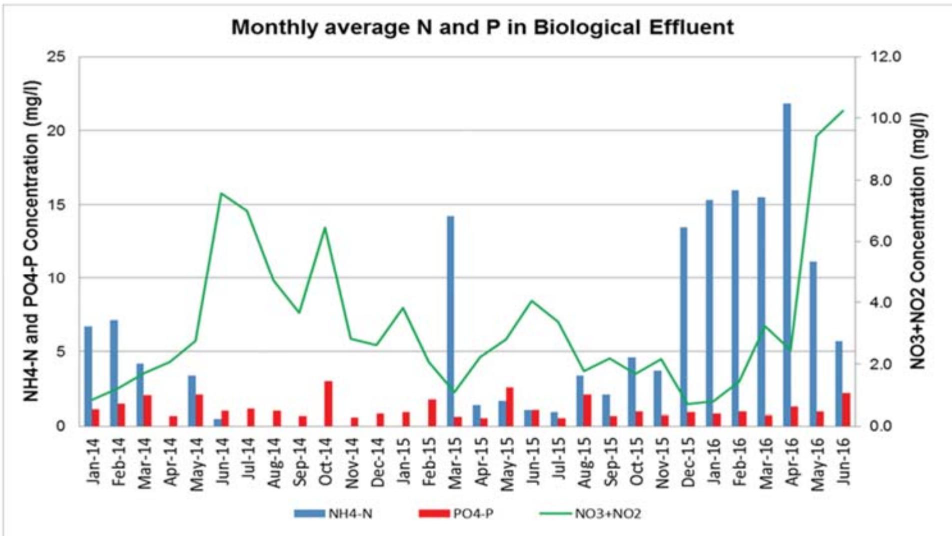

Figure 57: Monthly average ammonia, nitrate+nitrite and orthophosphate biological effluent quality at 'P' WWTP

4.6.4 Aeration demand

'P' WWTP currently has a conventional AS module arranged in two process trains. Each train has 4 aerators installed; totalling 8 aerators. However, aeration demand is not measured at the plant and can therefore only be calculated. There are no VSDs and no DO control sensors in the existing system; implying that no power optimization measure is in place at the moment. Design documents for the plant upgrade however indicate that VSDs and DO sensors will be included in the plant upgrade. Four of the 8 aerators each have a motor size of 75 kW, while the motor sizes of the remainder have a motor size of 50 kW. All aerators are run for 24 hours a day. Currently the aeration consumption is about 12 000 kWh/d. It is estimated that less than 10% of the aeration consumption is due to the current sludge liquors returns.

4.6.5 Biological treatment capacity

The plant has reached its design capacity for COD and TKN treatment. The loads are above 100% for both parameters with and without return liquors' flows (Table 39). This may justify higher level of ammonia in the final effluent (17.7 mg/ℓ) and consequent non-compliance with stipulated effluent requirements set at 6 mg/ℓ, hence the need for the on-going upgrade. Moreover, an application for review of the plant's Water Use Licence in terms of the discharge limits in relation to the proposed expansion of the works is in progress.

Table 39: Load comparison (actual vs. design) at 'P' WWTP

Parameters	Design	Without return liquors		With return liquors		Percentage change (%)
		Actual	Treatment capacity (%)	Actual	Treatment capacity (%)	
Flow (Mℓ/d)	25	24.5	98%	24.8	99%	1%
COD (kg/d)	17 500	17 687	101%	18 085	103%	2%
TKN (kg/d)	1 225	1 466	120%	1 590	130%	10%
TP (kg/d)	675	184	27%	243	36%	9%

4.7 Conclusions and recommendations

The site research conducted at 'P' WWTP indicates the following conclusions regarding the impact of the sludge return liquors in the plant performance:

1. Return liquors are recycled upstream of the PSTs as a combination of the belt press filtrate and secondary digester supernatant. The incoming ammonia and orthophosphate loads to the PSTs have an impact of 6.5% and 20% respectively in the influent loads.

2. Currently the plant is not compliant with the required effluent standard for ammonia. It is evident that that the plant is already overloaded in terms of COD and TKN even without the return of sludge liquors. The overloading of the plant is further aggravated upon recirculation of sludge return liquors to the PSTs.

In addition, the following generic conclusions and recommendations shall be noted:

3. The technical performance of the plant is generally good and shows a good level of maintenance.

4. The plant is presently undergoing an upgrade

5. The current hydraulic demand in the plant is 98% of the design capacity, when compared to its design capacity is 101% for COD, and 120% for TKN.

6. Final effluent quality is not complying with the ammonia discharge quality standards. The biological treatment may require optimisation to improve nitrification performance.

7. Although the plant is operating above its design capacity, improved process performance is expected upon completion and operation of the new section of the plant. Further optimization of the process is expected upon installation of VSDs and DO level sensors in the AS process. This may improve the plant's aeration demand and its electricity consumption.

CHAPTER 5: ‘C’ Wastewater Treatment Plant

The ‘C’ WWTP lies next to Muizenberg in the Southern Suburbs of Cape Town (refer to Figure 58). The plant primarily treats domestic wastewater and some industrial wastewater. The works are owned and operated by the City of Cape Town (CoCT).

The plant was initially designed to treat an ADWF of 150 Mℓ/d and consisted of six parallel modules, each of 25 Mℓ/d capacity. In 1999, an additional two 25 Mℓ/d modules were constructed. Currently, the plant has a total capacity of 200 Mℓ/d over eight parallel modules.

Figure 58: Aerial view of ‘C’ WWTP (Google Earth, 2016)

5.1 Process description

The treatment process used at the ‘C’ WWTP includes primary sedimentation followed by AS reactors. An extensive maturation pond system is the final treatment step. ‘C’ WWTP was designed for partial denitrification and biological P removal. Primary and biological thickened sludge are anaerobically digested followed by mechanical dewatering (out of operation). Currently, the digested sludge is dewatered in drying beds and the filtrate is sent to ponds.

A description of the unit processes and unit operations of the works is indicated below as per the plant operational manual and the general process flow diagram of the treatment works provided in Figure 59.

- **Inlet works** consists of:
  - Five mechanical coarse screens and one manual screen on standby,
  - Two degritting channels,
  - Splitter box.
- **Primary Treatment**:
  - Eight PSTs (23 m diameter).

- **Biological treatment**:

    - Eight conventional activated sludge reactors including anaerobic, anoxic and aerobic compartments (6 × 2 391 m³ and 2 × 7 675 m³). Air is provided by fine bubble diffusion aeration,
    - Twenty-two final clarifiers (18 × 26 m diameter and 4 × 31 m diameter).

- **Final Treatment**:

    - Maturation pond.

- **Sludge handling and disposal** consists of:

    - PS thickened in three gravity thickeners,
    - Biological sludge thickened in two DAF units,
    - Combined thickened sludge that is anaerobically digested under mesophilic conditions with the provision of heat and mixing (6 × 5 280 m³),
    - Digested sludge is dewatered in drying beds.

- **Sludge return liquors**:

    - Return liquors from the gravity thickening and DAF process operations are blended and recycled to the beginning of the biological reactors,
    - The filtrate from the sludge drying beds is discharged into ponds and not it does not return to the treatment works.

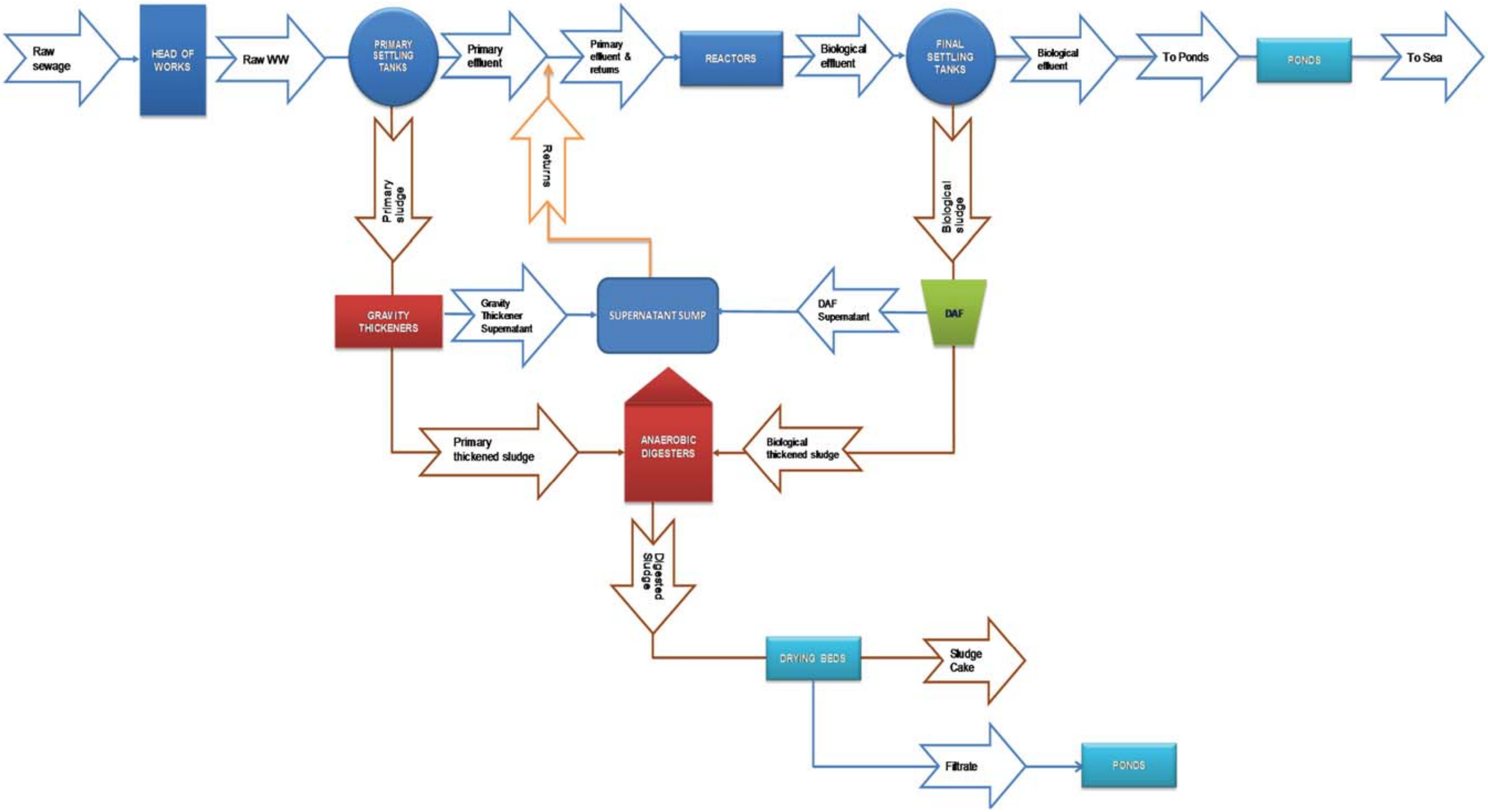

Figure 59: General process flow diagram of 'C' WWTP

5.2 Design capacity

The plant treatment capacity as per 'C' WWTP Process Controller Operational Handbook is shown below in Table 40.

Table 40: Design flows and loads at 'C' WWTP

Parameters	Each module	Total
Flow (Mℓ/d)	25	200
COD (kg/d)	15 000	120 000
TKN (kg/d)	1 465	11 720

5.3 Effluent standard requirements

The final treated effluent quality requirements currently stipulated in 'C' WWTP's water use licence are as per Table 41.

Table 41: Effluent standard requirements at 'C' WWTP

Parameter	Effluent standards	Method of compliance
COD (mg/ℓ)	75	90% compliance
TSS (mg/ℓ)	25	
NH_4 (mg N/ℓ)	10	
$NO_3 + NO_2$ (mg N/ℓ)	10	
PO_4 (mg P/ℓ)	1.0	

5.4 Technical performance

The technical performance of the 'C' WWTP appears to be fair with key unit operations not in use. The plant has a reasonable level of automation, including a SCADA system. The operation team on site consists of 4 process operators, 4 process controllers, 7 senior process controllers, 1 principal process controller, 1 assistant manager, 1 administration clerk and 1 plant manager. There is also additional grounds staff.

Three site audits where conducted on the 'C' WWTP with the last site audit carried out in October 2016. From the site visits the following items were noted as the main points for beneficiation from a technical point of view:

- The belt presses are currently not in use therefore, as per design the sludge is not dewatered and dried into pellets. Digested sludge is pumped to the drying beds instead.
- There is insufficient emergency sludge drying bed area, and insufficient dewatered sludge temporary stockpile area.
- There is a hydraulic restriction in few of the return sludge lines that limits the rate of sludge removal from secondary sedimentation leading to losses of sludge over the weirs at times that adversely affects effluent quality.
- There is an algae bloom in summer that adversely affects the final effluent quality with ammonia and phosphates increasing to 28 mg/ℓ and 6 mg/ℓ respectively in the ponds.

- Insufficient secondary sludge pre-thickening capacity; requires another DAF unit. PS thickening needs to be improved.

5.5 Process performance

5.5.1 Influent characteristics

As indicated in the Figure 60 during the operational window selected (September 2015 to August 2016), 'C' WWTP treated on average a total of 120 Mℓ/d (60% of the design capacity).

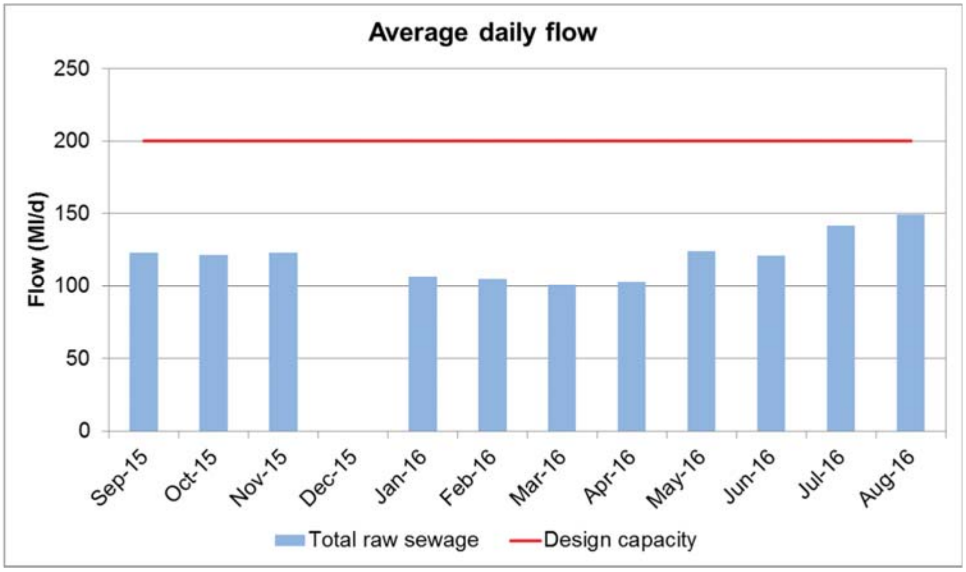

Figure 60: Average daily flow at 'C' WWTP

The average influent concentrations and loads are shown in Table 42. Currently, the plant is treating 94% of the COD design load and 83% of the TKN design load. The historical averages are illustrated below for the monthly average COD load and for the monthly average *N* and *P* influent load in Figure 61 and Figure 62 respectively.

Table 42: Average raw sewage concentrations and loads at 'C' WWTP

Parameter	Average concentration (September 2015 to August 2016)		Average load (September 2015 to August 2016)	
COD	940	mg/ℓ	112 603	kg/d
TSS	548	mg/ℓ	65 637	kg/d
TKN	81	mg/ℓ	9 719	kg/d
NH_4	43	mgN/ℓ	5 101	kg/d
PO_4	7	mgP/ℓ	890	kg/d
TP	14	mg/ℓ	1 637	kg/d

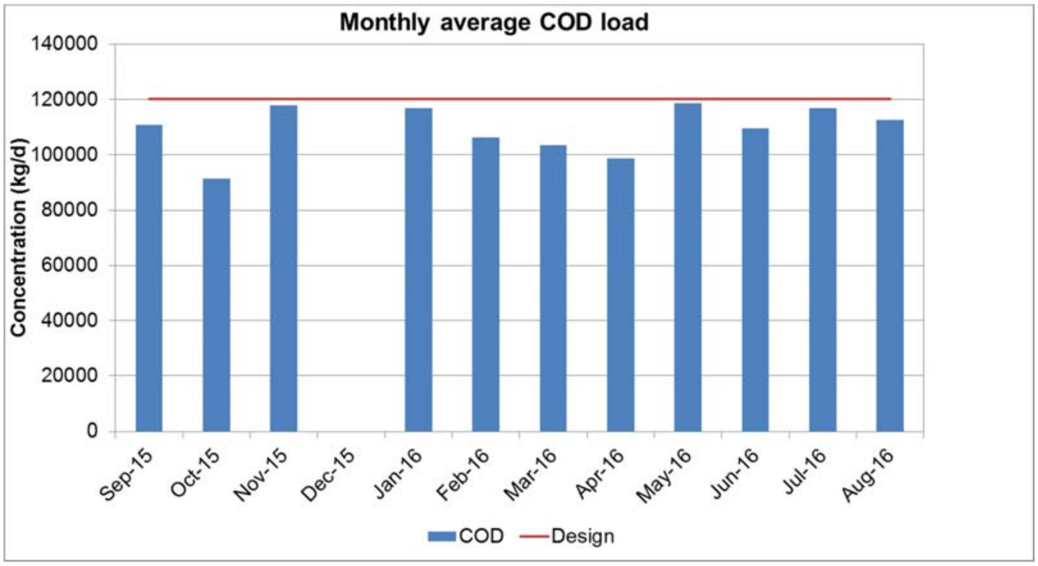

Figure 61: Average COD and TSS load at 'C' WWTP

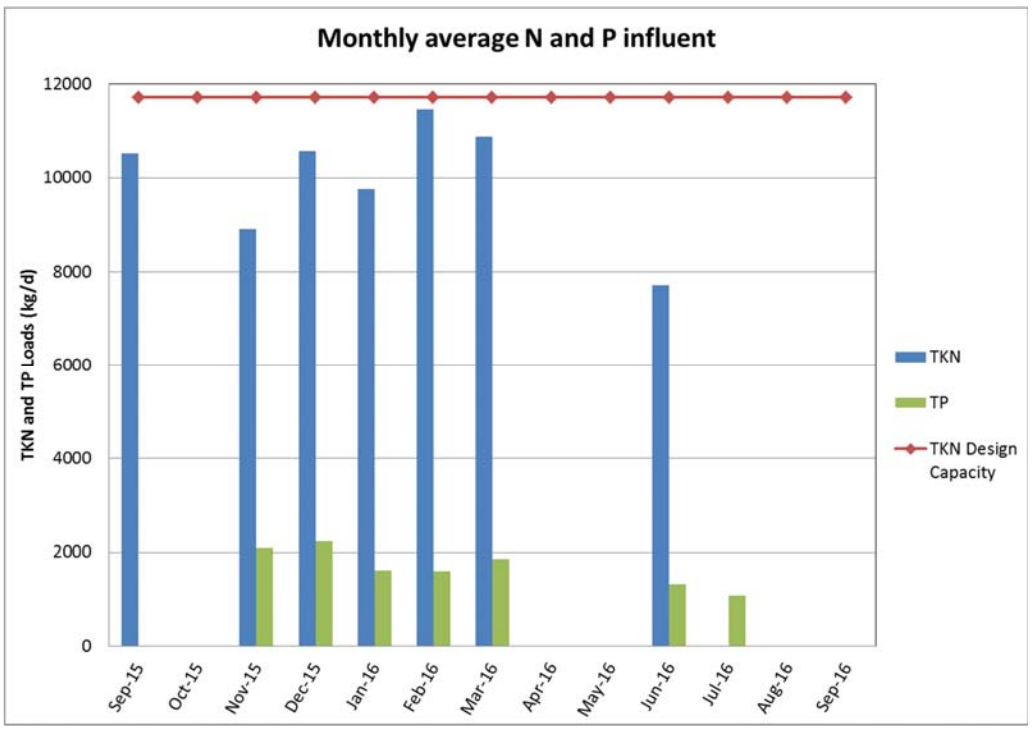

Figure 62: Average TKN and TP loads at 'C' WWTP

5.5.2 *Effluent quality*

As per the historical results from September 2015 to August 2016, the process performance of this plant is poor, with low compliance for most of the parameters. Table 43 indicates the average concentrations and compliance of the final effluent. The plant requires to be optimised for nutrient (N and P) and suspended solids removal. The historical monthly average concentrations in the final effluent from September 2015 to August 2016 are indicated in Figure 63 and Figure 64.

Table 43: Average final effluent quality and plant compliance at 'C' WWTP

Parameter	Effluent quality standards	Average concentration (September 2015 to August 2016)	Average compliance (September 2015 to August 2016)
COD	75 mg/ℓ	80 mg/ℓ	38%
TSS	25 mg/ℓ	26.5 mg/ℓ	62%
NH_4	10 mgN/ℓ	28 mgN/ℓ	0%
$NO_3 + NO_2$	10 mgN/ℓ	1 mgN/ℓ	100%
PO_4	1.0 mgP/ℓ	6 mgP/ℓ	0%

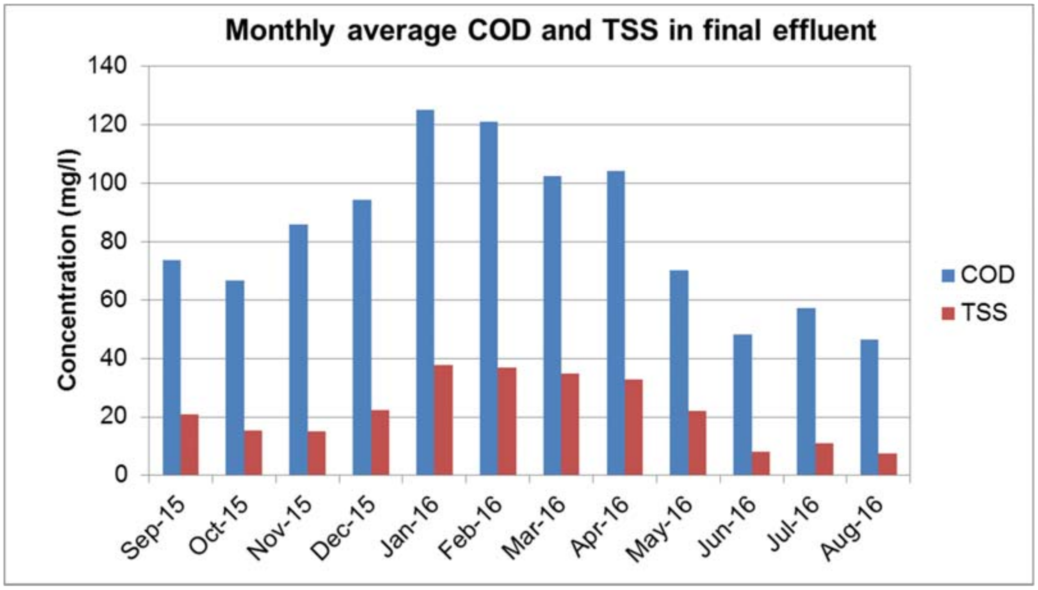

Figure 63: Monthly average COD and TSS in the final effluent at 'C' WWTP

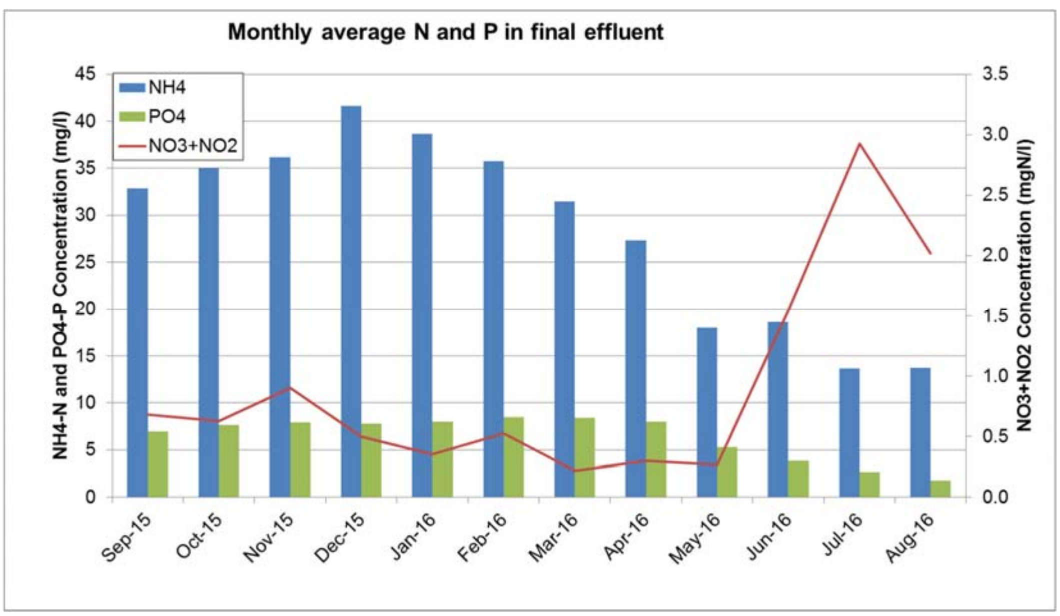

Figure 64: Monthly average ammonia, orthophosphate and nitrate+nitrite in the final effluent at 'C' WWTP

5.5.3 *Sludge treatment*

5.5.3.1 Sludge characteristics

At 'C' WWTP, PS is extracted from all eight PSTs. Table 44 indicates the characteristics of the PS and biological sludge prior to gravity thickening and DAF units, as well as prior to AD. The indicated values are derived from analytical results from the unit operations.

Table 44: Characteristics of the primary and biological sludge at 'C' WWTP

Parameter	Primary Sludge (from PST)		Biological sludge (from FST)	
	Before Thickening	After Gravity Thickening	Before floatation	After floatation
Flow (m^3/d)	2.77	0.76	1.30	0.35
Dry solids (%)	1.8	3.93	1.68	3.67
Sludge mass (kg/d)	45 946	29 859	15 731	15 155

5.5.3.2 Sludge thickening

There are two streams of sludge that undergo thickening. The sludge from the PSTs is pumped to gravity thickeners and sludge from the SSTs is sent to the DAF units. The average DS content of the gravity thickened sludge is 3.9%, while the average DS content of the biological thickened sludge is 3.7%. The organic fractions for the gravity thickened and biological thickened sludge are 83.2% and 82.6% respectively. The monthly averages for gravity thickened sludge and biological thickened sludge are illustrated in Figure 65 and Figure 66 respectively.

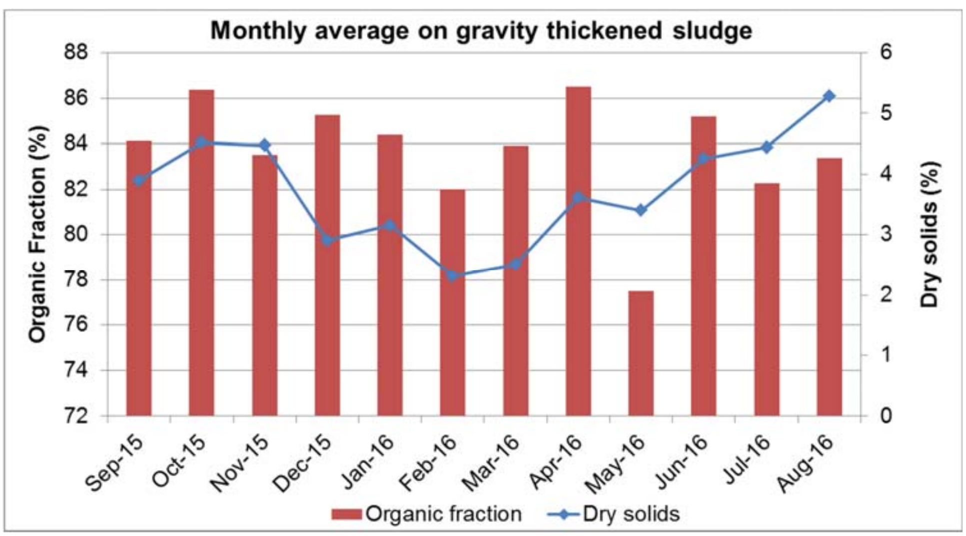

Figure 65: Monthly average organic fraction and dry solids content in the gravity thickened sludge at 'C' WWTP

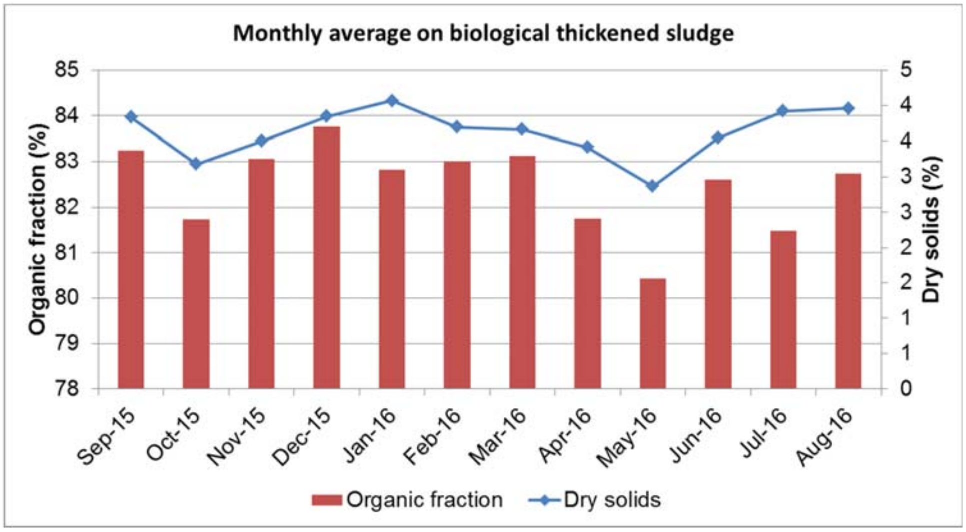

Figure 66: Monthly average organic fraction and dry solids content in the biological thickened sludge at 'C' WWTP

5.5.3.3 Anaerobic sludge digestion

Primary and biological sludge are digested under mesophilic conditions in three ADs that are pumped mixed and heated.

During the selected monitoring period (September 2015 to August 2016), the DS content in the digested sludge was, on average, 2.8% (w/v) and the organic fraction was, on average, 79.6% and the trend is illustrated in Figure 67. The average retention time in the ADs was approximately 14 days. Typically for digesters in mesophilic conditions (35ºC), the minimum recommended retention time is 18- 20 days. The Plant 'C' ADs are operated between 37-38ºC and indicate 64% VSS destruction. Considering the relatively high VSS destruction, it appears that 14 days is a reasonable retention time for these digesters at these temperatures and including mixing.

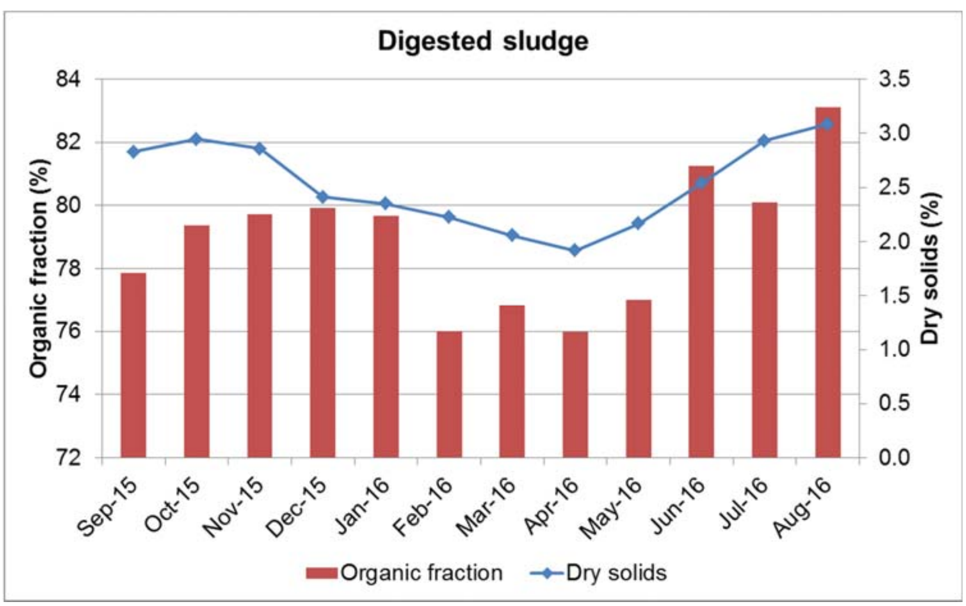

Figure 67: Monthly average organic fraction and dry solids content in the digested sludge a 'C' WWTP

5.5.3.4 *Sludge dewatering*

'C' WWTP has belt presses which are not currently in use. Sludge drying beds are used for the dewatering of sludge at the works. There is no analytical data available regarding the dryness of the sludge cake.

5.5.3.5 *Treatment of sludge return liquors*

Currently, there is no treatment of the sludge return liquors at 'C' WWTP. The supernatant from the gravity thickeners and DAF units is returned to the biological reactors and the analytical results indicate relatively high TSS concentrations (> 4 000 mg/ℓ). The filtrate from the drying beds gravitates to ponds. There is no analytical data available regarding the quality of the filtrate.

5.6 Impact of the sludge return liquors

5.6.1 Plant mass balance

A complete mass balance of the 'C' WWTW was prepared to understand and evaluate the magnitude of the impacts of the return liquors on the main treatment process. The results of the plant mass balance, elaborated with the average data available from September 2015 to August 2016, are provided in Table 45. Once the analytical data available did not cover all streams and parameters, the following assumptions were required to complete the mass balance:

- Efficiency of COD removal in PSTs = 53%
- Efficiency of TSS removal in PSTs = 70%
- Efficiency of TKN removal in PSTs = 11%
- Efficiency of NH_4 removal in PSTs = 0%
- Efficiency of TP removal in PSTs = 9%
- Efficiency of ortho-phosphate removal in PSTs = 0%
- COD in biological sludge: COD/MLVSS = 1.4
- Organic fraction in primary sludge = 83%
- TP removed with the biological sludge: TP/MLSS = 4%
- TKN removed with the biological sludge: TKN/MLSS = 7%
- Dryness of the sludge cake = 35%

To confirm the assumptions above and improve the accuracy of the mass balance, it would be recommended to double-check the following parameters with an analytical programme for at least a 3-day period:

- Primary sludge:
  - COD, TSS, TKN and TP.
- Gravity thickeners:
  - TSS in, TSS returned and DS sludge.
- DAF units:
  - TSS in, TSS returned and DS sludge.
- Digested sludge:
  - COD, TKN, NH_4^-N, TP, PO_4^-P and DS.

- Sludge cake:
    - DS sludge

- Filtrate from the Drying beds:
    - COD, TKN, NH_4^-N, TP, PO_4^-P and DS.

The following flows/volumes should be also confirmed:

- Supernatant from gravity thickeners
- Supernatant from DAF units
- Filtrate from the drying beds
- Sludge cake
- Biological thickened sludge to digestion

Table 45: Results of the mass balance at 'C' WWTP

Water streams	Raw sewage	Primary effluent	Primary effluent & Returns	Biological Effluent	Final Effluent
Flow (Ml/d)	120	117	120	119	119
COD (kg/d)	112603	52923	74484	10297	9487
TKN (kg/d)	9719	8650	9066	2561	3438
NH4 (kg/d)	5101	5101	5123	2342	3265
NO3+NO2 (kg/d)	0	0	0	173	113
TP (kg/d)	1637	1489	1564	453	832
PO4 (kg/d)	890	890	892	297	709
TSS (kg/d)	65637	19691	36354	3118	2461
COD (mg/l)	940.2	452	444	87	80
TKN (mgN/l)	81.2	74	54	22	29
NH4 (mgN/l)	42.6	44	40	20	28
NO3+NO2 (mgN/l)	0.0	0	0	1.5	1.0
TP (mgP/l)	13.7	13	9	3.8	7.0
PO4 (mgP/l)	7.4	8	7	2.5	6.0
TSS (mg/l)	548.0	168	164	26	21

Sludge streams	Primary sludge	Biological sludge	Primary thickened sludge	Biological thickened sludge (DAF)	Digested sludge	Sludge Cake
Flow (Ml/d)	2.8	1.5	0.8	0.4	1.17	0.09
COD (kg/d)	59679	18187	38785	17522	37181	29418
TKN (kg/d)	1069	1131	695	1089	1784	809
NH4 (kg/d)	0	30	0	8.1	824	82
NO3+NO2 (kg/d)	0	0	0	0	0	0
TP (kg/d)	147	633	96	610	706	245
PO4 (kg/d)	0	3.8	0	1.0	467	140
TSS (kg/d)	45946	15731	29859	15155	33354	30019
COD (mg/l)	21555	12125	51032	42484	31713	343000
TKN (mgN/l)	386	754	914	2641	1522	9430
NH4 (mgN/l)	0	20	0	20	703	961
NO3+NO2 (mgN/l)	0	0	0	0	0	0
TP (mgP/l)	53	422	126	1479	602	2855
PO4 (mgP/l)	0	2.5	0	2.5	399	1635
TSS (mg/l)	16595	10487	39289	36745	28449	350000

Sludge return liquors streams	Gravity Thickener Returns	DAF returns	Supernatant from thickeners & DAF	Dewatering filtrate
Flow (Ml/d)	2.01	1.09	3.10	1.09
COD (kg/d)	20895	666	21561	7763
TKN (kg/d)	374	41	416	975
NH4 (kg/d)	0	21	21	742
NO3+NO2 (kg/d)	0	0.0	0	0
TP (kg/d)	52	23.2	75	461
PO4 (kg/d)	0	2.7	3	327
TSS (kg/d)	16087	576	16662	3335
COD (mg/l)	10402	612	6963	7144
TKN (mgN/l)	186	38	134	898
NH4 (mgN/l)	0	20	7	683
NO3+NO2 (mgN/l)	0	0	0	0
TP (mgP/l)	26	21	24	424
PO4 (mgP/l)	0	2.5	1	301
TSS (mg/l)	8009	529	5381	3069

5.6.2 Influent characteristics

The supernatant return liquors from the gravity thickener and DAF operation units are combined with the PST effluent, i.e. downstream of the PSTs. Return liquors are redistributed to all the bioreactors.

A desktop investigation was carried out to determine the impact of return liquors to the bioreactor if filtrate from the dewatering is returned to the bioreactor inflow. Since return liquors are introduced downstream to the PSTs, the analysis was carried out on primary effluent. Table 46 gives a summary of the calculations of the impacts of return liquors on the biological reactors

Table 46: Impact of return liquors and dewatering return liquors on influent characteristics at 'C' WWTP

Parameters	Primary Effluent	Return Liquors (Thickeners and DAF)	Primary Effluent and Return Liquors	Primary Effluent, Return Liquors and Filtrate	Impact without filtrate (current)	Potential impact with filtrate	Typical impact on raw ww (*)
Flow (Mℓ/d)	117	3.10	120	121	2.6%	3.6%	0.5% – 1.0%
COD (kg/d)	52 923	21 561	74 484	82 247	40.7%	55.4%	5% – 10%
TKN kg/d)	8 650	416	9 066	10 041	4.8%	16.1%	9% – 13%
NH_4 (kg/d)	5 101	21	5 123	5 864	0.4%	15.0%	9% – 13%
TP (kg/d)	1 489	75	1 564	1 564	5.0%	36%	5% – 30%
PO_4 (kg/d)	890	3	892	1 353	0.3%	52.1%	5% – 30%
TSS (kg/d)	19 691	16 662	36 354	36 681	84.6%	101%	2% – 5%

(*) Based on Royal HaskoningDHV process design tool and excluding any dedicated treatment to the sludge return liquors

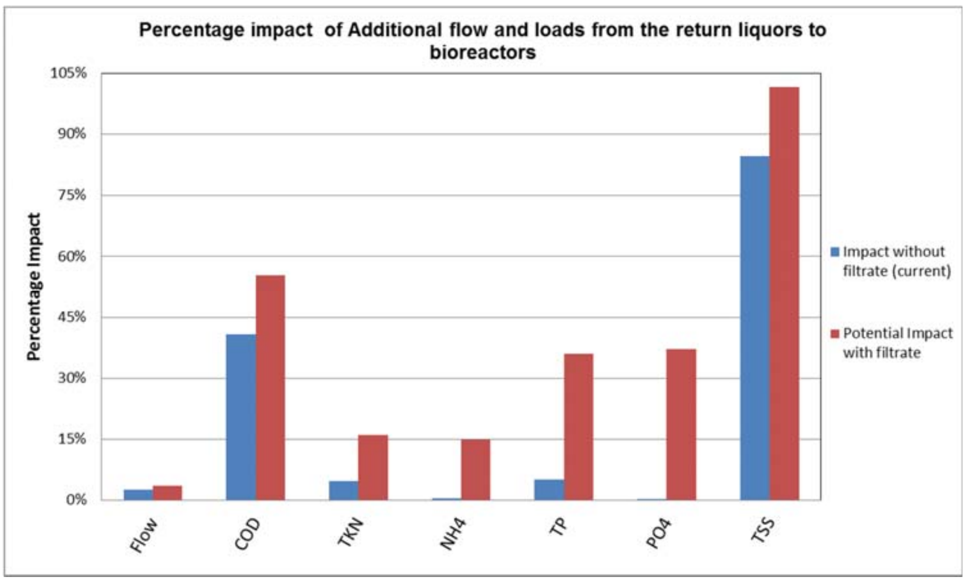

Figure 68: Additional flow and loads entering the bioreactors from the sludge return liquors and filtrate treatment at 'C' WWTP

Comparing the influent ratios for the Plant 'C' bioreactors with a typical South African sewage (Table 47), generally the primary effluent (settled wastewater) at Cape Flats is slightly unbalanced with the ratio of COD to nutrients.

Table 47: Influent ratios with and without return liquors at 'C' WWTP

Ratios	Primary Effluent	Primary Effluent & Return Liquors (Thickener & DAF)	Primary Effluent, Return Liquors and Filtrate (Future)	Typical SA Raw WW
COD/TSS	2.7	2.0	2.3	2.0
COD/TKN	6.1	8.2	7.2	8.2
COD/ NH_4	10	14.5	12.3	14
COD/TP	36	48	38	54
COD/ PO_4	59	83	64	117

(*) WRC Report TT389/09, Process Design Manual for Small Wastewater Treatment Works

5.6.3 Biological effluent quality

The average quality of biological effluent is presented in Table 48. On average, the biological treatment cannot meet the required standards for COD, ammonia, phosphate and TSS. Since most of the parameters are outside of the effluent requirements it is recommended to check the nitrification capacity, aeration capacity and anaerobic, anoxic and aerobic volumes required for the current and future influent loads.

Table 48: Average quality of the biological effluent at 'C' WWTP

Parameters	Biological Effluent
COD (mg/ℓ)	87
NH_4 (mgN/ℓ)	19.8
$NO_3 + NO_2$ (mgN/ℓ)	1.5
PO_4 (mgP/ℓ)	2.5
TSS (mg/ℓ)	26.3

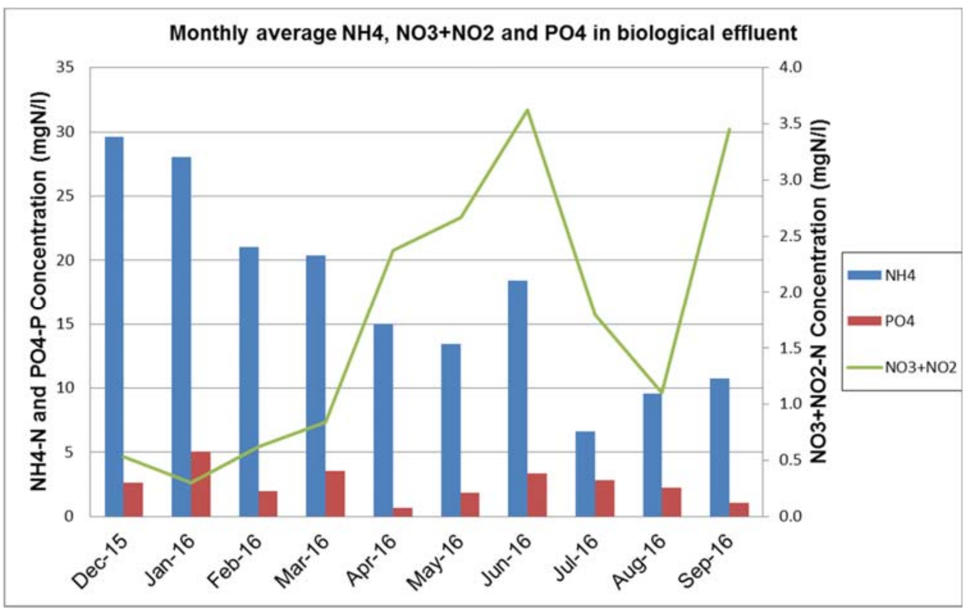

Figure 69: Monthly average ammonia, nitrate+nitrite and orthophosphate biological effluent quality at 'C' WWTP

5.6.4 Aeration demand

Information regarding the existing aeration capacity on site is not available. The 8 AS reactors are aerated with fine bubble diffusion. Theoretically, the current aeration energy consumption is roughly 63 400 kWh/d. If in future, the filtrate from the dewatering would be returned upstream of the biological reactors, the energy consumption should increase by ± 15%.

5.6.5 Biological treatment capacity

The bioreactors are currently treating 62% of the design COD load, 77% of the TKN design load. The specific biological sludge production is calculated in 0.25 kg MLSS/kgCOD removed. On average the sludge retention time have been around 9 days.

The current additional loads of ammonia and orthophosphate from the return liquors (supernatant from gravity thickeners and DAF units) are negligible such that they do not impact in the treatment capacity of the bioreactors. However, there is a significant increase in the COD and MLSS with respective increases of 40% and 84%. Naturally, the impact of the nutrient loads will be much higher if, in the future, the dewatering returns are recycled to the biological reactors.

5.7 Conclusions and recommendations

The site research conducted at ‘C’ WWTP indicates the following conclusions regarding the impact of the sludge return liquors in the plant performance:

1. Only the return liquors from the gravity thickeners and DAF units are recycled to all bioreactors, the incoming ammonia and orthophosphate loads to the bioreactors are marginal, with negligible impact on the bioreactors. The impact was determined to be 0.4% and 0.3% for ammonia and ortho-phosphate respectively.

2. If filtrate from the dewatering (drying beds or mechanical dewatering) is included in the return flows, then the impact was determined to be 15% and 52% for ammonia and ortho-phosphate respectively. These are significant impacts on the bioreactor’s performance, especially as the biological treatment is continuously showing a poor performance. Considering this eventual future scenario, the aeration consumption would raise in ± 15% compared with the current situation.

In addition, the following generic conclusions and recommendations should be noted:

3. The technical performance of the plant is satisfactory and shows a need for maintenance and repairs of some unit operations. A tender for the refurbishment of the dewatering operations unit has been put out in the year 2017.

4. The current hydraulic demand in the plant is 60% of the design capacity. The current loading for the plant compared to its design capacity is 94% for COD, and 83% for TKN. However, considering the plant is non-compliant with the effluent requirements it can be concluded that the plant is operating over its actual capacity.

5. Biological and final effluent quality is not complying with the COD, TSS, ammonia and orthophosphate discharge quality standards. The biological treatment requires optimisation to improve its performance. A more detailed process audit should be carried out.

CHAPTER 6: 'D' Wastewater Treatment Plant

The 'D' WWTP is located within the metropolis of Port Elizabeth. It is in the flood plain of the Swartkops river (refer to Figure 70). The plant treats primarily domestic wastewater with some industrial wastewater. The plant is owned and operated by the Nelson Mandela Bay Municipality (NMBM).

Phase 1 of the plant (Unit 1), built in 1977, is a Huisman Orbal Aeration System, designed to treat 1.86 Mℓ/day. Capacity was increased with the addition of a 2.75 Mℓ/day BNR (Ames Costa, Unit 2) reactor in 1977, built to comply with general standards. Considering future growth, the addition of Unit 3, a 4.25 Mℓ/day 3-stage Phoredox reactor was built in 2009. However, the raw sewage flows have been much lower than initially expected, resulting in only the latest BNR reactor being operated.

WAS was pumped to Kuduskloof landfill site until 2009, this was due to the upgrade in 2009 that included a new chlorine contact tank, chemical dosing for the effluent from the oxidation ditch and refurbishment of the sludge lagoon. A further phase envisioned is the onsite dewatering of the WAS from the sludge lagoon as an alternative method of sludge disposal.

Figure 70: Aerial view of 'D' WWTP (Google Earth, 2016)

6.1 Process description

A description of the plant is below, based on site visits and drawings obtained from Hatch Goba. As mentioned, due to low flow (~4 Mℓ/day), only Unit 3 is in operation. Thus, Units 1 and 2 will be discussed briefly and without results. The general process flow diagram of the treatment works is provided in Figure 71:

- Sewage is pumped to the plant; this causes the flow to be controlled using a controlled flood peak. On days of power failure, the plant receives no flow.

- **Inlet works** consists of:
  - Two mechanical front raked coarse screens (8 mm) and a bypass channel for peak wet weather overflow,
  - Two vortex degritters,
  - Flow split with flumes between the units.

- **Unit 1** is a Huisman Orbal System, an oxidation ditch type reactor, with horizontal disc aerators, with four 7.1 m diameter Dortmund cone clarifiers are in the centre.

- **Unit 2** is an Ames Crosta system with one 23 m diameter clarifier.

- **Unit 3** is a BNR plant designed as a 3-stage Phoredox system, for N removal, but built with the option of changing to either a UCT or Johannesburg system, should P removal be required. According to process controller records, this system is operated at a sludge age of about 30 days. This 3-Stage Phoredox reactor has a volume of 5 400 m^3 with anaerobic, anoxic and aerobic mass fractions of 7.2%, 14.3% and 78.5% respectively. The system has 3 mixers (anaerobic and anoxic zones) and 4 surface aerators with VSDs controlled by influent flow and immersion depth.

- **Chemical dosing** consists of:
  - Ferric dosing with a 29 m diameter phosphate settling tank (not in operation).

- **Disinfection** consists of:
  - A chlorine dosing station, shallow mixing channel and chlorine contact tank before entry into the maturation ponds,
  - Maturation is either a pond, or a reed-bed (which had been de-weeded and moved at the time of the site visit, thus currently out-of-use).

- **Sludge handling and disposal** consists of:
  - Two sludge lagoons (each 61.75 m × 62.1 m × approximately 1.4 m deep), with a multi-level withdrawal of supernatant,
  - No sludge had been removed from the lagoons since pumping to the landfill stopped in 2009. The lagoons overflowed in July 2016. The sludge lagoons require emptying, a contract is currently being arranged by the metro to empty the lagoons and dry the sludge.

- **Return liquors treatment** consists of:
  - Supernatant of the sludge lagoon, which is returned to Unit 3 at the start of the aeration section.

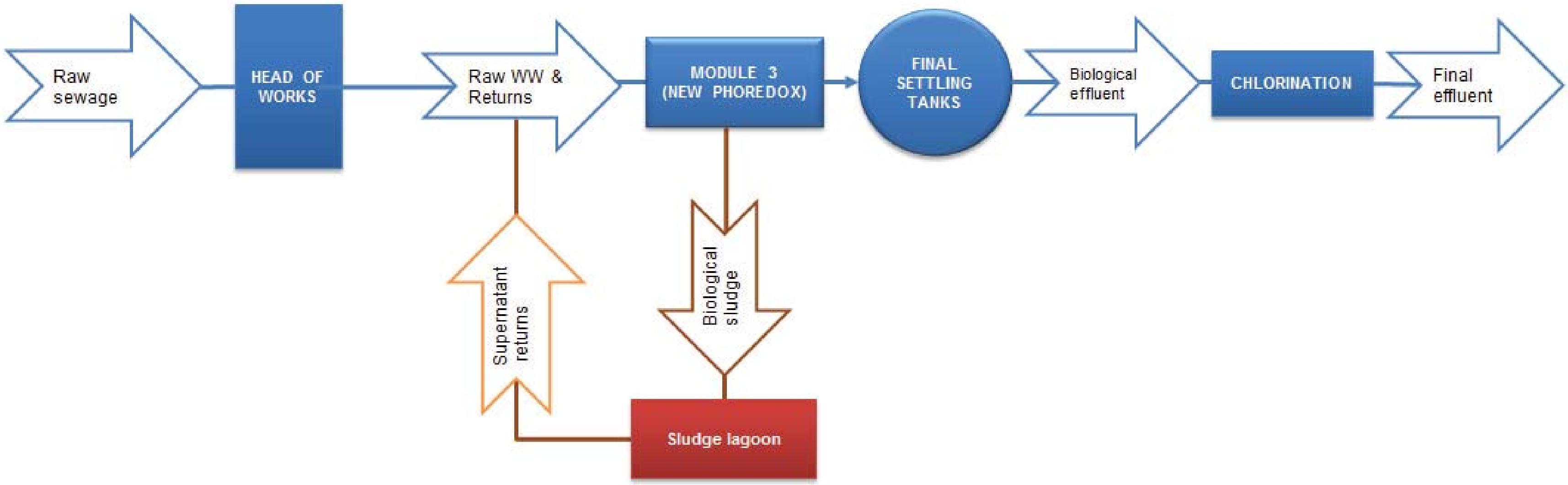

Figure 71: General process flow diagram of 'D' WWTP

6.2 Design capacity

The total design capacity of the plant is indicated in Table 49. It is noted that the original designs of Units 1 and 2 probably did not consider the additional load and flows from the sludge return liquors. The design characteristics of Units 1 and 2 are not available.

Table 49: Design flows and loads at 'D' WWTP

Parameters	Unit 1	Unit 2	Unit 3	Total
Flow (Mℓ/d)	1.86	2.75	4.25	8.86
COD (kg/d)	837	1 238	1 913	3 988
TKN (kg/d)	93	137	212	442
TP (kg/d)	30	44	68	142

6.3 Effluent standard requirements

The latest water use license for 'D' WWTP was granted to NMBM in 2011 by the Department of Water Affairs. The final treated effluent quality requirements currently stipulated in the water use licence are as per Table 50. These requirements are more lenient than general standards for ammonia, but more stringent for COD, TSS and phosphate.

Table 50: Effluent standard requirements at 'D' WWTP

Parameter	Effluent standards	Method of compliance
COD (mg/ℓ)	65	90% compliance
TSS (mg/ℓ)	18	
NH_4 (mg N/ℓ)	8	
$NO_3 + NO_2$ (mg N/ℓ)	15	
PO_4 (mg P/ℓ)	1.0	

6.4 Technical performance

'D' WWTP appears to be a well operated and maintained facility. Current items down for maintenance, at the time of site visit, include the recycle pump for the ferric dosing and the supernatant pump at the sludge lagoons. The plant has a reasonable level of automation, including SCADA system. The operation team on site consists of 6 process controllers divided by 3 shifts per day and a plant manager and a plant super intendant.

6.5 Process performance

6.5.1 Influent characteristics

As indicated in Figure 72 below, during the operational window selected (September 2015 to August 2016) 'D' WWTP treated on average a total of 4 Mℓ/d (45% of the design capacity). Units 1 and 2 are currently not operational and are therefore not studied in this report.

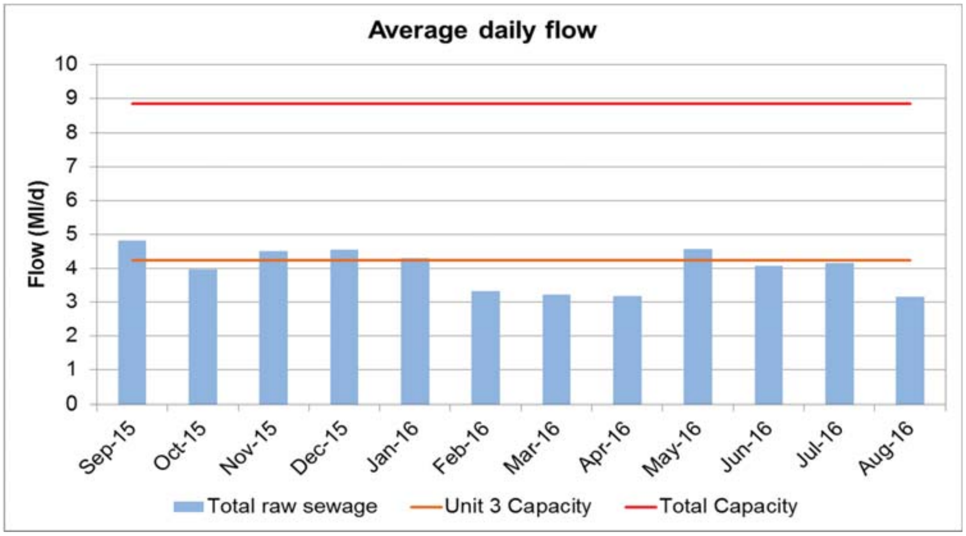

Figure 72: Average daily flow at 'D' WWTP

The average influent concentrations and loads are indicated in Table 51, with historical data for COD in Figure 73 and NH_4^-N and PO_4^-N in Figure 74. The design was made for primarily domestic sewage of 450 mg/ℓ and, per the year's results studied, this is accurate. However, TP is lower than predicted. To calculate the design load capacity of the whole plant, Unit 3's design info was used for the other two Units, with their respective design flows.

Table 51: Average raw sewage concentrations and loads at 'D' WWTP

Parameter	Average concentration (September 2015 to August 2016)		Average load (September 2015 to August 2016)	
COD	468	mg/ℓ	1 882	kg/d
TSS	234	mg/ℓ	942	kg/d
TKN	56	mg/ℓ	225	kg/d
NH_4	42	mgN/ℓ	168	kg/d
PO_4	4.2	mgP/ℓ	17	kg/d
TP	6.5	mg/ℓ	20	kg/d

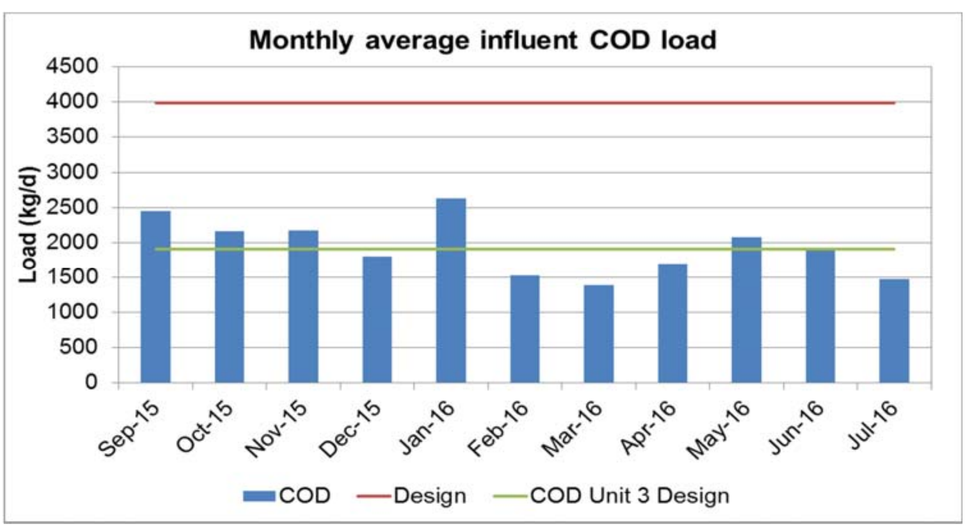

Figure 73: Average COD concentrations in the influent at 'D' WWTP

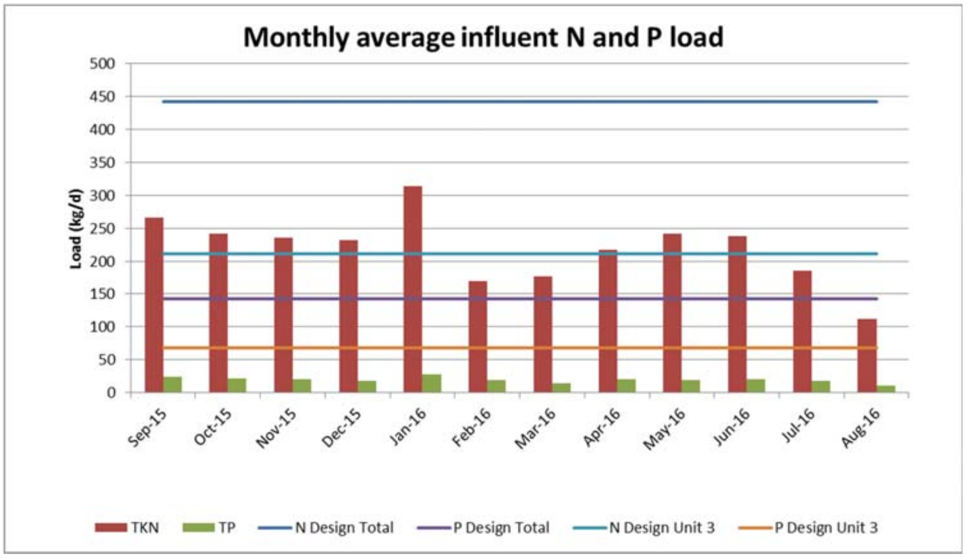

Figure 74: Average TKN and TP concentrations in the influent at 'D' WWTP (calculated proportionately as per assumptions given in mass balance section 6.6.1)

6.5.2 *Effluent quality*

With the re-application for licence in 2011, the effluent requirements on Plant 'D' were less stringent (Table 52). Average final effluent quality is shown in Table 52 with historical graphs in Figure 75 and Figure 76 below. Unit 3 has generally complied; the only parameter which fails is phosphate. From the results below, unit 3 has generally complied; the only characteristic which fails is phosphate. From the results below, the unit removed COD and TSS well. Ammonia at 5.0 mg/ℓ is higher than the Unit 3 design of 0.5 mg/ℓ, but it does not exceed the effluent quality limits required by the Water Use Licence.

Table 52: Average final effluent quality and plant compliance at 'D' WWTP

Parameter	Effluent standards	Average concentration (August 2015 to July 2016)	Average compliance (August 2015 to July 2016)
COD	65	49 mg/ℓ	100%
TSS	18	13 mg/ℓ	100%
NH_4	8.0	5.0 mgN/ℓ	100%
$NO_3 + NO_2$	15	3.3 mgN/ℓ	100%
PO_4	1.0	3.4 mgP/ℓ	10%

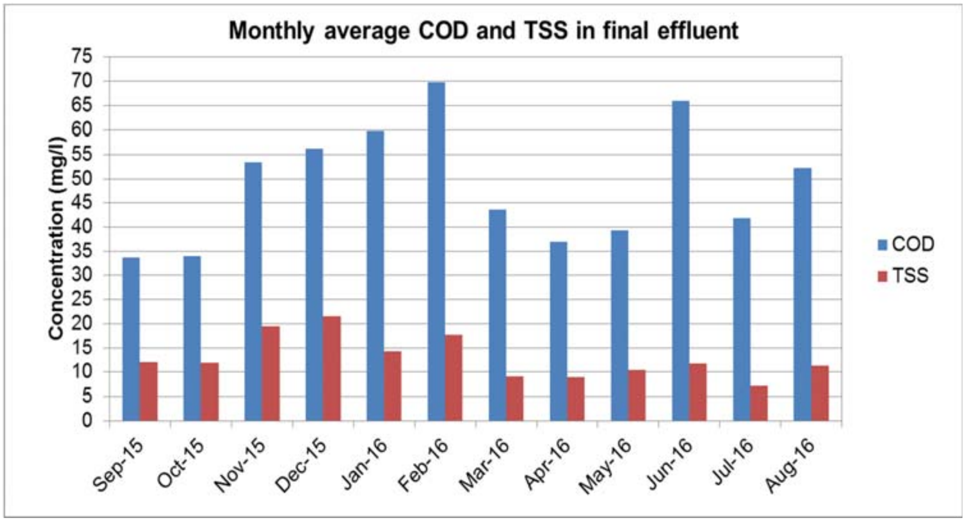

Figure 75: Monthly average COD and TSS in the final effluent at 'D' WWTP

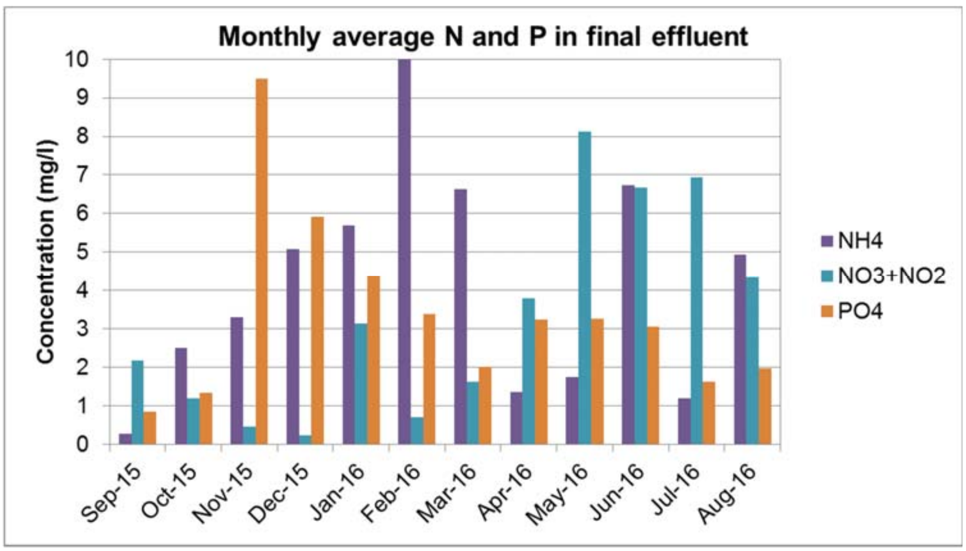

Figure 76: Monthly average ammonia, nitrate+nitrite and orthophosphate in the final effluent at 'D' WWTP[2]

6.5.3 Sludge treatment

6.5.3.1 Sludge characteristics

At 'D' WWTP, WAS is removed from Unit 3 via the clarifier under flow (RAS line). Table 53 indicates the characteristics of the WAS withdrawn from Unit 3 via the underflow.

Table 53: Characteristics of the biological sludge at 'D' WWTP

Parameter	Biological Sludge
Flow (m³/d)	130
Dry solids (%)	0.72
Sludge mass (kg/d)	941

[2] *Final effluent concentration for NH_4 February 2016 is 20.3 mg/ℓ. Suppressed to enhance visualisation.*

6.5.3.2 Sludge thickening

Wasted sludge is thicker than the sludge in the reactor, as it comes from the RAS line. Further thickening occurs in the sludge lagoons. However, no results are available for the sludge lagoon as no sludge samples are taken and sludge is not withdrawn from the lagoon allowing no steady state digester" concentration. The lagoon can therefore be thought of as permanent storage with the occasional measured addition of fresh wasted activated sludge.

6.5.4 Sludge return liquors

Unit 3, a Phoredox layout reactor, is operated for N and P removal, and therefore the supernatant from the sludge lagoon is high in P as well as N. This is seen in the average monthly concentrations in Figure 77 below.

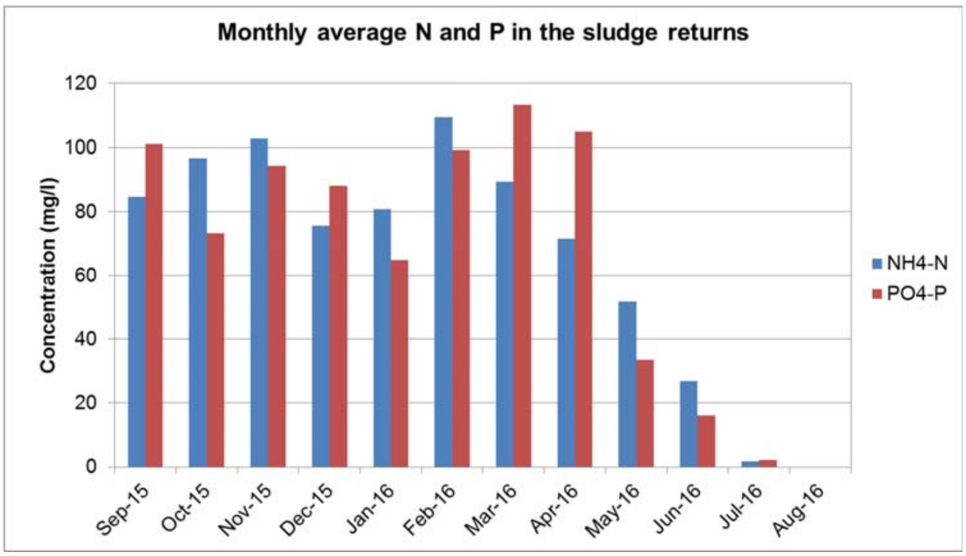

Figure 77: Average ammonia and orthophosphate concentrations in the sludge return liquors at 'D' WWTP

6.6 Impact of the sludge return liquors

6.6.1 Plant mass balance

A complete mass balance of the 'D' WWTP was prepared to understand and evaluate the magnitude of the impacts of the sludge return liquors on the main treatment process addressed in the following sections. The result of the plant mass balance elaborated with the average data available from September 2015 to August 2016 is provided in Table 54. When the analytical data available did not cover all streams and parameters, the following assumptions were required to complete the mass balance:

- COD in biological sludge: COD/MLVSS = 1.481
- TP removed with the biological sludge: TP/MLSS = 3%
- PO_4/TP in influent = 0.65
- NH_4/TKN ratio in influent = 0.75
- NH_4/TKN ratio in solution = 0.85
- f_n (TKN:VSS ratio of activated sludge) = 0.08

Flow measurement on the effluent is consistently lower than that on the influent. This is due to the use of reclaimed effluent on site, for grit washing, irrigation etc.

Table 54: Results of the mass balance at 'D' WWTP

Water streams	Raw sewage	Raw WW U3 & Returns	Biological effluent U3	Final effluent	Biological sludge	Supernatant returns
Flow (Ml/d)	4.02	4.09	3.97	3.03	0.13	0.08
COD (kg/d)	1882	1987	159	148	1046	105
TKN (kg/d)	225	235	28	18	56	11
NH4 (kg/d)	168	174	16	15	1	5
NO3+NO2 (kg/d)	0.0	0.0	13.6	9.9	0.6	0.0
TP (kg/d)	26	34.1	7.8	15.7	21.2	8.1
PO4 (kg/d)	17	22.4	5.1	10.2	0.2	5.5
TSS (kg/d)	942	1028	58	39	706	86
COD (mg/l)	468	485	53	49	8056	1380
TKN (mgN/l)	56	57	7	6	435	140
NH4 (mgN/l)	42	42	5	5	5	72
NO3+NO2 (mgN/l)	0.0	0.0	4.5	3.3	4.5	0.0
TP (mgP/l)	6.5	8.3	2.6	5.2	163.2	106
PO4 (mgP/l)	4.2	5.5	1.7	3.4	1.7	72
TSS (mg/l)	234	251	19	13	5439	1136

6.6.2 *Influent characteristics*

The supernatant from the sludge lagoon is returned to Unit 3 at the start of the aerated zone. This supernatant contributes to the load on the reactor, particularly in terms of nitrogen, phosphate and suspended solids. For simplicity, it will be added to the raw sewage load on the reactor. The impact of the supernatant load on Unit 3 is shown in Table 55 and Figure 78 below. The current return liquors have a low impact in the influent flow, as well as in COD and nitrogen loads. However, the influent phosphate load is significantly impacted through the additional load recycled from the supernatant of the lagoon (additional 32% orthophosphate). As per Table 54 above, Unit 3 is not complying with the phosphate standard effluent requirement. This can be easily explained as there is currently no removal mechanism of phosphate from the WWTW. The phosphate removed from the waterline is transformed into in particulate phosphate in the form of sludge. The sludge will accumulate in the lagoon. As the lagoon is acting as an anaerobic tank, phosphate shall be released in the lagoon and then returned to the biological treatment. If no outlet in the form of an external sludge discharge is facilitated the influent concentration will become eventually the effluent concentration.

Table 55: Impact of dewatering return liquors in the influent characteristics at 'D' WWTP

Parameter	Raw sewage to the plant	Supernatant returns	Unit 3 raw ww (incl. returns)	Impact on Unit 3 raw ww	Typical impact on raw ww (*)
Flow (kℓ/d)	3 991.6	76.11	4 067.7	1.9%	0.5% – 1.,0%
COD (kg/d)	1 869	105	1 974	5.6%	5% – 10%
TKN (kg/d)	223	13	236	5.9%	9% – 13%
NH_4 (kg/d)	167	5	173	3.2%	9% – 13%
TP (kgP/d)	26	8.1	34.1	31%	5 – 30%
PO_4^-P (kg/d)	16.8	5.5	22.3	32.3%	5 – 30%
TSS (kg/d)	936	86	1 022	9.2%	2% - 5%

(*) Excluding any dedicated treatment to the sludge return liquors

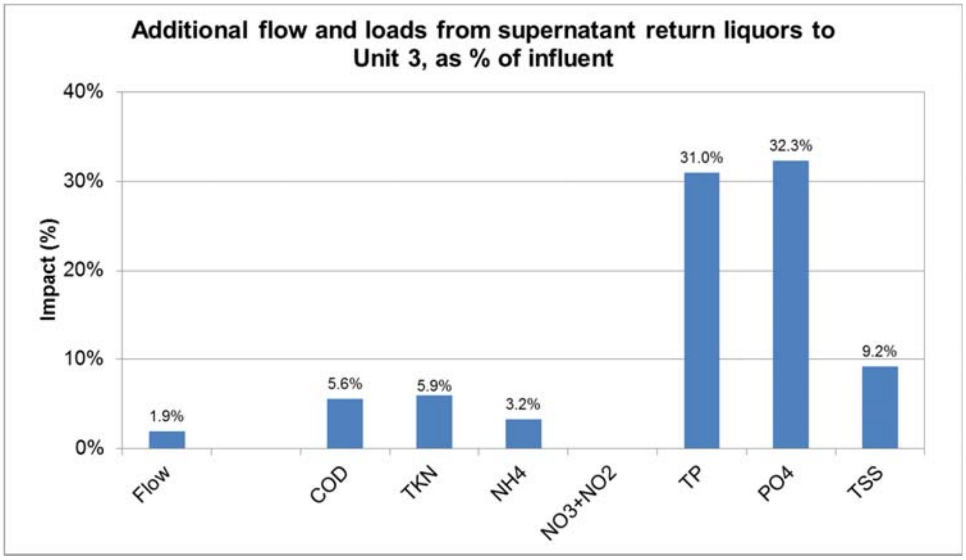

Figure 78: Additional flow and loads entering Unit 3 from the sludge return liquors treatment facility at 'D' WWTP

Comparing the influent ratios from Unit 3 (without return liquors) with a typical South African sewage (Table 56), generally the raw sewage at Plant 'D' is balanced, but a bit low in *P*. When the return liquors are included, the *P* increases, but the TP:COD ratio remains lower than average, continuing to be favourable for removal.

Table 56: Influent ratios with and without return liquors at 'D' WWTP

Ratios	Unit 3 influent (without return liquors)	Unit 3 influent (with return liquors)	Typical values in South African ww
COD/TSS	0.501	0.518	0.5
TKN/COD	0.119	0.120	0.122
TKN/COD	0.090	0.088	0.07 – 0.09
TP/COD	0.014	0.017	0.019
PO_4/COD	0.009	0.011	0.009

6.6.3 Biological effluent quality

The quality of the biological effluent leaving Unit 3 (before the non-operational ferric dosing and before chlorination and maturation), is as follows:

Table 57: Average biological effluent quality and final effluent at 'D' WWTP

Parameter	Average biological effluent	Average final effluent
COD	53 mg/ℓ	49 mg/ℓ
TSS	13.0 mg/ℓ	13 mg/ℓ
NH_4	5.3 mgN/ℓ	5.0 mgN/ℓ
$NO_3 + NO_2$	4.5 mgN/ℓ	3.3 mgN/ℓ
PO_4	1.7 mgP/ℓ	3.4 mgP/ℓ

From the above table, it can be seen that, after having passed through the maturation ponds, the nitrate concentration has dropped, and the phosphate has increased. This can be partly attributed to sludge spills from the lagoon into the maturation pond, when the lagoon became full in the first half of 2016.

6.6.4 Aeration demand

At ‘D’ WWTP, Unit 3 has four surface aerators with 37 kW each running 24 hours per day. Energy is not measured and can therefore only be estimated. The current energy consumption with aeration is about 3 552 kWh/d. In the current process treatment, the additional loads of ammonia and COD from the supernatant returns are low and not having a critical impact in the aeration energy consumption (lower than 5%).

6.6.5 Biological treatment capacity

Unit 3 is currently treating about 100% of its design load, see Table 58 below. Actually, 98% of COD and 106% of TKN loads are currently treated on site. These loads refer to the raw wastewater (excluding returns). This might explain the higher effluent ammonia (5 mg/ℓ) compared to the design figure (0.5 mg/ℓ). Considering the biological reactor and aeration capacity are fully optimised, it appears that Unit 3 in Plant ‘D’ is operating at its max capacity. Any future increase in load (even coming from the internal sludge return liquors) will require either one of the old reactors to be brought back into operation, or a new replacement to be built and operated.

The sludge retention time aimed by the process controllers is 30 days, higher than the design of 20 days. However, a brief calculation based on influent characteristics and reactor MLSS give the sludge age at 18 days. This difference can be due to inconsistent wasting of sludge, or that sludge is wasted from the underflow and not directly from the reactor, making concentration less consistent and therefore sludge age less easily defined.

Table 58: Unit 3 load comparison (actual vs design) at ‘D’ WWTP

Parameters	Unit 3		
	Design	Actual	
Flow (Mℓ/d)	4.25	4.02	95%
COD (kg/d)	1913	1882	98%
TKN (kg/d)	212	225	106%
TP (kg/d)	68	19.9	29%

6.7 Conclusions and recommendations

From the site research conducted at ‘D’ WWTP, the following conclusions and recommendations are applicable:

1. The plant is currently under loaded since the measured raw sewage flow is about half the design capacity. Concentration is within design range.

2. Unit 3, being the only unit currently in operation, is running at full capacity about COD and *N* loads.

3. Unit 3 receives 100% of the flow and loads from the sludge lagoon supernatant, with a contribution of 34% TP. This return flow consumes 5% of the aeration capacity of Unit 3.

4. The *P* is not removed from the system, as sludge is not removed from the plant, and no treatment of dewatering liquor is provided. Therefore, the effluent *P* is high.

5. The effluent ammonia, at 5 mg/ℓ is higher than the design of 0.5 mg/ℓ, but within effluent quality limits. Incomplete nitrification at an AS plant point in general to challenges in aeration or low

SRT. Incomplete nitrification can make an WWTP unstable therefor it is recommended to start a second module.

In addition, the following generic conclusions and recommendations shall be noted:

6. The plant is generally well operated and shows a good level of maintenance.

7. The sludge lagoons should be emptied at 5-year intervals as per design. It must be noted that this mitigating action will likely not be sufficient to ensure compliance on orthophosphate.

8. It is should be checked if there are further optimisations to be applicable in Unit 3 and if required bring other unit into operation to further improve the plant performance.

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APPENDIX 2

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CHAPTER 1: ‘W’ WWTP

‘W’ WWTP has a total design capacity of 170 Mℓ/d; module 1 has a capacity of 40 Mℓ/d, modules 2 and 3 each having a capacity of 40 Mℓ/d and the fourth module has a capacity of 50 Mℓ/d. The results for the impact of SRL are presented in this section. The impact was determined on:

- Influent Characteristics
- Biological Treatment Capacity
- Biological Effluent Quality

1.1 Process Description

A description of the ‘W’ WWTP is indicated below as per information found in the operation and maintenance manuals for Modules 1, 2-3 and Module 4. Table 1 and Table 2 give a summary of the unit operations and process data. The general process flow diagram of the works is indicated in Figure 1 below. Flow is split between Modules 1-3 and Module 4.

Table 1: ‘W’ WWTP Unit Operations and Process

Key Unit Operations and Processes	Module 1	Module 2& 3	Module 4
Primary Settling Tanks	Yes	Yes	Yes
BNR System	Yes	Yes	Yes
Secondary Settling Tanks	Yes	Yes	Yes
Dissolved Air Flotation	Yes	Yes	Yes
Anaerobic Digesters	Yes	Yes	Yes
Dewatering	Yes	Yes	Yes

The pertinent data for the above unit operations and processes is summarised below in Table 2.

Table 2: ‘W’ WWTP Data

Key Unit Operations and Processes	Module 1	Module 2&3	Module 4
Primary Settling Tanks			
• Diameter (m)	25	25	34
BNR System			
• Volume (m³)	5 940	15 898 ea.	21 688
Secondary Settling Tanks			
• Diameter	30	25	34
Dissolved Air Flotation × 7			
• Diameter of ea. Unit (m)	10	10	10
• Volume of each unit (m³)	424	424	424
• Anaerobic Digesters	4	6	4
Dewatering Operates 12 h, 7 days per week			

- Thickened biological sludge is pumped to ADs.
- PS and biological thickened sludge are anaerobically digested in 16 units:
- SRL flows:
  - SRL from the DAF units of modules 1-3 are recycled to the beginning of the biological reactors.

- SRL from the DAF units of module 4 are recycled upstream of the balancing tank.
- Sludge dewatering returns (filtrate) and wash water (from belt press cleaning) split equally between modules 1-3 and 4 and are recycled to downstream of the inlet works of the respective modules.
- 50% of the SRL flow is recycled to Modules 1-3 while the remaining 50% is recycled to Module 4.

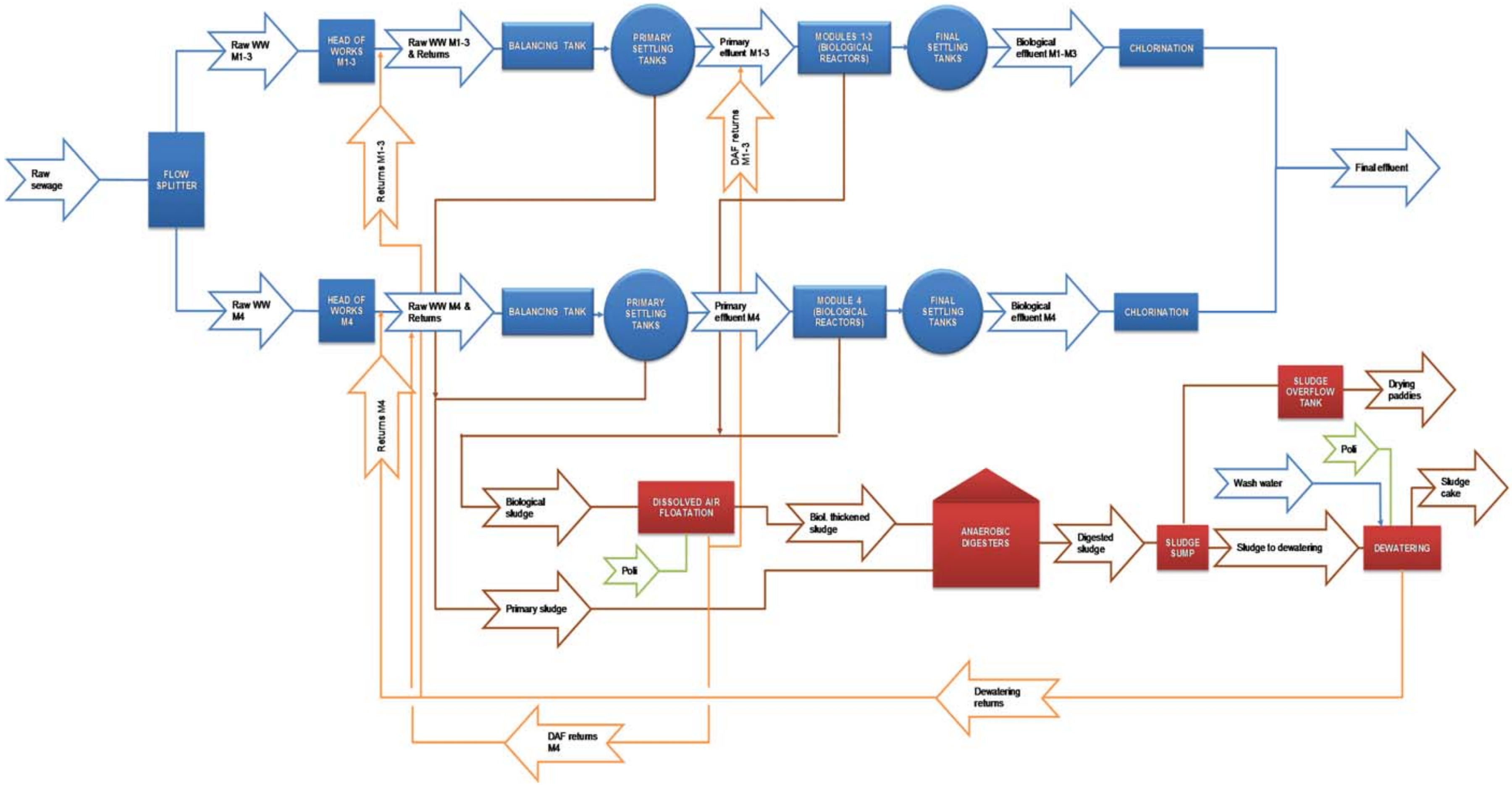

Figure 1: 'W' WWTP Process Flow Diagram

1.2 *Impact of SRL on Influent Characteristics at 'W' WWTP*

The influent characteristics impacted on by SRL flows are:

- Influent flow rate
- Influent COD Load
- Influent Ammonia Load
- Influent PO_4 Load

The impact of SRL on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of SRL for a given percentage side-stream treatment (0% side-stream treatment to 100% side-stream treatment and treated SRL stream is discharged with the final effluent) prior to return to the main water line.

1.2.1 *Influent Flowrate*

The impact of percentage side-stream treatment on the flow rate is illustrated below in Figure 2. Without side-stream treatment, 100% of SRL flow is returned to the activated sludge system. The flow to each module decreases along with side-stream treatment, and the treated SRL is discharged to the final effluent. The flow to Module 1 decreases from 40 Mℓ/d to 39 Mℓ/d. Flow to Modules 2 & 3 decrease from 83 to 79 Mℓ/d and the flow to Module 4 decreases from 52 Mℓ/d to 49 Mℓ/d.

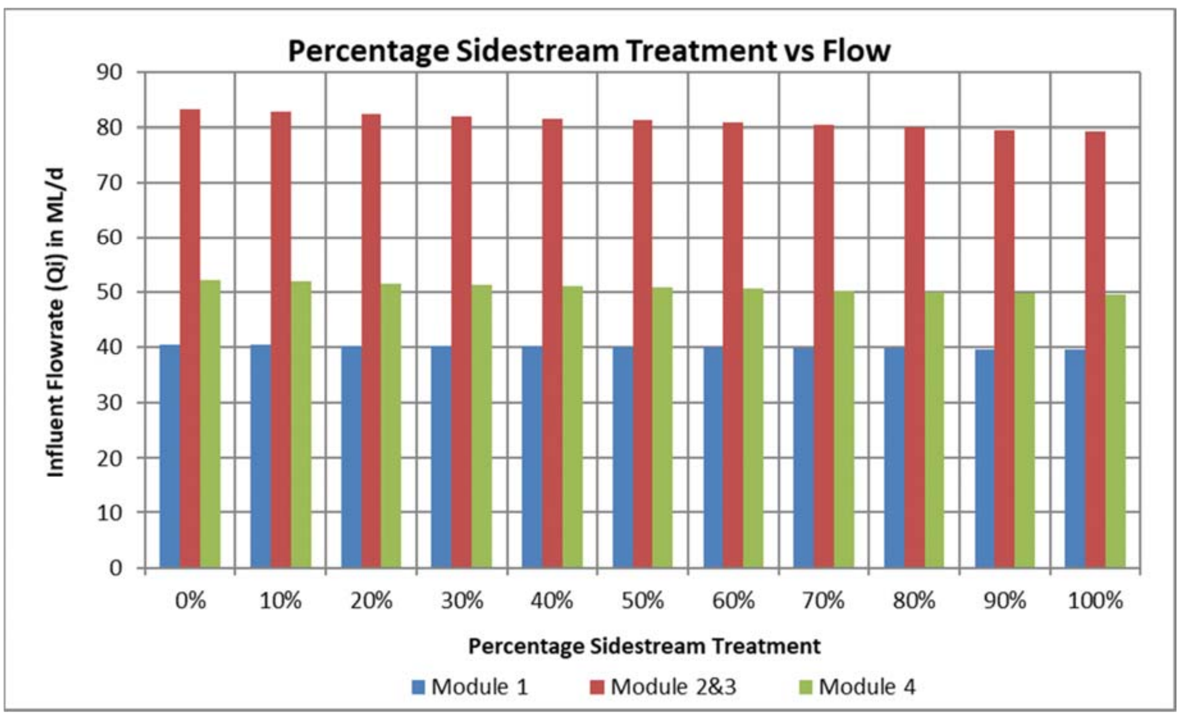

Figure 2: Impact of side-stream treatment on influent flow at 'W' WWTP

1.2.2 *Influent COD Load*

The impact of percentage side-stream treatment on the influent COD load to the AS system is illustrated below in Figure 3. Total COD load to Modules 1, 2&3 and 4 decreases respectively, from 17 386 kgCOD/d, 34 913 kgCOD/d and 21 834 kgCOD/d in relationship to the percentage side-stream treatment to 17 321 kgCOD/d, 34 642 kgCOD/d and 21 651 kgCOD/d.

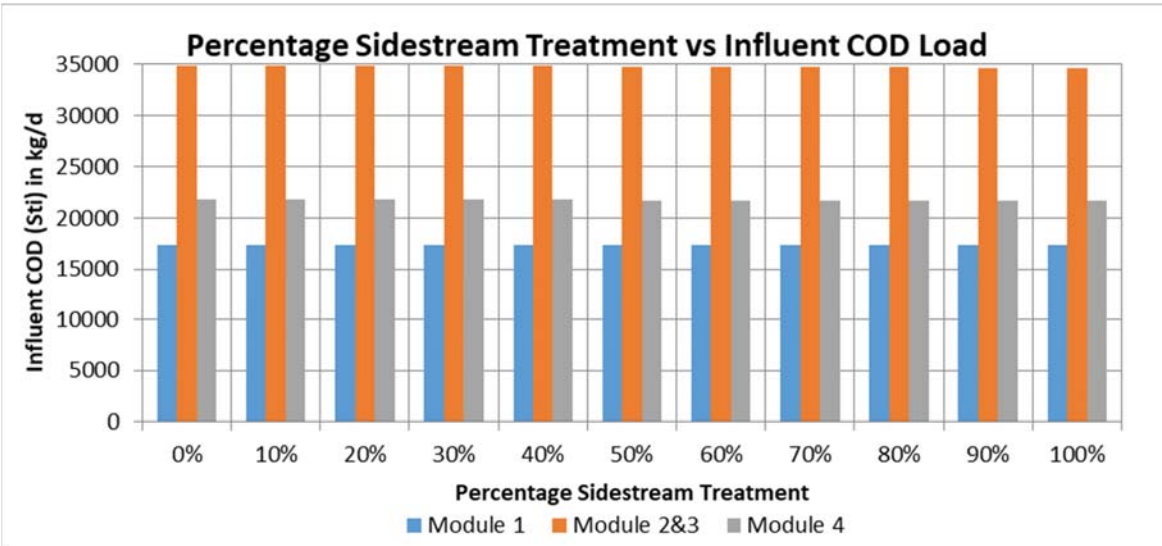

Figure 3: Impact of side-stream treatment on the influent COD at 'W' WWTP

1.2.3 *Influent Ammonia Load*

The impact of percentage side-stream treatment on the influent ammonia load to the AS system is illustrated below in Figure 4. Influent ammonia load to Modules 1, 2&3 and 4 decreases respectively from 1 890 kgN/d, 3 865 kgN/d and 2 420 kgN/d in relationship to the percentage side-stream treatment to 1 789 kgN/d, 3 579 kgN/d and 2 237 kgN/d.

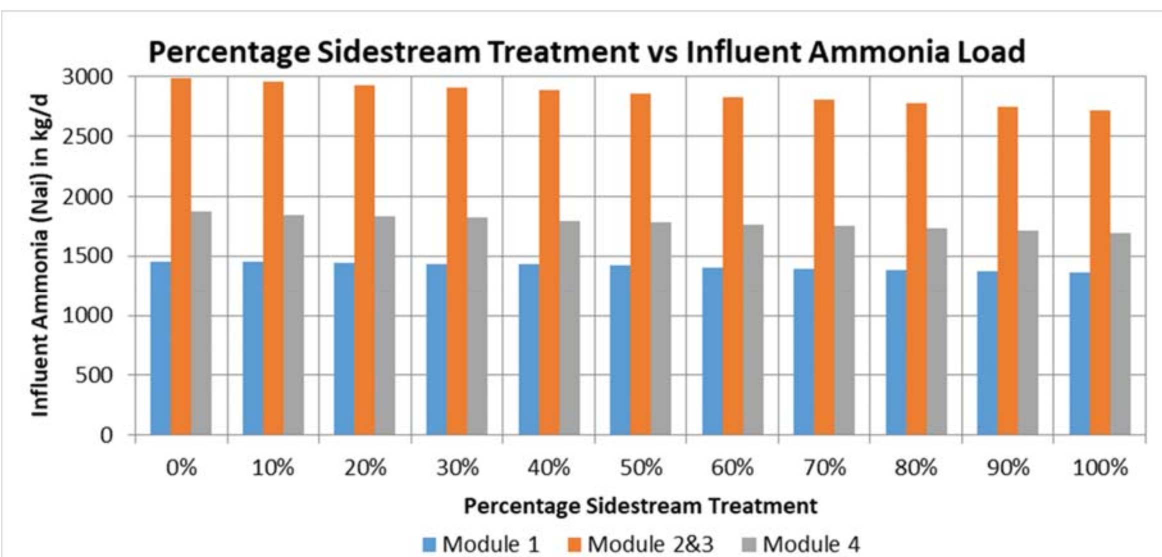

Figure 4: Impact of side-stream treatment on the influent ammonia at 'W' WWTP

1.2.4 Influent Phosphate Load

The impact of percentage side-stream treatment on the influent phosphate load to the AS system is illustrated below in Figure 5. Influent phosphate load to Modules 1, 2&3 and 4 decreases respectively from 478 kgP/d, 669 kgP/d and 427 kgP/d in relationship to the percentage side-stream treatment to 115 kgP/d, 230 kgP/d, 144 kgP/d.

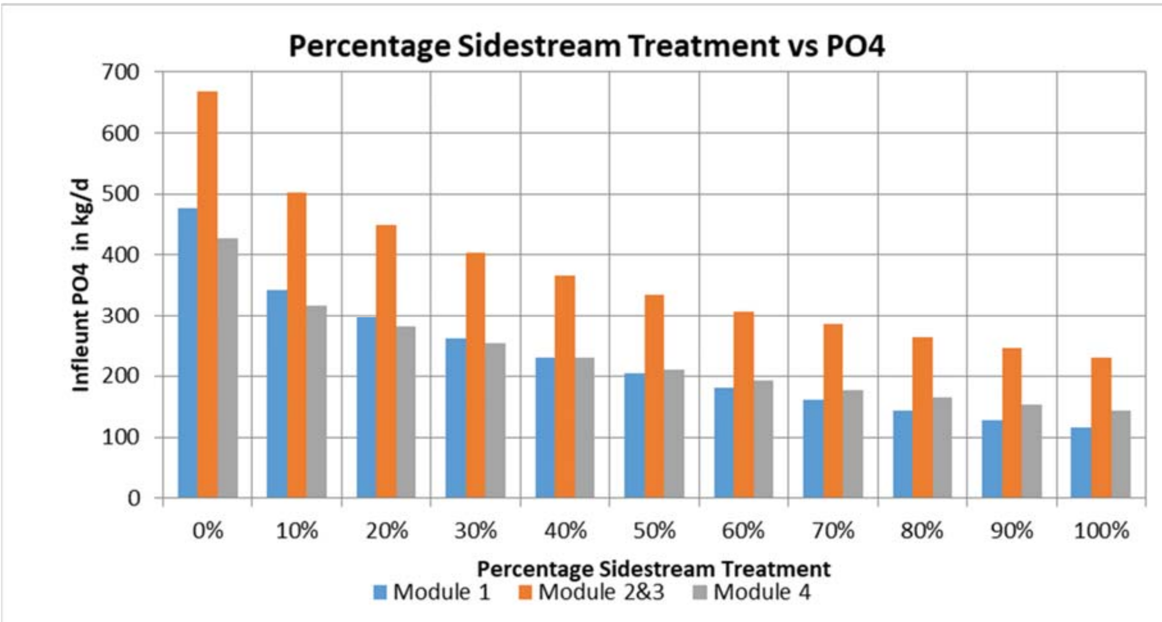

Figure 5: Impact of side-stream treatment on influent phosphate at 'W' WWTP

1.3 Impact of SRL on Biological Treatment Capacity at 'W' WWTP

The biological treatment capacity parameters impacted on by sludge return flows are:

- A-recycle
- Total oxygen demand
- Secondary sludge production

The impact of sludge return flows on each of the above influent characteristics is summarised in this section. Figure 6 to Figure 8 illustrate the impact of SRL for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

1.3.1 A-recycle

The impact of percentage side-stream treatment on the a-recycle ratio (nitrate aerobic to anoxic zone optimum flow rate/influent flow rate) of the AS system is illustrated below in Figure 6. The a-recycle flow ratio for each module increases along with side-stream treatment. The flow ratio for Module 1 increases from 3 to 4 while for Modules 2 & 3 and Module 4 the increase is from 3 to 4.

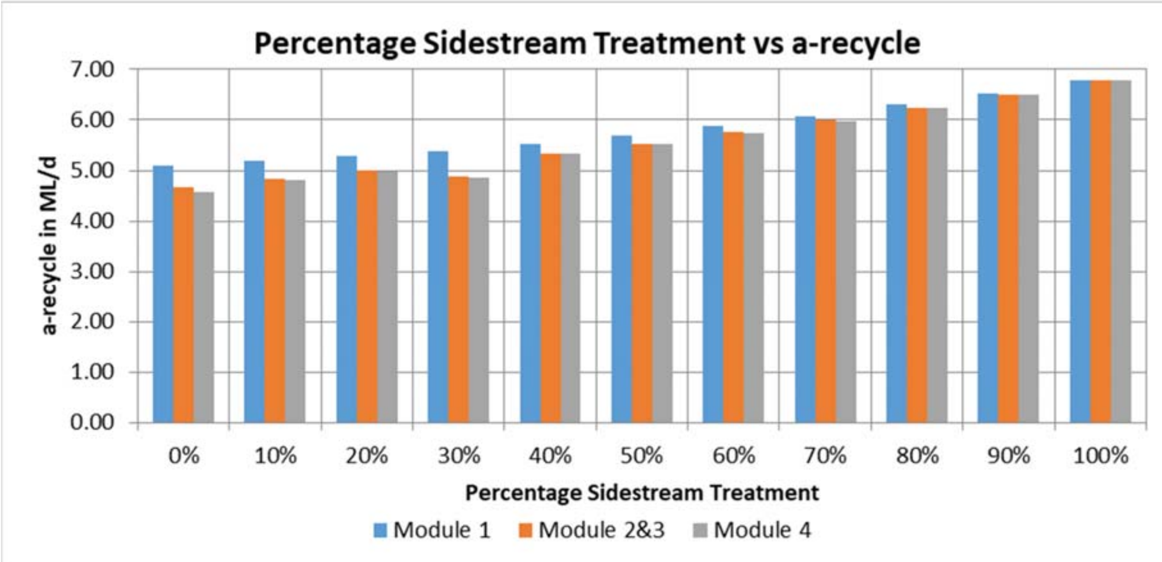

Figure 6: Impact of side-stream treatment on a-recycle at 'W' WWTP

1.3.2 Total Oxygen Demand

The impact of percentage side-stream treatment on the total oxygen demand (FOt) of the AS system is illustrated below in Figure 7. The FOt for each module decreases along with side-stream treatment capacity. The total oxygen demand for Module 1 decreases from 10 225 kgO/d to 10 117 kg/d. Total oxygen demand for Modules 2 & 3 decrease from 20 646 kgO/d to 20 234 kgO/d and the total oxygen demand for Module 4 decreases from 12 877 kgO/d to 12 646 kgO/d.

The aeration power requirement for each module decreases along with side-stream treatment. Aeration power requirement for Module 1 decreases from 511 kW to 505 kW, Modules 2 & 3 decrease from 1 032 kW to 1 012 kW and Module 4 decreases from 644 kW to 632 kW.

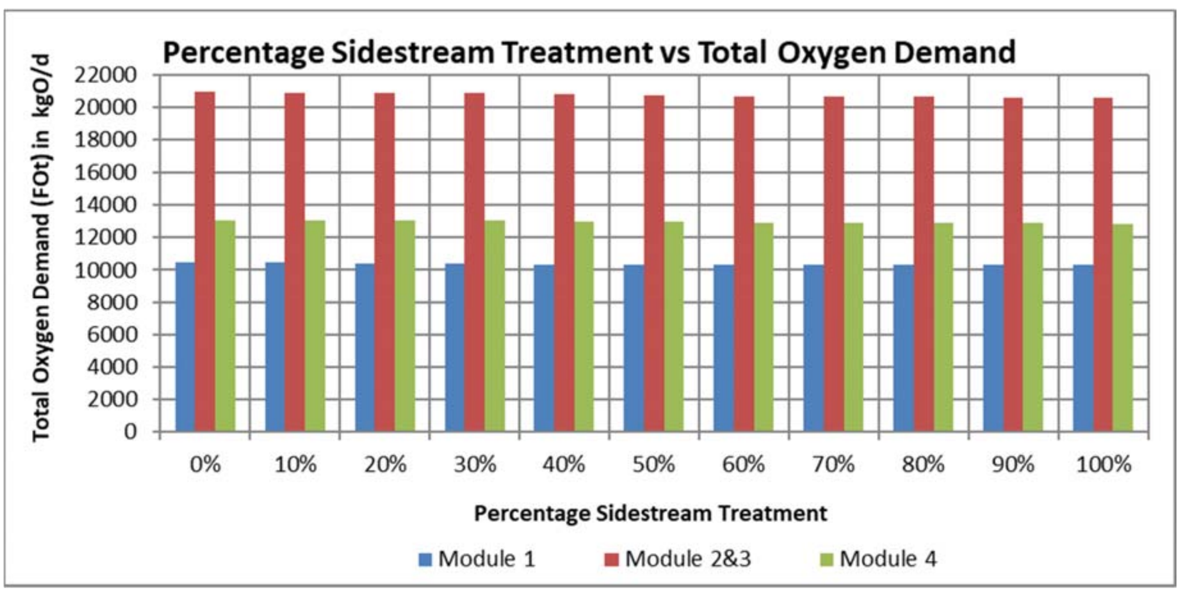

Figure 7: Impact of side-stream treatment on total oxygen demand at 'W' WWTP

1.3.3 Secondary Sludge Produced

The impact of percentage side-stream treatment on secondary sludge production from the AS system is illustrated below in Figure 8. The secondary sludge production for each module decreases along with side-stream treatment capacity. Secondary sludge production for Module 1 decreases from 7 109 kgTSS/d to 5 182 kgTSS/d, Modules 2 & 3 decreases from 13 267 kgTSS/d to 11 564 kg/d and for Module 4 decreases from 8 347 kgTSS/d to 7 228 kgTSS/d.

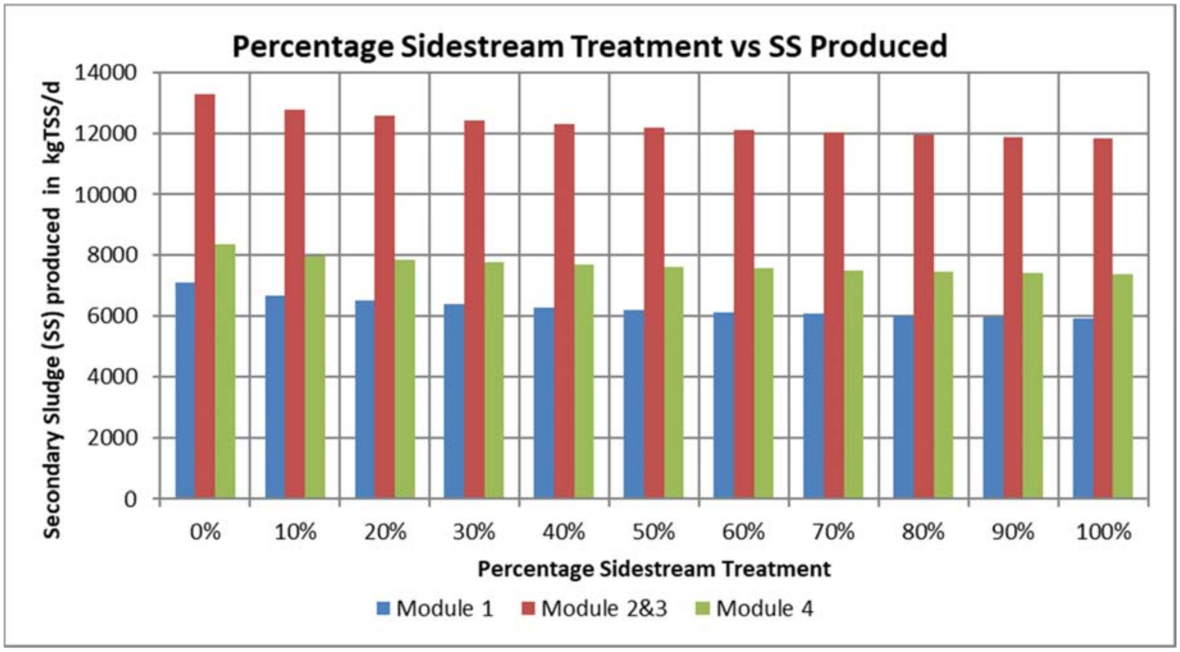

Figure 8: Impact of side-stream treatment on secondary sludge production at 'W' WWTP

1.4 Biological Effluent Quality

The biological effluent quality parameters impacted on be sludge return flows are:

- COD Concentration
- Ammonia Concentration
- Phosphates Concentration

1.4.1 Effluent COD Concentration

The impact of percentage side-stream treatment on the effluent COD from the AS system is illustrated below in Figure 9. The effluent COD concentration from Modules 1, 2 & 3 and 4 remains close to 70 mgCOD/ℓ with no variation. This predicted value is the COD concentration of the unbiodegradable organics from the influent, assuming that all influent biodegradable soluble organics have been utilised in the AS system.

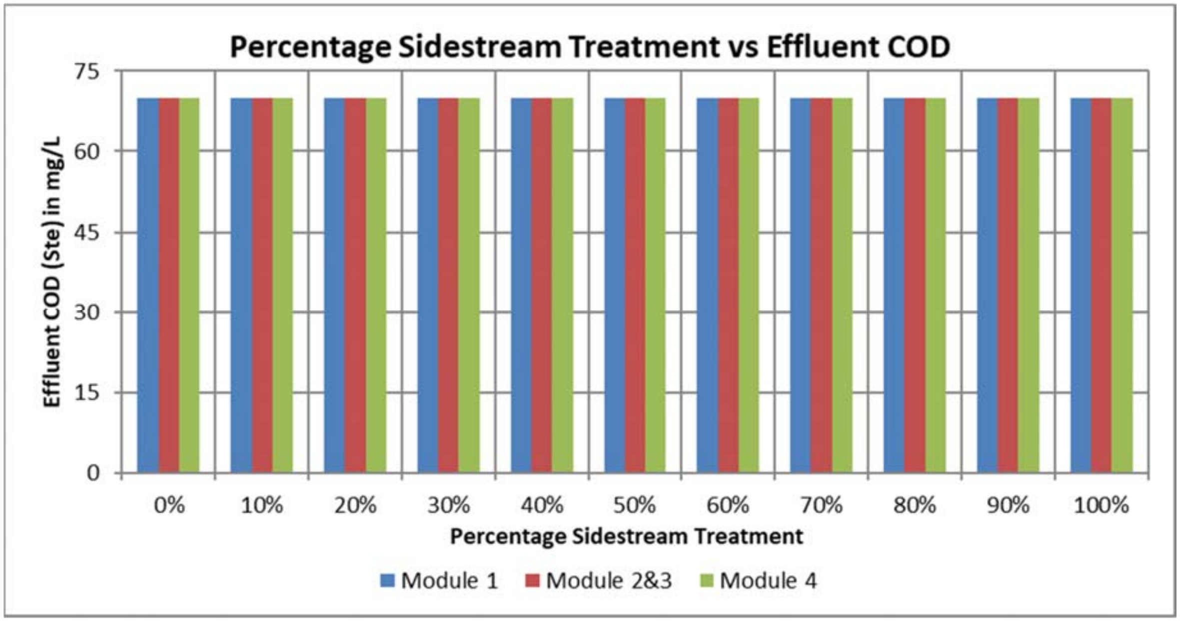

Figure 9: Impact of side-stream treatment on effluent COD at 'W' WWTP

1.4.2 Effluent Ammonia Concentration

The impact of percentage side-stream treatment on the effluent ammonia from the AS system is illustrated below in Figure 10. The effluent ammonia concentration from all modules remains constant at 2.20 mg/ℓ.

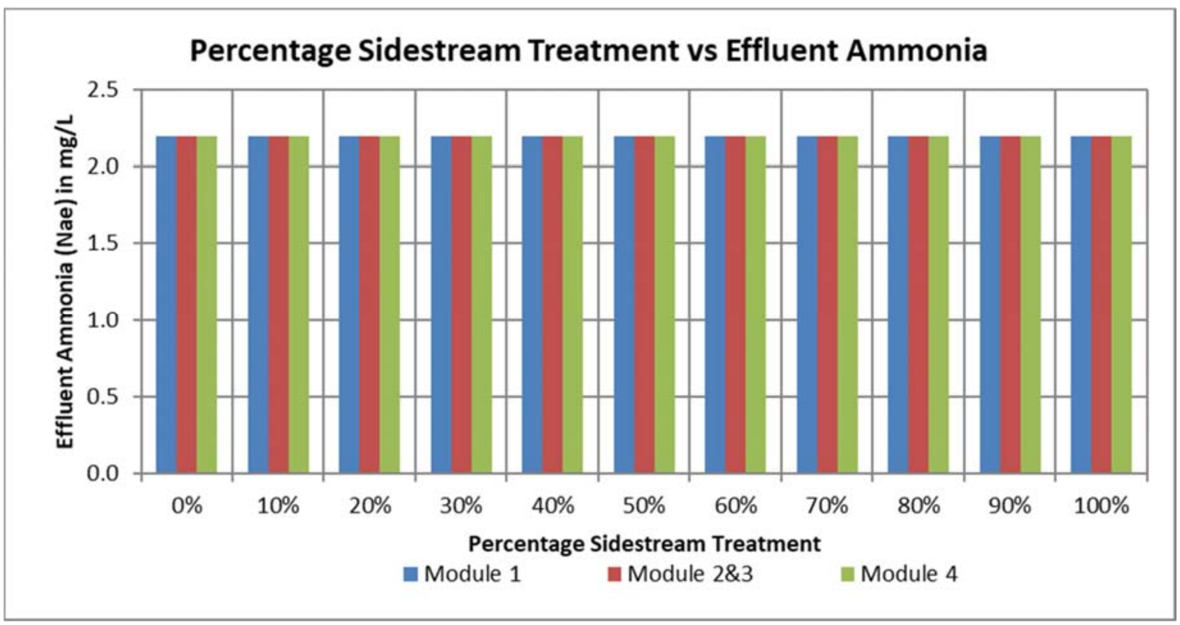

Figure 10: Impact of side-stream treatment on effluent ammonia at 'W' WWTP

1.4.3 Effluent Nitrate Concertation

The impact of percentage side-stream treatment on the effluent nitrate concentration from the AS system is illustrated below in Figure 11. The effluent nitrate concentration from Modules 1, 2 & 3 and 4 decrease respectively from 6.43 to 6.09 mg/ℓ; 6.47 to 6.09 mg/ℓ and 6.46 to 6.09 mg/ℓ.

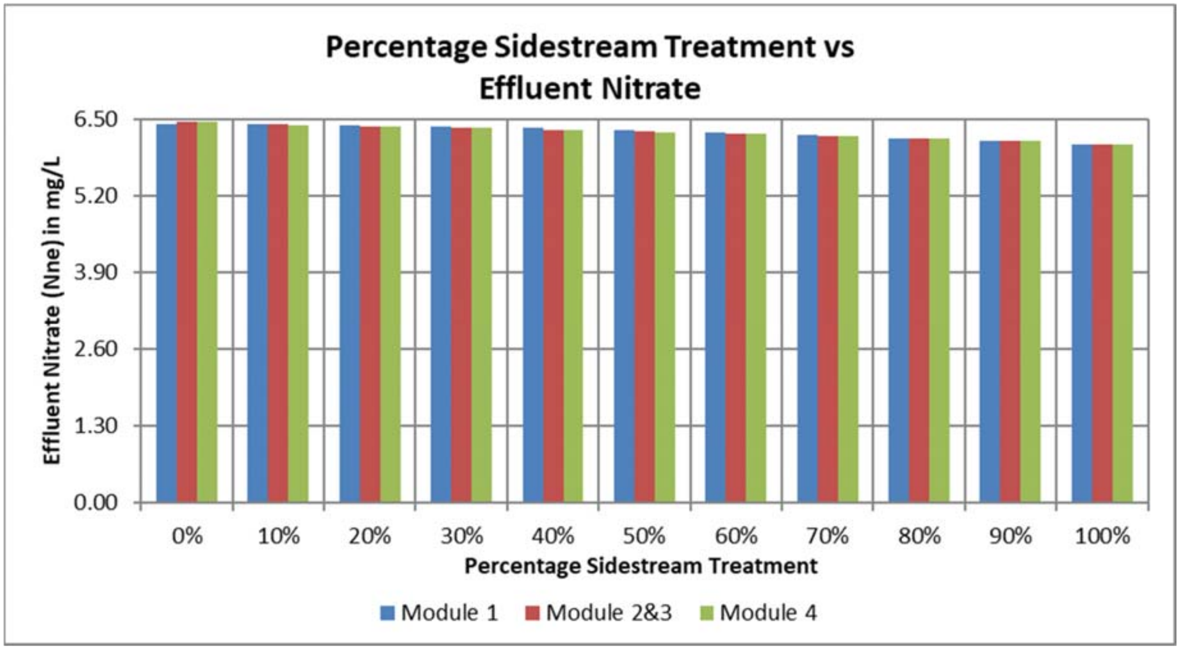

Figure 11: Impact of side-stream treatment on effluent nitrate at 'W' WWTP

1.4.4 Effluent Ortho-Phosphates Concentration

The side-stream treatment has no predicted impact on the effluent phosphates as the effluent OP remains constant at 0 mgP/ℓ.

1.5 Summary of Impacts of SLR on the 'W' WWTP AS System

Table 3 below summarises the percentage impact at a given percentage side-stream treatment starting from 0% to 100% side-stream treatment. The table shows both the average impact and the impact for each module at Plant 'W'.

Table 3: Percentage impact at given percentage side-stream treatment

Percentage Impact at given Percentage Side-stream Treatment at 'W' WWTP							
	Parameter	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Influent	**Flow rate (Average)**	**4.2%**	**3.3%**	**2.5%**	**1.7%**	**0.8%**	**0.0%**
	Module 1	2.4%	1.9%	1.4%	0.9%	0.5%	0.0%
	Module 2&3	4.9%	3.9%	2.9%	2.0%	1.0%	0.0%
	Module 4	5.3%	4.2%	3.2%	2.1%	1.1%	0.0%
	COD (Average)	**0.67%**	**0.5%**	**0.4%**	**0.3%**	**0.1%**	**0.0%**
	Module 1	0.38%	0.30%	0.23%	0.15%	0.08%	0.00%
	Module 2&3	0.78%	0.63%	0.47%	0.31%	0.16%	0.00%
	Module 4	0.84%	0.67%	0.51%	0.34%	0.17%	0.00%
	Ammonia (Average)	**9.1%**	**7.5%**	**5.7%**	**3.8%**	**2.1%**	**0.0%**
	Module 1	7.1%	6.4%	5.1%	3.6%	1.9%	0.0%
	Module 2&3	9.9%	7.9%	6.2%	4.2%	2.1%	0.0%
	Module 4	10.1%	8.1%	5.7%	3.7%	2.2%	0.0%
	PO_4 (Average)	**234.7%**	**117.0%**	**73.3%**	**41.9%**	**18.4%**	**0.0%**
	Module 1	315.8%	159.5%	100.4%	57.6%	25.3%	0.0%
	Module 2&3	191.1%	95.2%	59.7%	34.1%	14.9%	0.0%
	Module 4	197.3%	96.4%	59.9%	34.1%	14.9%	0.0%
Biological Reactor	**a-recycle (Average)**	**-29.5%**	**-25.1%**	**-20.3%**	**-14.5%**	**-7.7%**	**0.0%**
	Module 1	-24.7%	-22.1%	-18.3%	-13.2%	-7.0%	0.0%
	Module 2&3	-31.2%	-26.4%	-21.2%	-15.0%	-8.0%	0.0%
	Module 4	-32.5%	-26.7%	-21.5%	-15.3%	-8.1%	0.0%
	Total Oxygen Demand (Ave.)	**2.2%**	**1.8%**	**1.4%**	**0.9%**	**0.5%**	**0.0%**
	Module 1	1.7%	1.5%	1.2%	0.8%	0.4%	0.0%
	Module 2&3	2.6%	1.9%	1.5%	1.0%	0.5%	0.0%
	Module 4	2.4%	1.9%	1.5%	1.0%	0.5%	0.0%
	Power Requirement (Ave.)	**2.2%**	**1.8%**	**1.4%**	**0.9%**	**0.5%**	**0.0%**
	Module 1	1.7%	1.5%	1.2%	0.8%	0.4%	0.0%
	Module 2&3	2.6%	1.9%	1.5%	1.0%	0.5%	0.0%
	Module 4	2.4%	1.9%	1.5%	1.0%	0.5%	0.0%
	SS Produced	**15.1%**	**7.6%**	**4.8%**	**2.7%**	**1.2%**	**0.0%**
	Module 1	20.2%	10.2%	6.4%	3.7%	1.6%	0.0%
	Module 2&3	12.1%	6.3%	4.0%	2.3%	1.0%	0.0%
	Module 4	12.9%	6.4%	4.0%	2.3%	1.0%	0.0%
Effluent	**COD Average**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Module 1	107.7%	107.4%	86.9%	61.2%	31.8%	0.0%
	Module 2&3	146.2%	131.0%	102.7%	70.9%	36.5%	0.0%
	Module 4	148.6%	133.0%	104.4%	72.2%	37.2%	0.0%
	NO_3	**6.1%**	**5.1%**	**4.1%**	**2.9%**	**1.5%**	**0.0%**
	Module 1	5.7%	5.3%	4.4%	3.2%	1.7%	0.0%
	Module 2&3	6.4%	5.0%	4.0%	2.8%	1.5%	0.0%
	Module 4	6.1%	4.9%	4.0%	2.8%	1.5%	0.0%
	PO_4 (Average)	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

Figure 12 below shows the SRL impact on 'W' WWTP at 0% side-stream treatment. The highest impact was observed for influent phosphate load at 235% the effluent ammonia concentration.

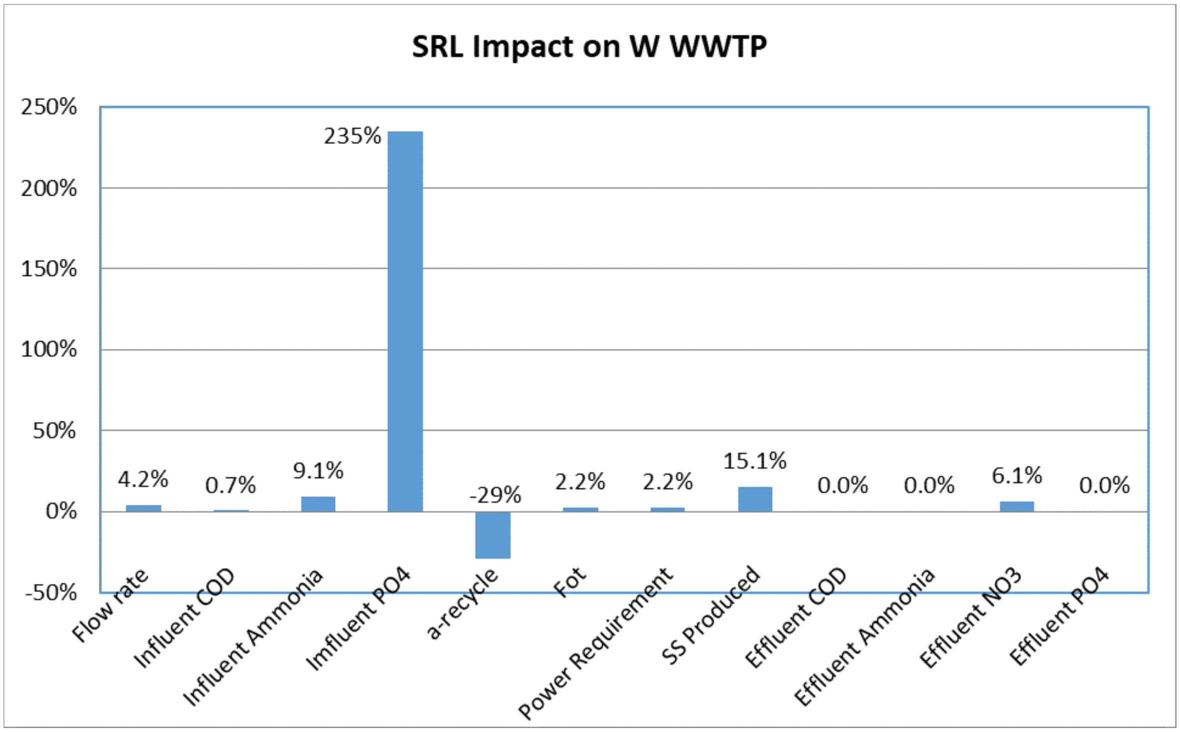

Figure 12: SRL Impact on 'W' WWTP at 0% side-stream treatment

CHAPTER 2: ‘Z’ WWTP

The results of the impact of return sludge liquors at ‘Z’ WWTP are presented in this section. The impact of the sludge return flows was determined on:

- Influent Characteristics
- Biological Treatment Capacity
- Biological Effluent Quality

2.1 Process Description

A description of the ‘Z’ WWTP is indicated below as per information found in the operation and maintenance manuals for Modules 1 and Module 2. Table 4 and Table 5 give a summary of the unit operations and process data. A general process flow diagram of the works in indicated below in Figure 13. SRL is returned to Module 2. At the current flow, Modules 1 & 2 have design capacity of 45 Mℓ/d and 40 Mℓ/d respectively.

Table 4: ‘Z’ WWTP Unit Operations and Processes

Key Unit Operations and Processes	Module 1	Module 2
Primary Settling Tanks	Yes	Yes
BNR System	Yes	Yes
Secondary Settling Tanks	Yes	Yes
Fermenters	Yes	Yes
Dissolved Air Flotation	Yes	Yes
Anaerobic Digesters	Yes	Yes
Dewatering	Yes	Yes

The pertinent data for the above unit operations and processes is summarised in Table 5.

Table 5: ‘Z’ WWTP Data Summary

Key Unit Operations and Processes	Module 1	Module 2
Primary Settling Tanks diameter	4 × 22 m	3 × 25 m
Balancing Tank Volume (m^3)	5 000	12 000
BNR System Volume (m^3)	2 × 19 575	2 × 19 575
Secondary Settling Tank Diameter	4 × 32 m	4 × 35 m
DAF Units	1 Unit	
Anaerobic Digesters	2 × 6 000 + 2 × 5 380 m^3	

SLR treatment consists of:

- Dewatering return liquors conveyed to two precipitation tanks where lime slurry is dosed to increase the pH and precipitate orthophosphate. The same precipitation tanks were designed to strip ammonia.
- The precipitate is settled out via two sedimentation/thickening tanks (10 m diameter each).
- The thickened sludge is transported to the day tank and the treated return liquors are pumped to the beginning of Module 2 PSTs.

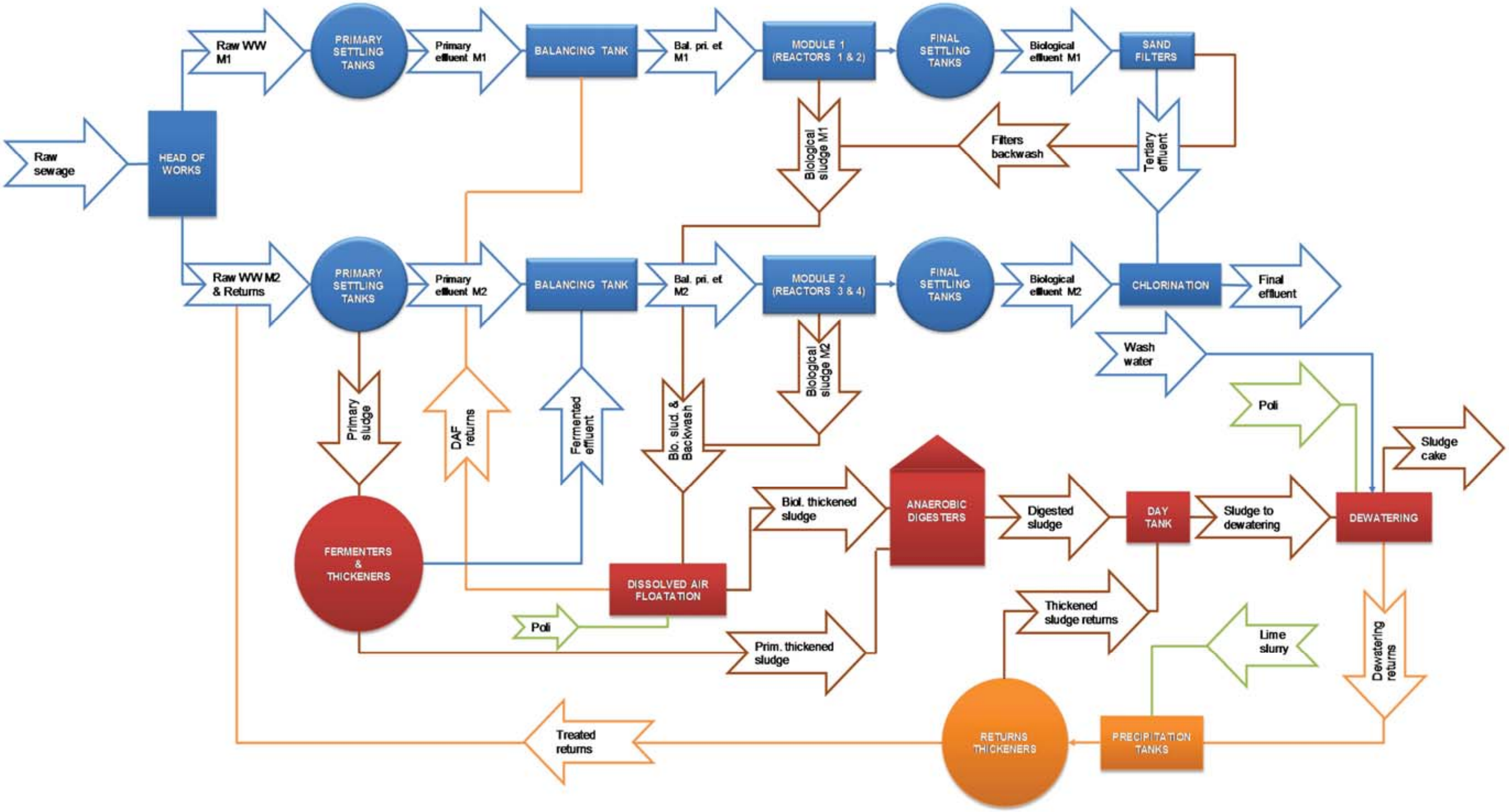

Figure 13: 'Z' WWTP Process Flow Diagram

2.2 Impact of SRL on the Influent Characteristics on Module 2 at 'Z' WWTP

The influent characteristics impacted on by sludge return flows are:

- Influent flow rate
- Influent COD load
- Influent ammonia load
- Influent PO_4 load

The impact of SRL on each of the above influent characteristics is summarised here and Figure 14 illustrates the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line of Module Influent Flow Rate 2.

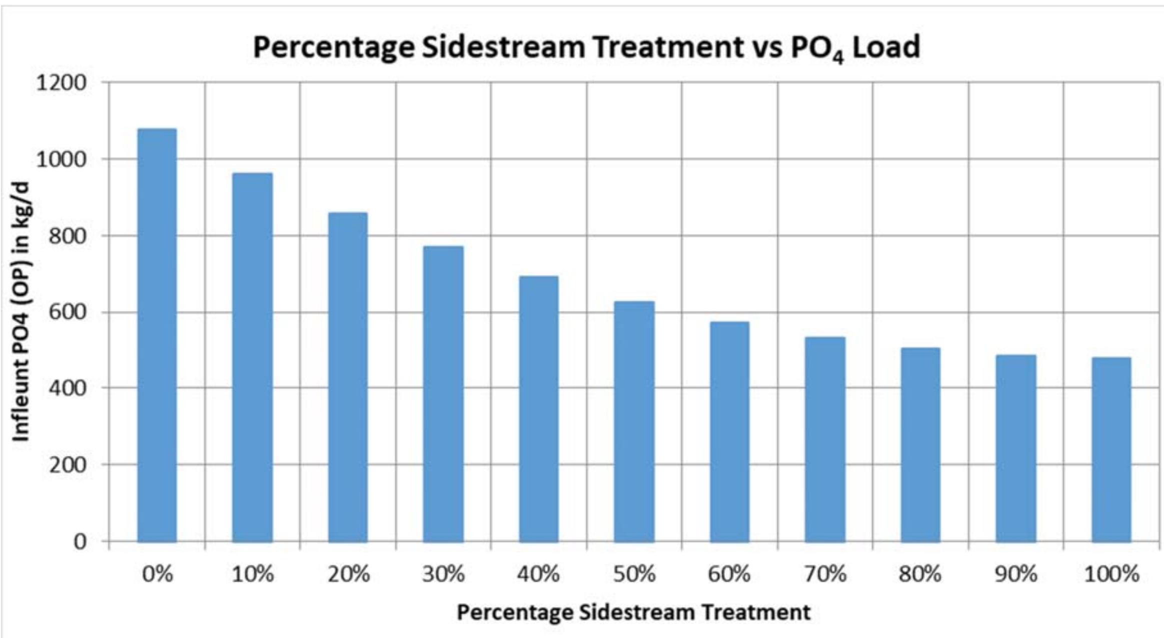

Figure 14: Impact of side-stream treatment on Module 2 influent phosphate at 'Z' WWTP

The impact of percentage side-stream treatment on the flow rate is illustrated below in Figure 15. Without side-stream treatment, i.e. 0% side-stream treatment, 100% of return sludge liquors flow back to the AS system and the treated SRL is discharged to the final effluent. The flow to Module 2 decreases along with side-stream treatment from 63 Mℓ/d to 58 Mℓ/d.

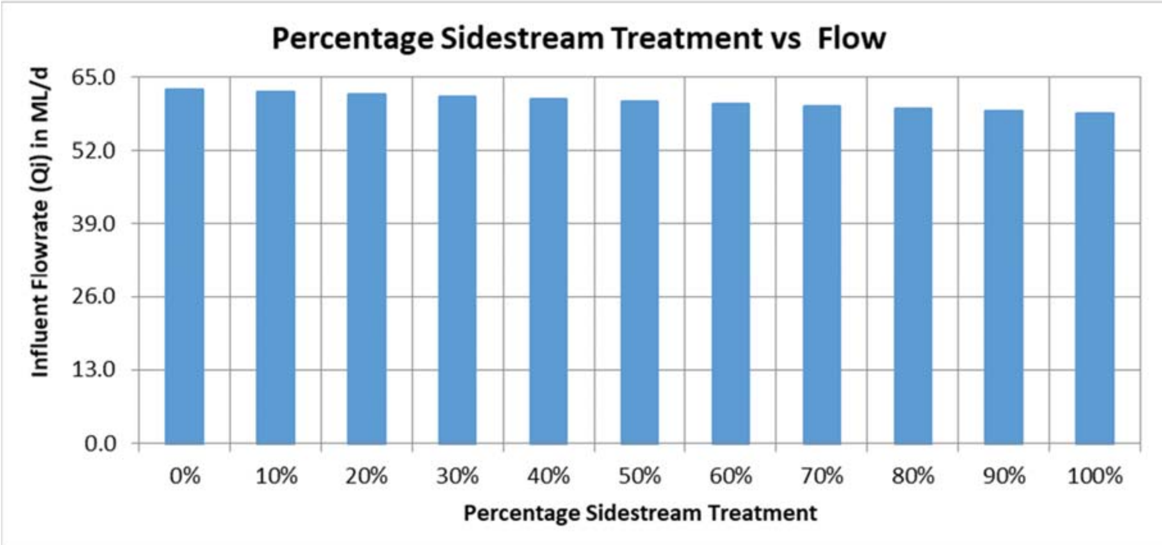

Figure 15: Impact of side-stream treatment on Module 2 influent flow at 'Z' WWTP

2.2.1 *Influent COD Load*

The impact of percentage side-stream treatment on the total influent COD load to the AS system is illustrated in Figure 16 below. Influent COD load to Module 2 decreases from 26 512 mgCOD/ℓ to 26 284 kgCOD/d.

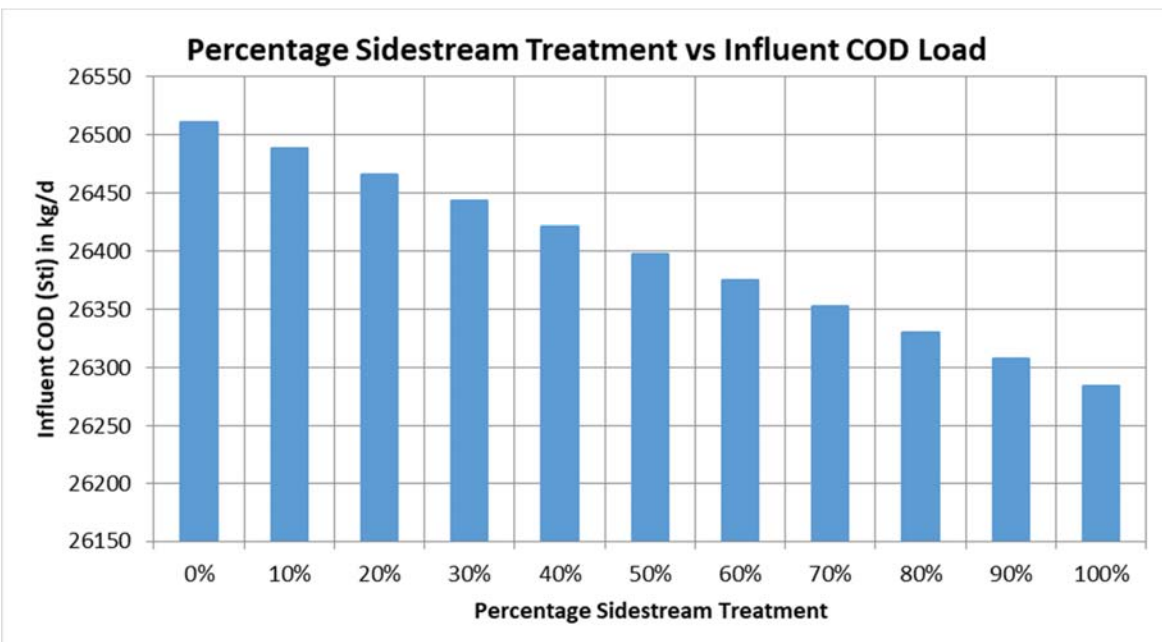

Figure 16: Impact of side-stream treatment on Module 2 influent COD at 'Z' WWTP

2.2.2 *Influent Ammonia Load*

The impact of percentage side-stream treatment on the influent ammonia load to the AS system is illustrated below in Figure 17 below. Influent ammonia load to Module 2 decreases from 2 926 kgN/d to 2,529 kgN/d, this trend is similar to the model predictions for the other plants.

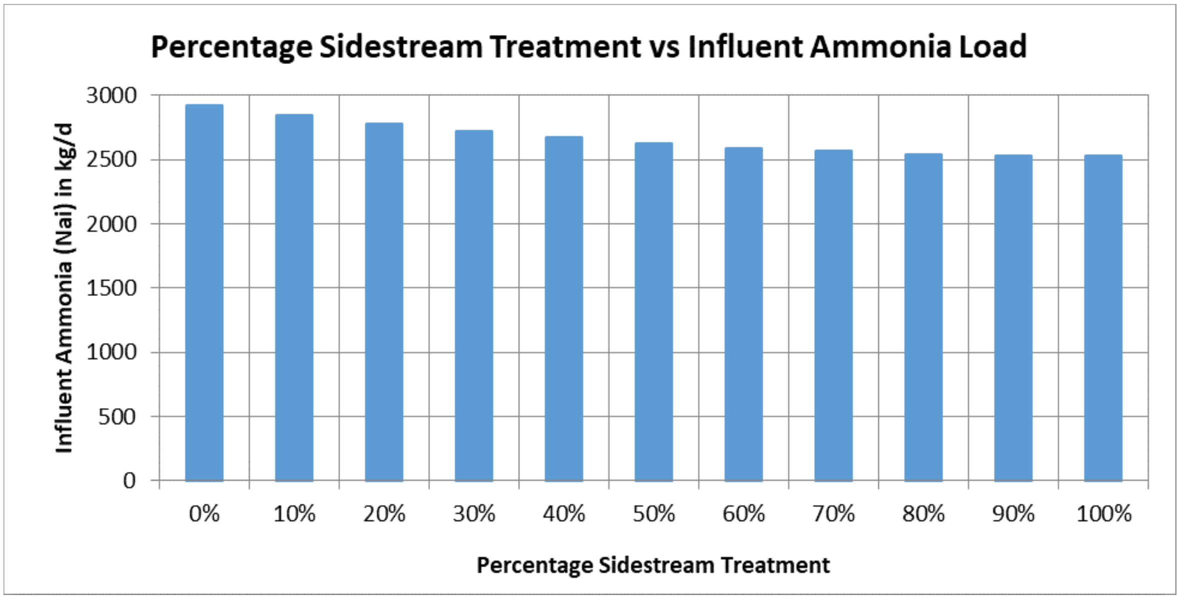

Figure 17: Impact of side-stream treatment on Module 2 influent ammonia at 'Z' WWTP

2.2.3 *Influent Phosphate Load*

The impact of percentage side-stream treatment on influent phosphate load to the AS system is illustrated in below in Figure 18.

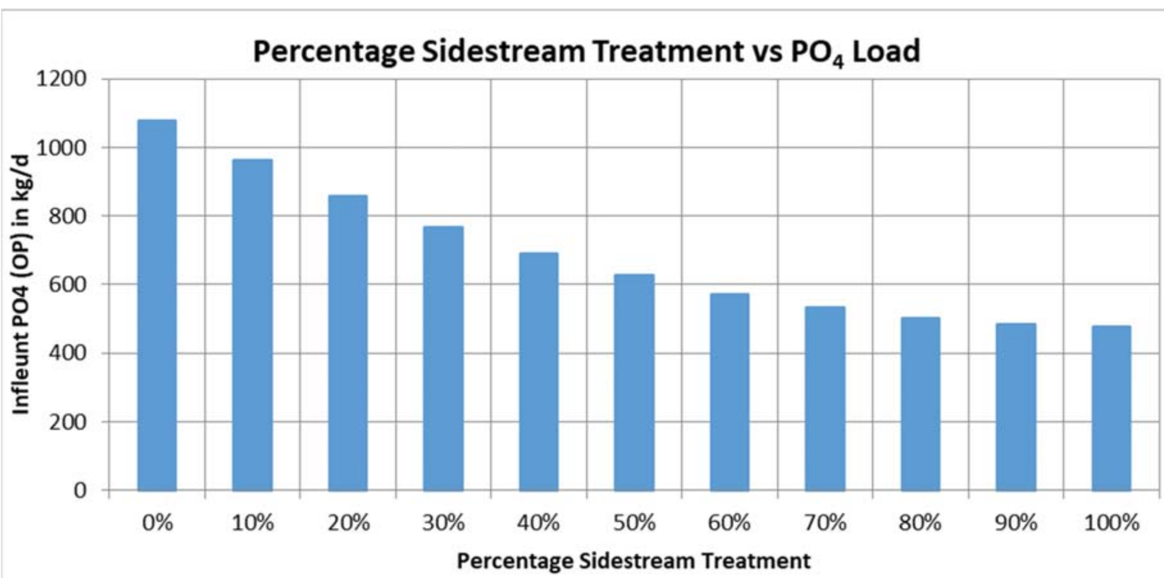

Figure 18: Impact of side-stream treatment on Module 2 influent phosphate at 'Z' WWTP

Influent phosphate load to Module 2 decreases from 1 077 kgP/d to 479 kgP/d. This trend is similar to the model predictions for the other plants. It is important to note that Module 2 at Plant 'Z' receives all the SRL from sludge treated for both modules.

2.3 Impact of SRL on Biological Treatment Capacity on 'Z' WWTP Module 2 AS System

The biological treatment capacity parameters impacted on by sludge return flows are:

- A-recycle
- Total oxygen demand
- Secondary sludge production

The impact of SRL on each of the above biological treatment capacity parameters is summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

2.3.1 A-recycle

The impact of percentage side-stream treatment on the a-recycle to the AS system is illustrated below in Figure 19. The a-recycle ratio for Module 2 increases from 3.68 Mℓ/d to 7.51 Mℓ/d. This trend is similar to that observed in the other plants.

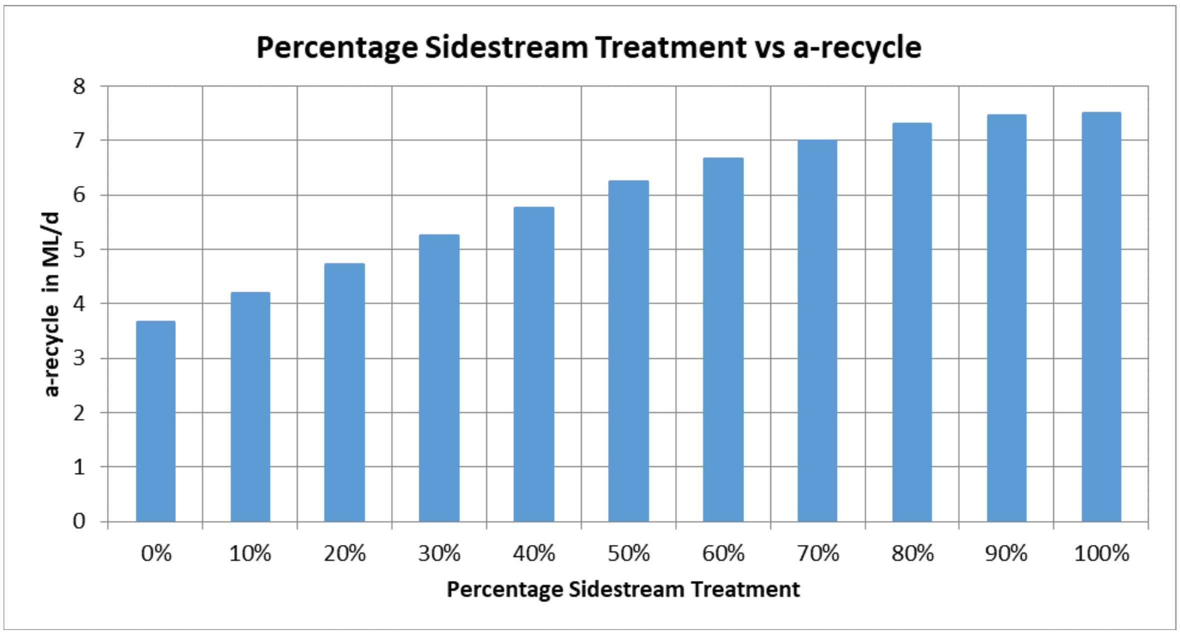

Figure 19: Impact of side-stream treatment on Module 2 a-recycle at 'Z' WWTP

2.3.2 Total Oxygen Demand

The impact of percentage side-stream treatment on the total oxygen demand (FOt) for the AS system is illustrated below in Figure 20. The FOt for Module 2 decreases along with side-stream treatment capacity from 22 569 kgO/d to 21 607 kgO/d.

The aeration power requirement for each module decreases along with side-stream treatment. Aeration power requirement for Module 1 decreases from 96 kW to 93 kW, Module 2's decreases from 496 kW to 474 kW. Similar trend is observed in the other plants.

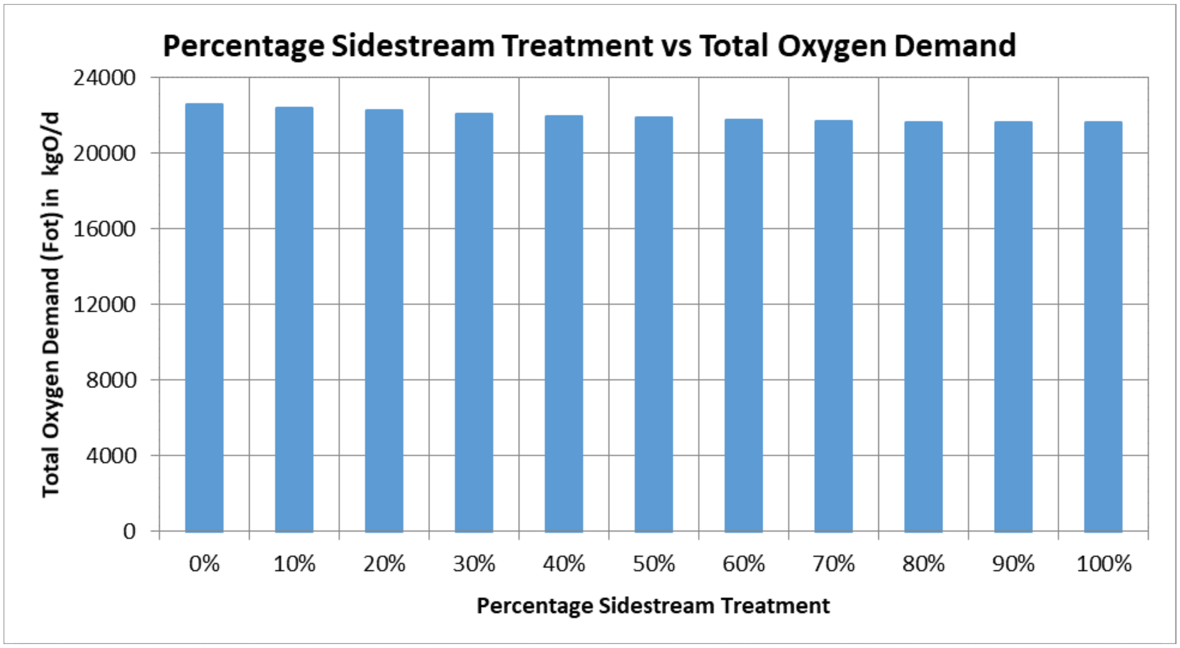

Figure 20: Impact of side-stream treatment on Module 2 total oxygen demand at 'Z' WWTP

2.3.3 Secondary Sludge Produced

The impact of percentage side-stream treatment on secondary sludge production in the AS system is illustrated below in Figure 21. Secondary sludge production in Module 2 AS system decreases marginally along with side-stream treatment from 7 174 kgTSS/d to 7 171 kgTSS/d.

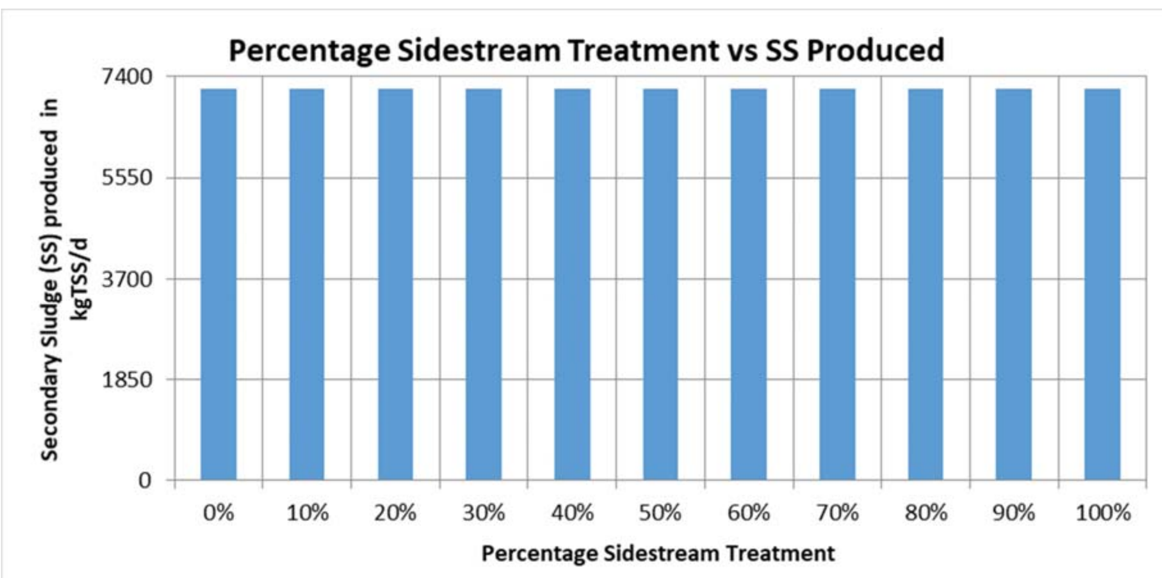

Figure 21: Impact of side-stream treatment on Module 2 secondary sludge production at 'Z' WWTP

2.4 *Impact of SRL on Biological Effluent Quality from Module 2 at 'Z' WWTP*

The biological effluent quality parameters impacted on be sludge return flows are:

- COD Concentration
- Ammonia Concentration
- Nitrates Concentration
- Phosphate Concentration

The impact of SRL on each of the above biological effluent parameters is summarised in this section. Figures below illustrate the impact of sludge return flows on biological effluent quality for a given percentage side-stream treatment (0% to 100% side-stream treatment).

2.4.1 *Effluent COD Concentration*

The impact of percentage side-stream treatment on the effluent COD from the AS system is illustrated below in Figure 22. The effluent COD concentration remains constant at 52 mgCOD/ℓ. This is the unbiodegradable soluble organics COD that is ideally the sole organic component found in the AS. This trend is similar in to other plants.

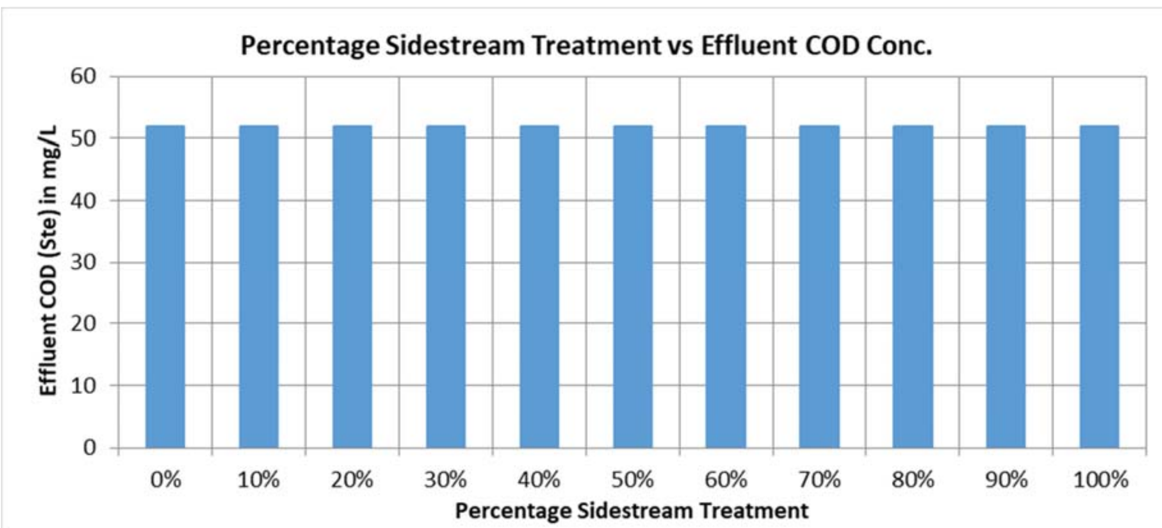

Figure 22: Impact of side-stream treatment on Module 2 effluent COD at 'Z' WWTP

2.4.2 *Effluent Ammonia Concentration*

The impact of percentage side-stream treatment on the effluent ammonia from the AS system is illustrated below in Figure 23. The effluent ammonia concentration remains constant at 0.66 mgN/ℓ. This trend is similar to trends in other plants.

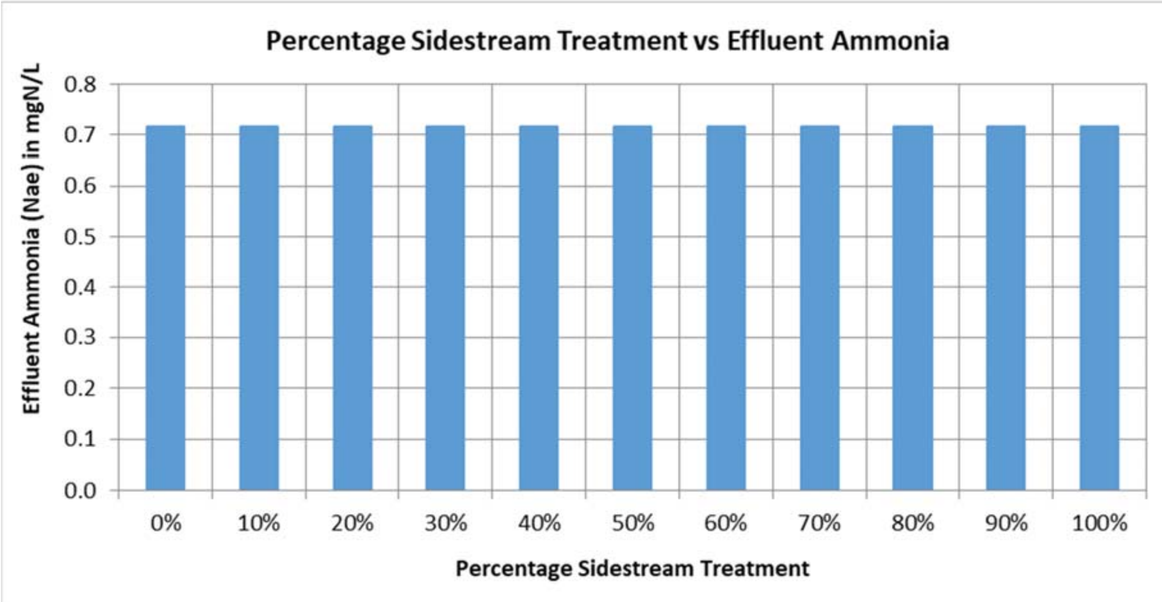

Figure 23: Impact of side-stream treatment on effluent ammonia at 'Z' WWTP

2.4.3 *Effluent Nitrate Concertation*

Figure 24 illustrates the effluent nitrate concentration which decreases marginally, from around 11.1 mgN/ℓ to 10.2 mgN/ℓ. A high effluent nitrate can contribute significantly to poor effluent quality, directly or indirectly. The trend is similar to other plants.

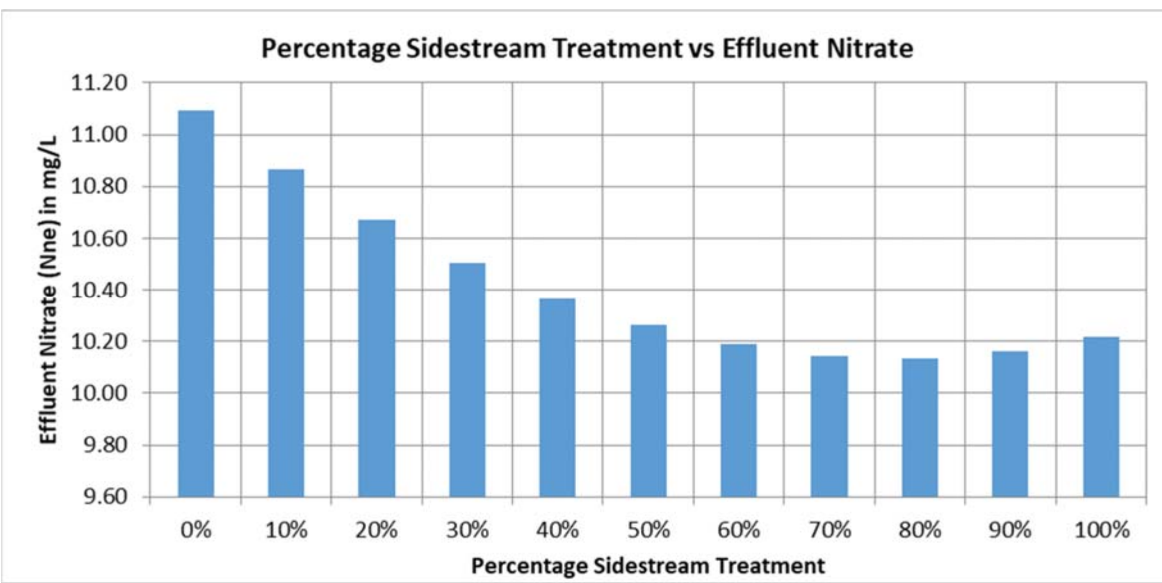

Figure 24: Impact of side-stream treatment on effluent nitrates at 'Z' WWTP

2.4.4 *Effluent Phosphate Concentration*

The impact of percentage side-stream treatment on the effluent phosphate from the secondary settling tank is illustrated below in Figure 25. The effluent phosphate concentration from Module 2 decreases from 11 mgP/ℓ to 1 mgP/ℓ. The results are as indicated because flux of phosphates into the system is beyond the removal capacity of the PAO biomass generated in the. Hence, the influent *P* that is not removed, i.e.

used as nutrients for biomass growth or as PP accumulated by PAOs, reflects in the effluent. The trend is similar to other plants.

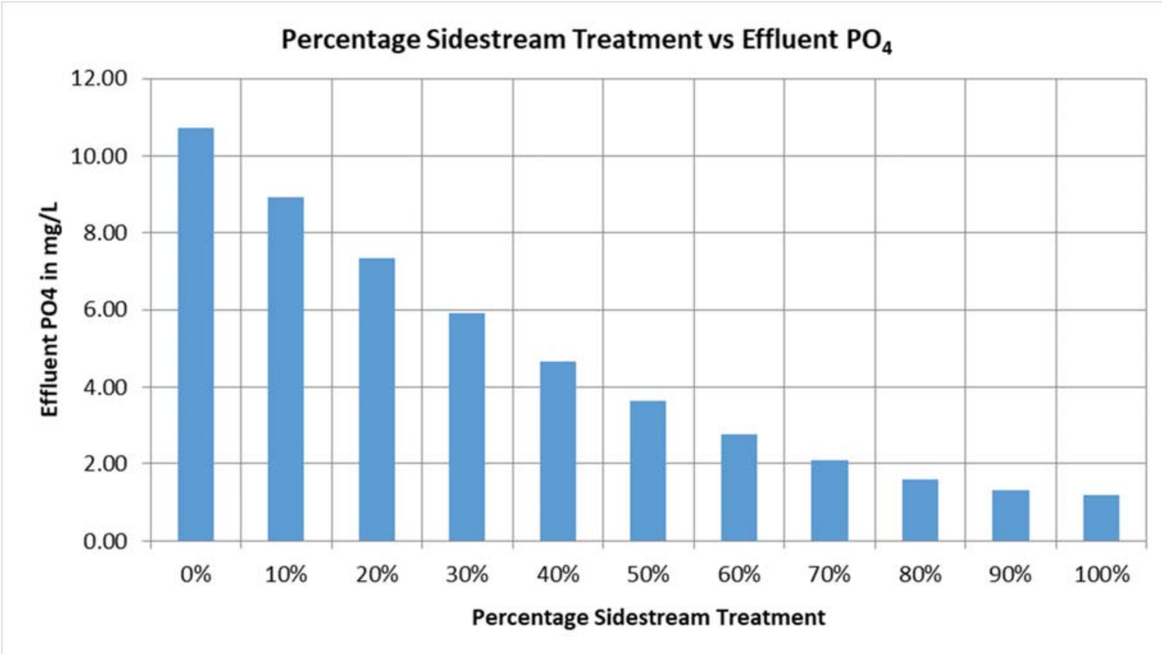

Figure 25: Impact of side-stream treatment on effluent phosphate at 'Z' WWTP

2.5 Summary of Impacts of SRL on the 'Z' WWTP AS System

Table 6 below summarises the percentage impact at a given percentage side-stream treatment starting from 0% to 100% side-stream treatment at 'Z' WWTP.

Table 6: Percentage impact at given percentage side-stream treatment

Percentage Impact at given Percentage Side-stream Treatment at 'Z' WWTP							
Parameters		0%	20%	40%	60%	80%	100%
Influent	Flow rate	7.5%	6.0%	4.5%	3.0%	1.5%	0.0%
	COD	0.9%	0.7%	0.5%	0.3%	0.2%	0.0%
	Ammonia	15.7%	10.0%	5.6%	2.5%	0.6%	0.0%
	PO_4	124.8%	79.3%	44.3%	19.6%	4.9%	0.0%
Biological Reactor	a-recycle	-51.0%	-37.1%	-23.2%	-11.3%	-2.6%	0.0%
	Total Oxygen Demand	4.5%	2.9%	1.6%	0.7%	0.2%	0.0%
	Power Requirement	4.5%	2.9%	1.6%	0.7%	0.2%	0.0%
	SS Produced	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	8.5%	4.4%	1.5%	-0.3%	-0.8%	0.0%
	PO_4	790.1%	508.7%	288.4%	129.5%	32.8%	0.0%

Figure 27 below shows the SRL impact on 'Z' WWTP at 0% side-stream treatment. The major impact was observed for influent PO_4 load and effluent PO_4 were the impact was 125% and 790% respectively.

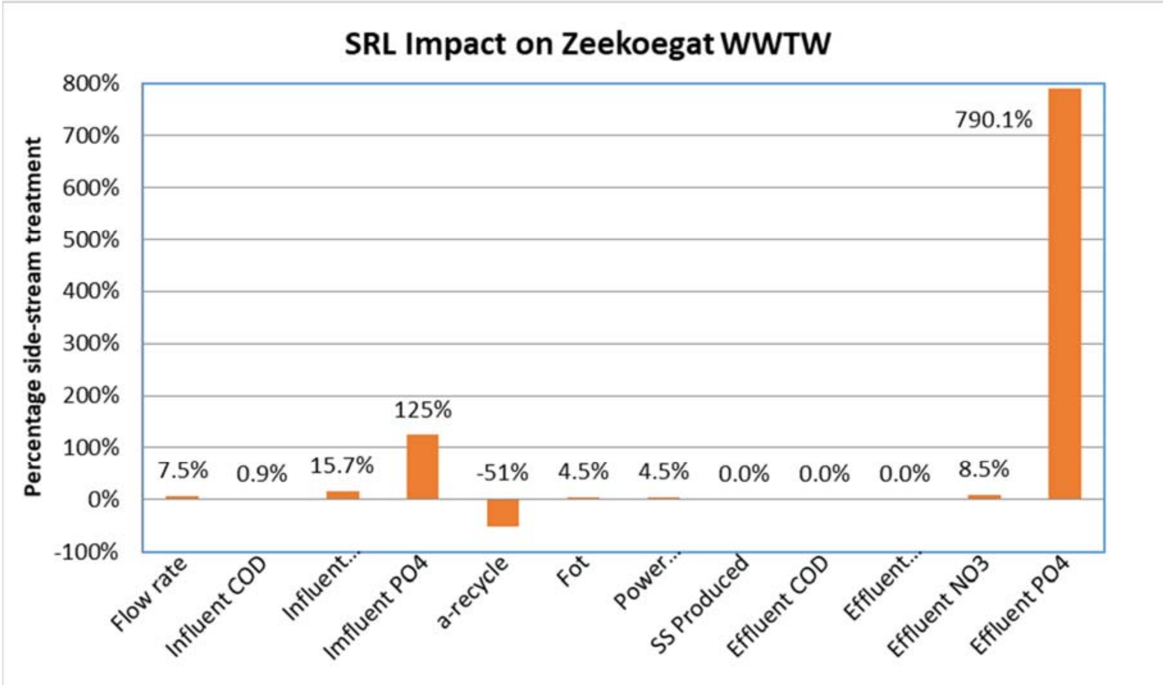

Figure 26: SRL impact on 'Z' WWTP at 0% side-stream treatment.

CHAPTER 3: ‘P’ WWTP

The results of the impact of return sludge liquors at ‘P’ WWTP are presented in this section. The impact of the sludge return flows was determined on:

- Influent Characteristics
- Biological Treatment Capacity
- Biological Effluent Quality

3.1 Process Description

A description of the ‘P’ WWTP is indicated below as per information found in the operation and maintenance manuals. Table 7 and Table 8 give a summary of the unit operations and process data. The general process flow diagram of the works in indicated below in Figure 27, ‘P’ WWTP has a design capacity of 25 Mℓ/d.

Table 7: ‘P’ WWTP Unit Operations and Processes

Key Unit Operations and Processes	AS System
Primary Settling Tanks	Yes
BNR System	Yes
Secondary Settling Tanks	Yes
Dissolved Air Flotation	No
Anaerobic Digesters	Yes
Dewatering	Yes

The pertinent data for the above unit operations and processes is summarised in Table 8.

Table 8: ‘P’ WWTP Data Summary

Key Unit Operations and Processes	AS System
Primary Settling Tanks diameter	4 Units
BNR System Volume (m³)	25 000
Secondary Settling Tank Diameter	6 Units
Anaerobic Digesters	2 × 2 600m³ + 3 × 510m³ (secondary digesters) + 5 380m³

SRL treatment consists of:

- Dewatering sludge return liquors recycles upstream of the primary settling tanks.

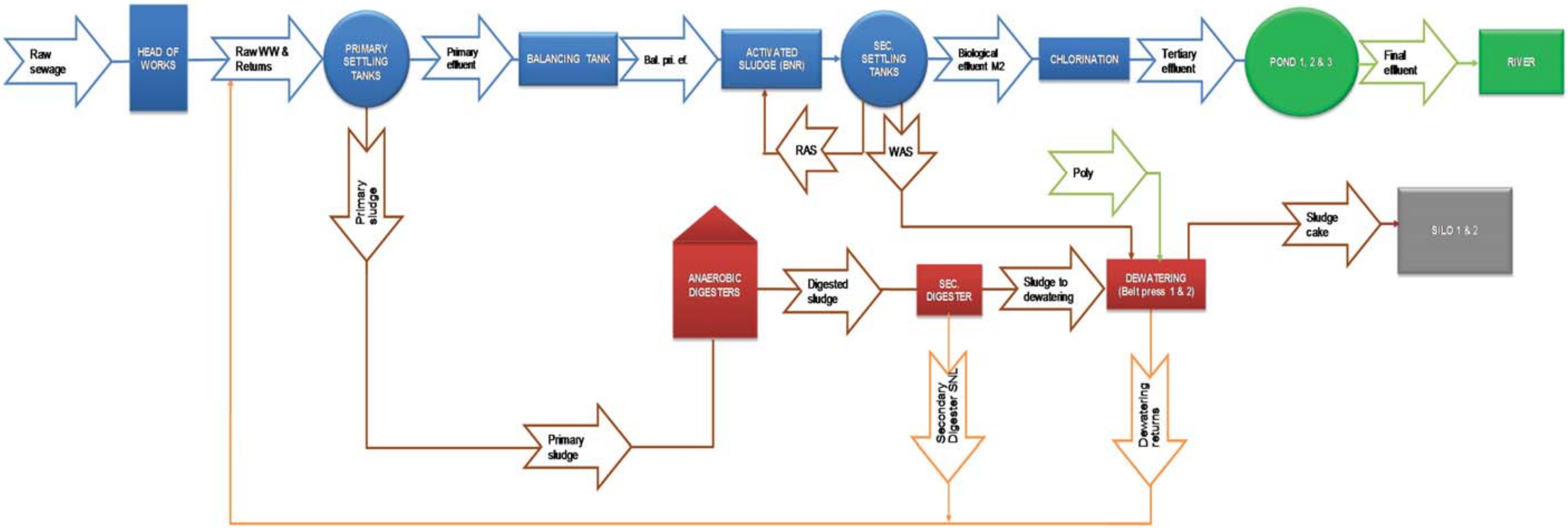

Figure 27: 'P' WWTP Process Flow Diagram

3.2 Influent Characteristics

The influent characteristics impacted on by sludge return flows are:

- Influent flow rate
- Influent COD Load
- Influent Ammonia Load
- Influent PO_4 Load

The impact of SRL on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

3.2.1 Influent Flow rate

The impact of percentage side-stream treatment on the flowrate is illustrated below in Figure 28. Without side-stream treatment, i.e. 0% side-stream treatment, means that 100% of return sludge liquors flow back to the AS system. The flow to the water line module decreases along with side-stream treatment from 25 Mℓ/d to 24 Mℓ/d.

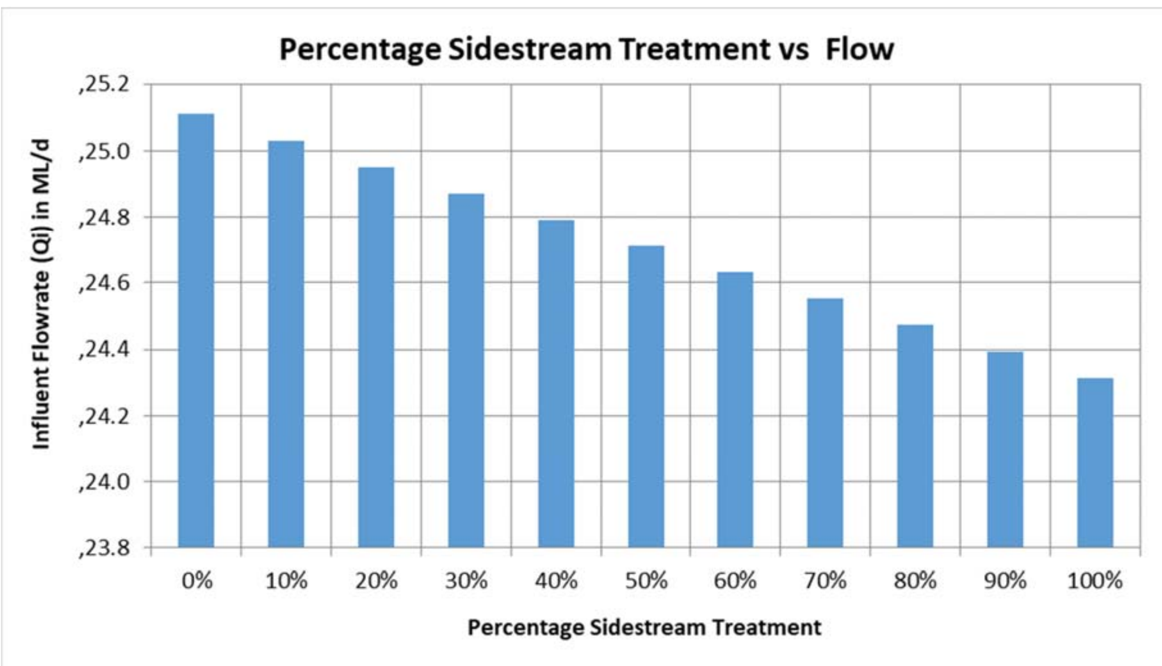

Figure 28: Impact of side-stream treatment on influent flow rate at 'P' WWTP

3.2.2 Influent COD Load

The impact of percentage side-stream treatment on the influent COD load to the AS system is illustrated below in Figure 29. Influent COD load to the AS system decreases from 10 733 to 10 694 kgCOD/d.

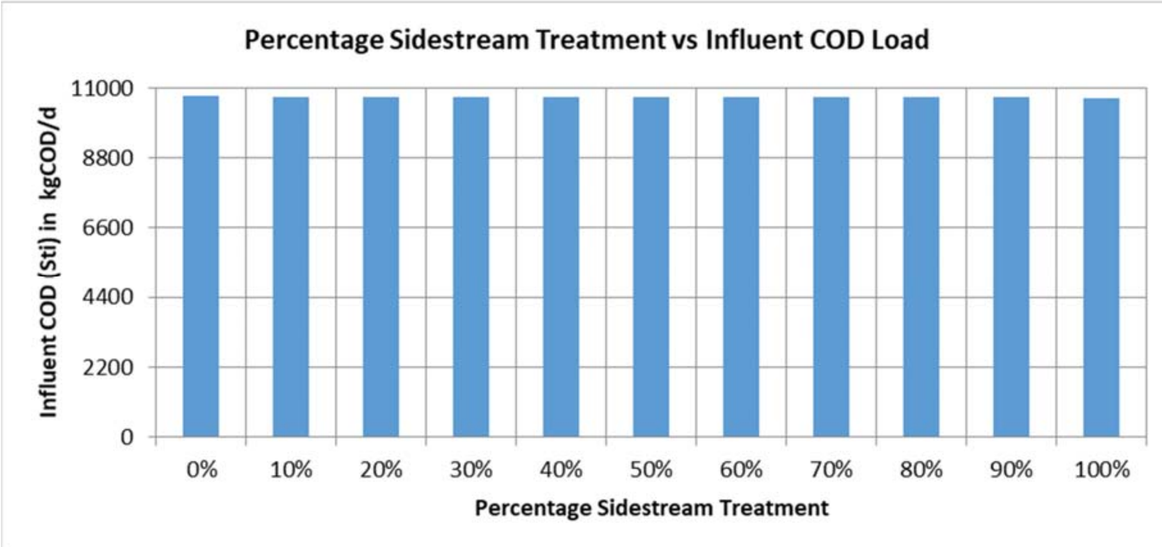

Figure 29: Impact of side-stream treatment on influent COD load at 'P' WWTP

3.2.3 Influent Ammonia Load

The impact of percentage side-stream treatment on the influent ammonia load to the AS system is illustrated below in Figure 30. Influent ammonia load to AS system decreases from 1 149 kgN/d to 1 041 kgN/d.

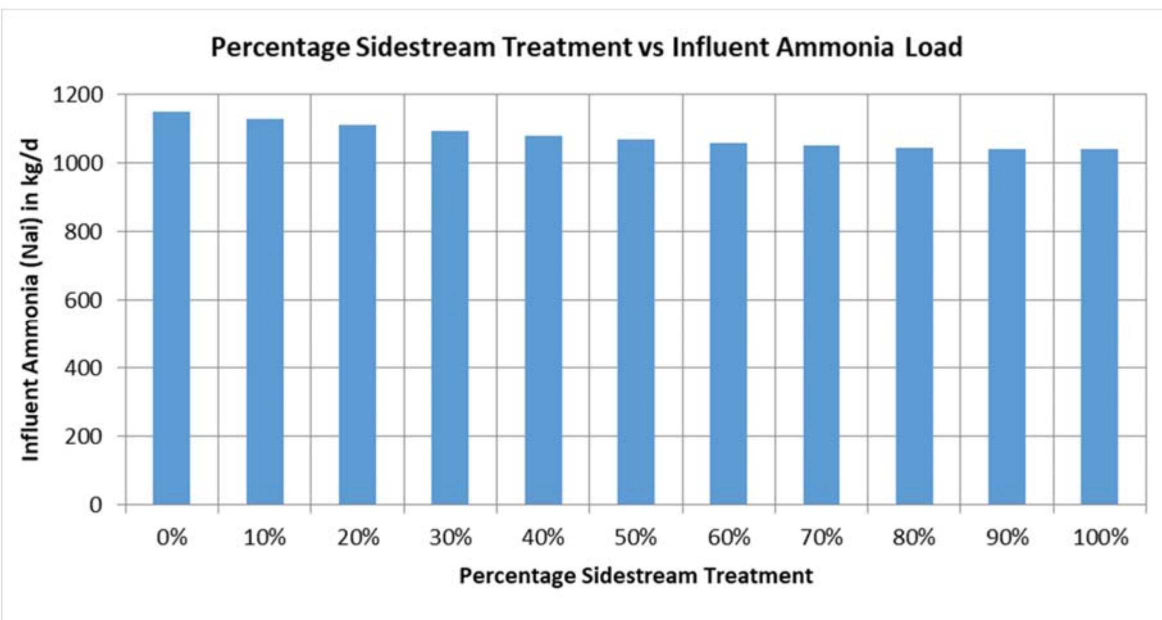

Figure 30: Impact of side-stream treatment on influent ammonia load at 'P' WWTP

3.2.4 Influent Phosphate

The impact of percentage side-stream treatment on influent phosphate to the AS system is illustrated below in Figure 31. The influent phosphate load to the AS system decreases marginally from 110 kgP/d to 109 kgP/d.

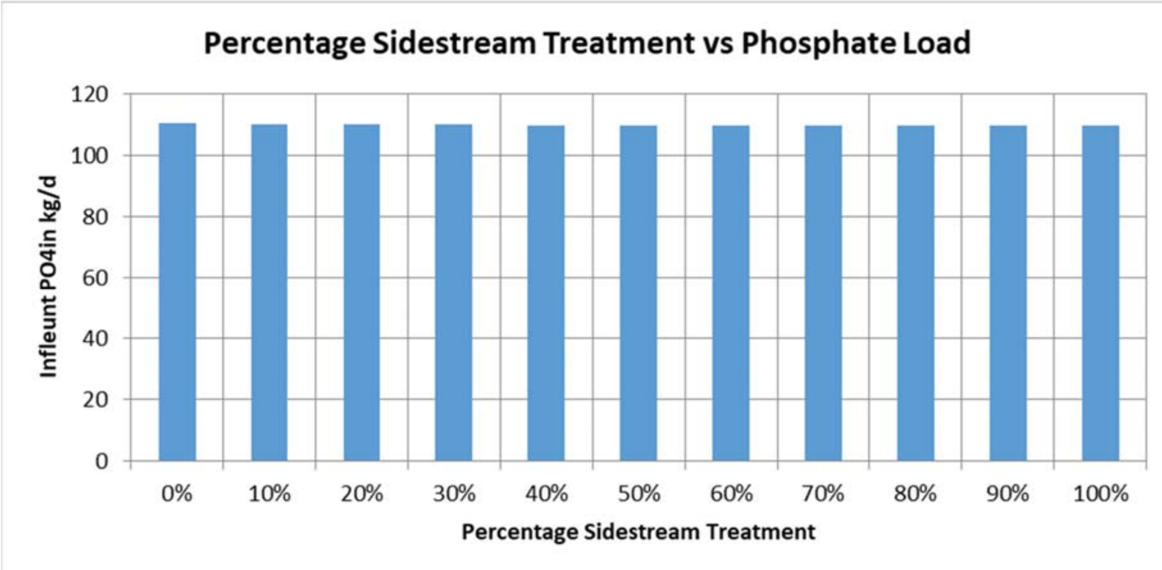

Figure 31: Impact of side-stream treatment on influent phosphate load at 'P' WWTP

3.3 Impact of SRL on Biological Treatment Capacity at 'P' WWTP

The biological treatment capacity parameters impacted on by sludge return flows are:

- A-recycle
- Total oxygen demand
- Secondary sludge production

The impact of sludge return flows on each of the above biological treatment capacity parameters is summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

3.3.1 A-recycle

The impact of percentage side-stream treatment on the a-recycle to the AS system is illustrated below in Figure 32. The a-recycle ratio increases from 0.74 to 1.19.

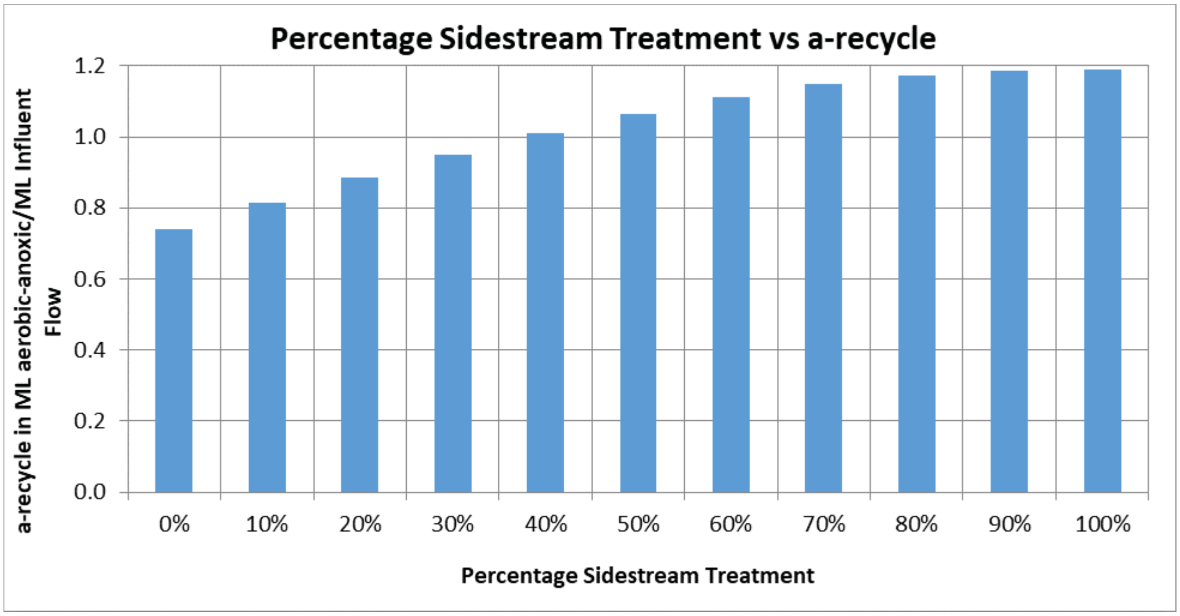

Figure 32: Impact of side-stream treatment on a-recycle at 'P' WWTP

3.3.2 Total Oxygen Demand

The impact of percentage side-stream treatment on the total oxygen demand (FOt) of the AS system is illustrated below in Figure 33. The FOt for the AS system decreases along with side-stream treatment capacity. The total oxygen demand for Plant 'P's AS system decreases from 9 514 kgO/d to 9 248 kgO/d.

The aeration power requirement for the AS system decreases along with side-stream treatment, from 209 kW to 203 kW.

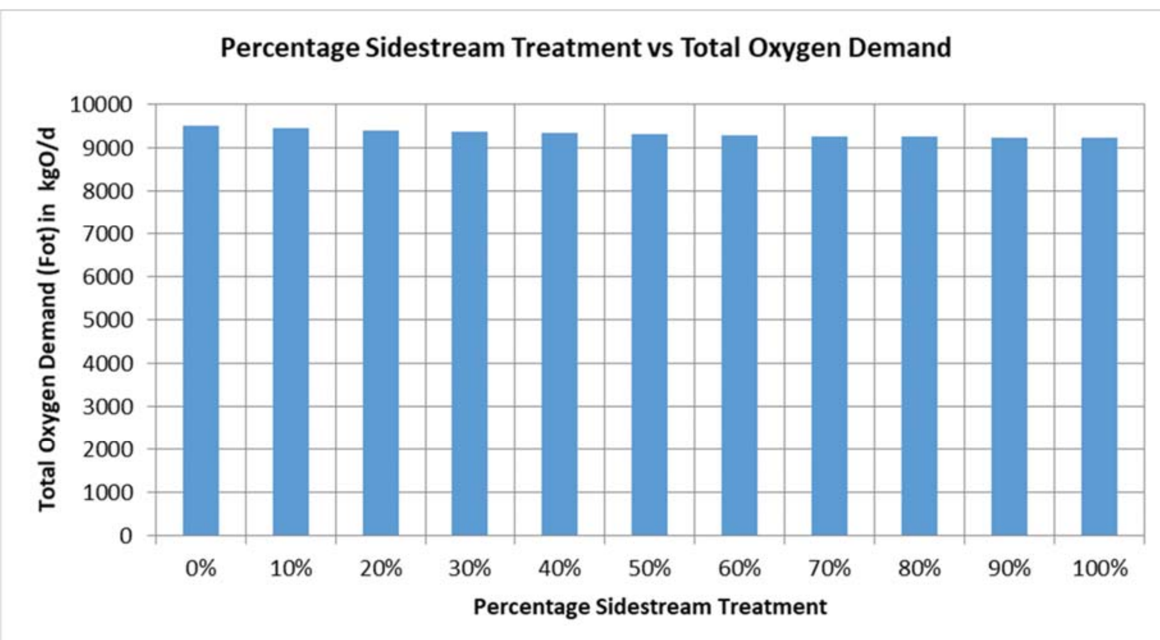

Figure 33: Impact of side-stream treatment on total oxygen demand at 'P' WWTP

3.3.3 *Secondary Sludge Produced*

The impact of percentage side-stream treatment on secondary sludge production from the AS system is illustrated below in Figure 34. Secondary sludge production in the AS system decreases along with side-stream treatment. Secondary sludge production for the AS system decreases from 2 432 kgTSS/d to 2 429 kgTSS/d.

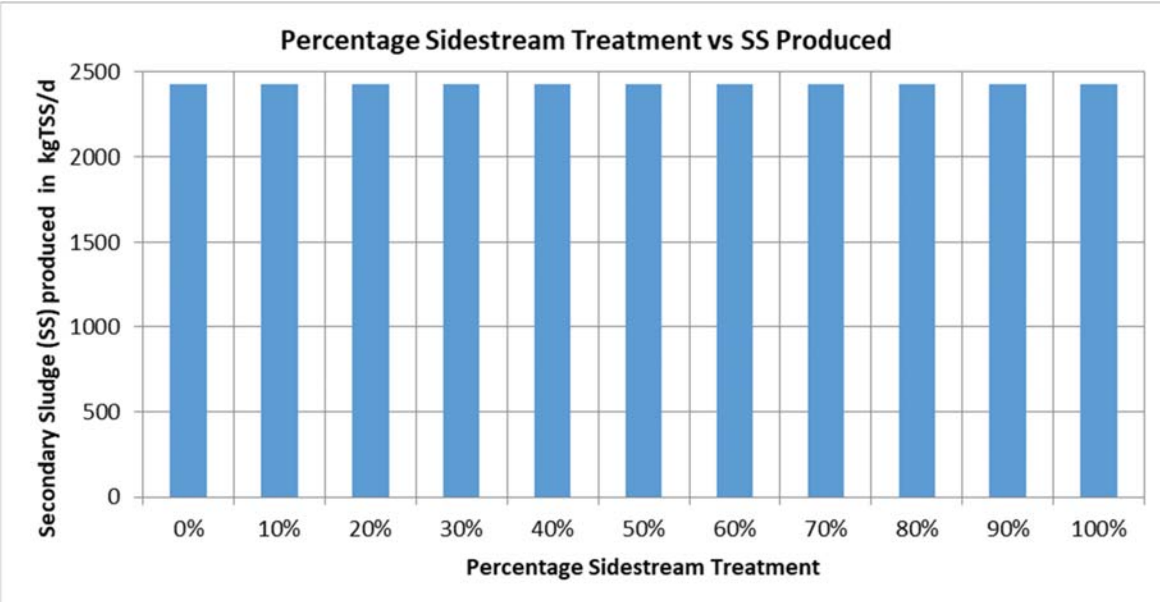

Figure 34: Impact of side-stream treatment on secondary sludge production at 'P' WWTP

3.4 ***Biological Effluent Quality***

The biological effluent quality parameters impacted on be sludge return flows are:

- COD concentration
- Ammonia concentration
- Phosphates concentration

The impact SRL on each of the abovementioned effluent parameters is summarised in this section. Figures below illustrate the impact of sludge return flows on biological effluent quality for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

3.4.1 *Effluent COD Concentration*

The impact of percentage side-stream treatment on the effluent COD from the AS system is illustrated below in Figure 35. The effluent COD concentration is constant at 49 mgCOD/ℓ.

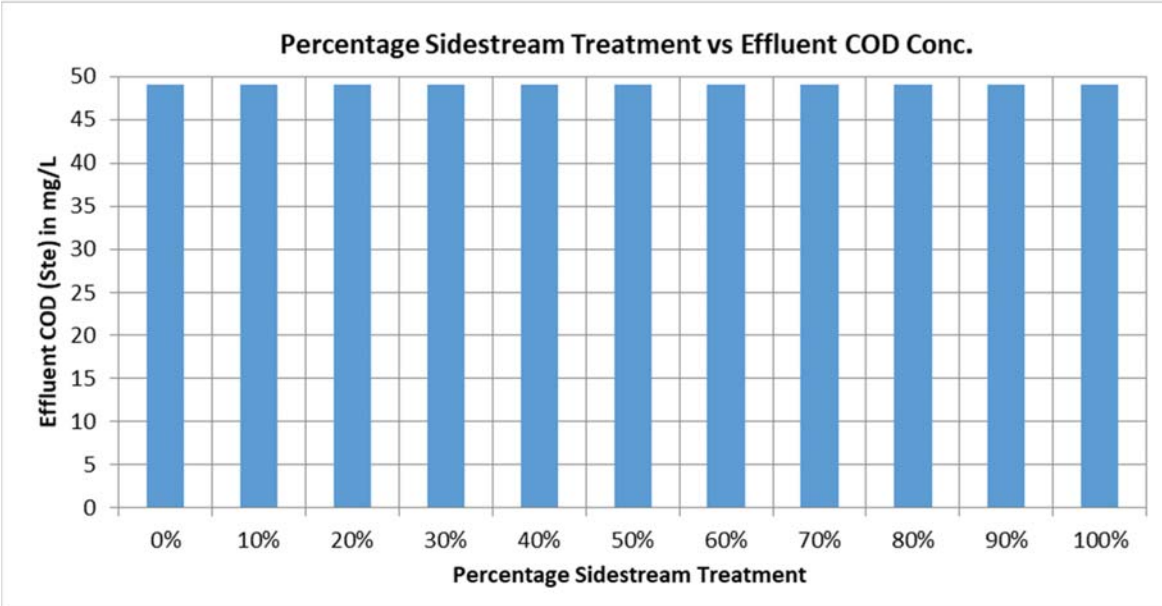

Figure 35: Impact of side-stream treatment on effluent COD concentration at 'P' WWTP

3.4.2 Effluent Ammonia Concentration

The impact of percentage side-stream treatment on the effluent ammonia from the AS system is illustrated below in Figure 36. The effluent ammonia concentration from the AS system remains constant at 0.37mgN/ℓ.

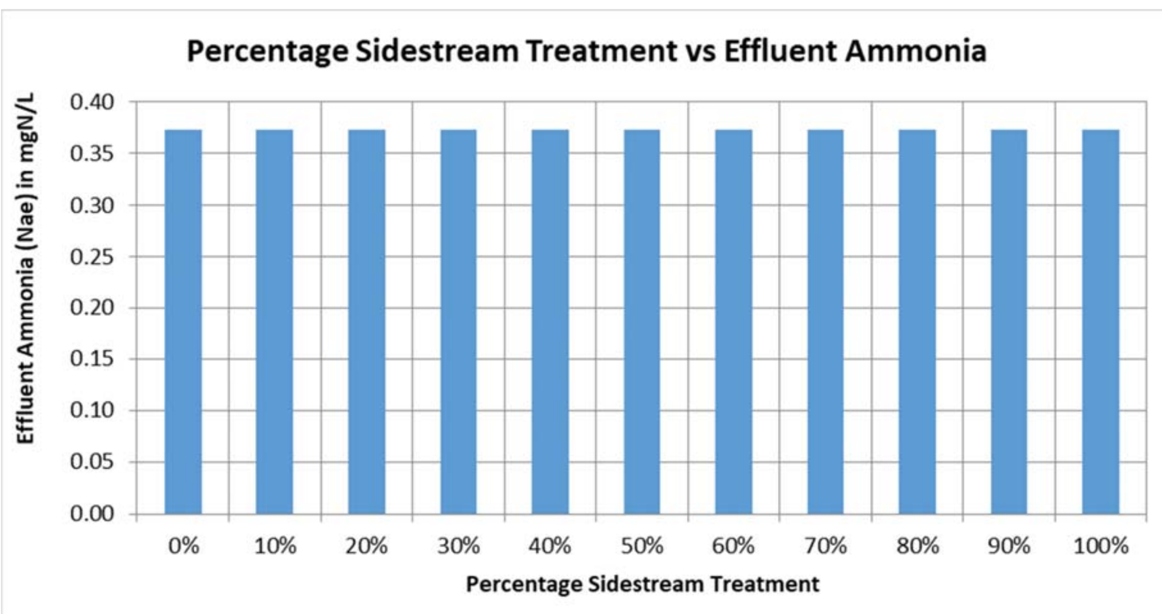

Figure 36: Impact of side-stream treatment on effluent ammonia at 'P' WWTP

3.4.3 *Effluent Nitrate Concentration*

The effluent nitrate concentration decreases with decrease in nitrification capacity, when the aeration for conversion of ammonia to nitrates is not limited (see Figure 37 – the effluent nitrate concentration decreases marginally from around 13.9 mgN/ℓ to 12.4 mgN/ℓ).

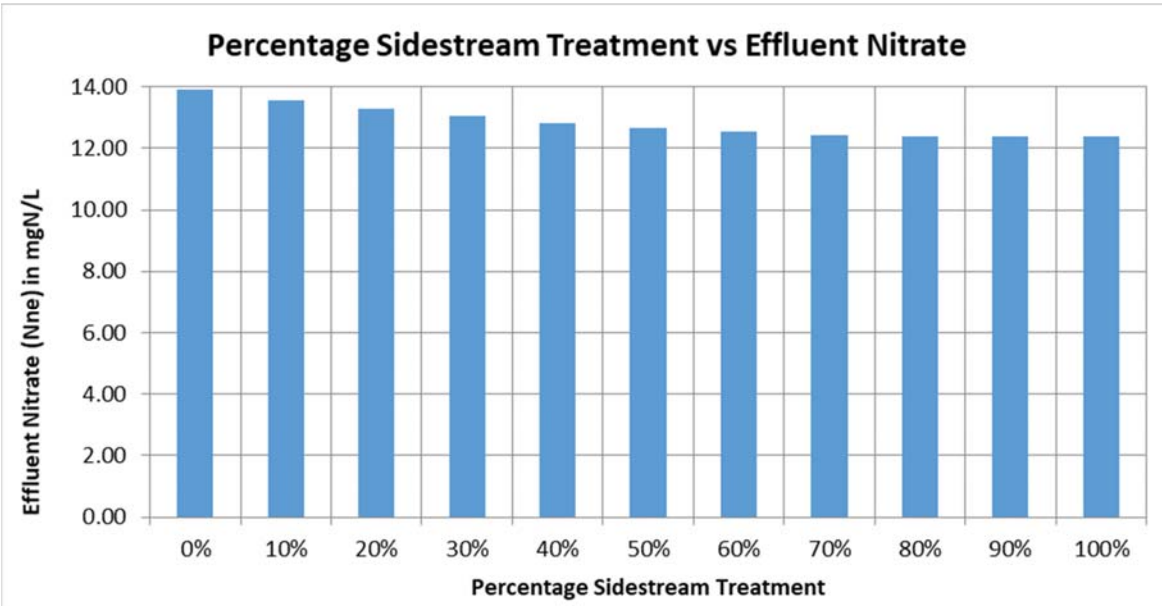

Figure 37: Impact of side-stream treatment on effluent nitrate concentration at 'P' WWTP

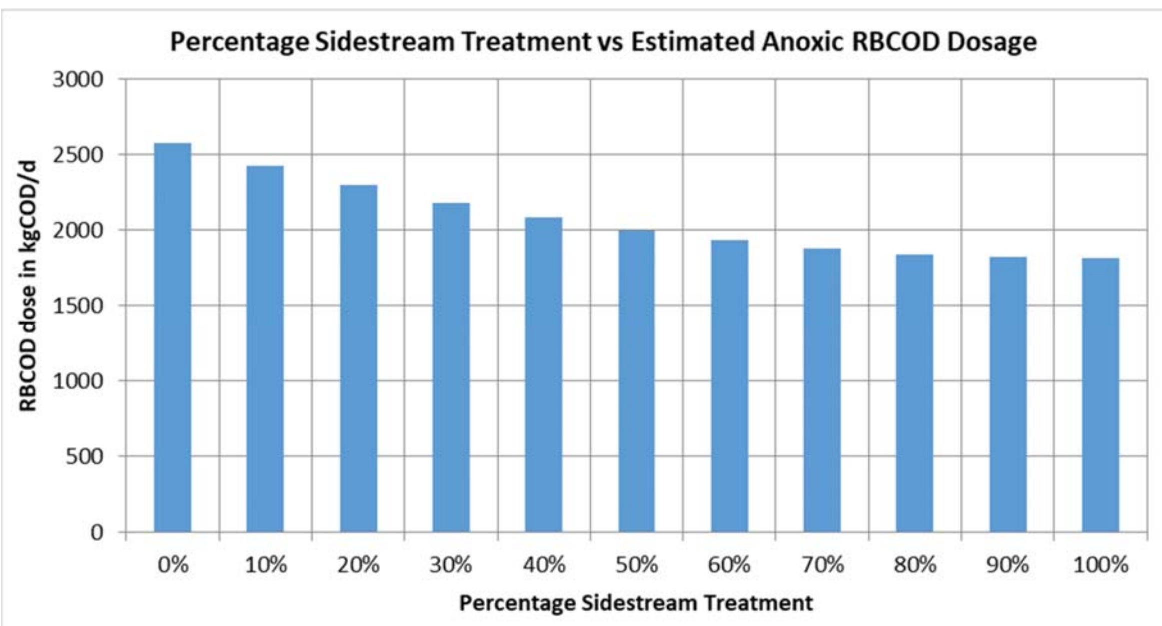

Figure 38: Impact of side-stream on estimated readily biodegradable organics COD to be dosed anoxically towards obtaining minimum effluent nitrate concentration at 'P' WWTP

3.4.4 Effluent Phosphate Concentration

The impact side-stream treatment has no predicted impact on the effluent phosphates as the effluent OP remains at 0 mgP/ℓ. However, there are chances that, for non-ideal scenarios, the effluent OP would increase with increased flux of SRL. The possible causes are inefficient metabolism of PAOs due to high nitrates, recycled anaerobically and utilization of organics by OHOs. In the steady state model, the system is assumed to be functioning under ideal conditions, with up to the maximum (0.35 mgP/mgPAOVSS) of P storage capacity by PAOs.

3.5 Summary of Impacts of SRL on Influent Characteristics at 'P' WWTP

Table 9 below summarises the percentage impact at a given percentage side-stream treatment starting from 0% to 100% side-stream treatment at 'P' WWTP.

Table 9: Percentage impact of SRL at given side-stream treatment at 'P' WWTP

Percentage Impact at given Percentage Side-stream Treatment at 'P' WWTP							
	Parameter	0%	20%	40%	60%	80%	100%
Influent	Flow rate	3.3%	2.6%	2.0%	1.3%	0.7%	0.0%
	COD	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%
	Ammonia	10.4%	6.7%	3.8%	1.7%	0.4%	0.0%
	PO_4	0.8%	0.5%	0.3%	0.1%	0.0%	0.0%
Biological Reactor	a-recycle	-37.8%	-25.7%	-15.0%	-6.6%	-1.4%	0.0%
	Total Oxygen Demand	2.9%	1.8%	1.0%	0.5%	0.1%	0.0%
	Aeration Power Requirement	2.9%	1.8%	1.0%	0.5%	0.1%	0.0%
	SS Produced	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	12.2%	7.3%	3.6%	1.1%	0.0%	0.0%
	PO_4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 39 below shows the SRL impact on 'P' WWTP at 0% side-stream treatment. The major impact was observed for influent ammonia load and effluent nitrate were the impact was 10.4% and 12.2% respectively.

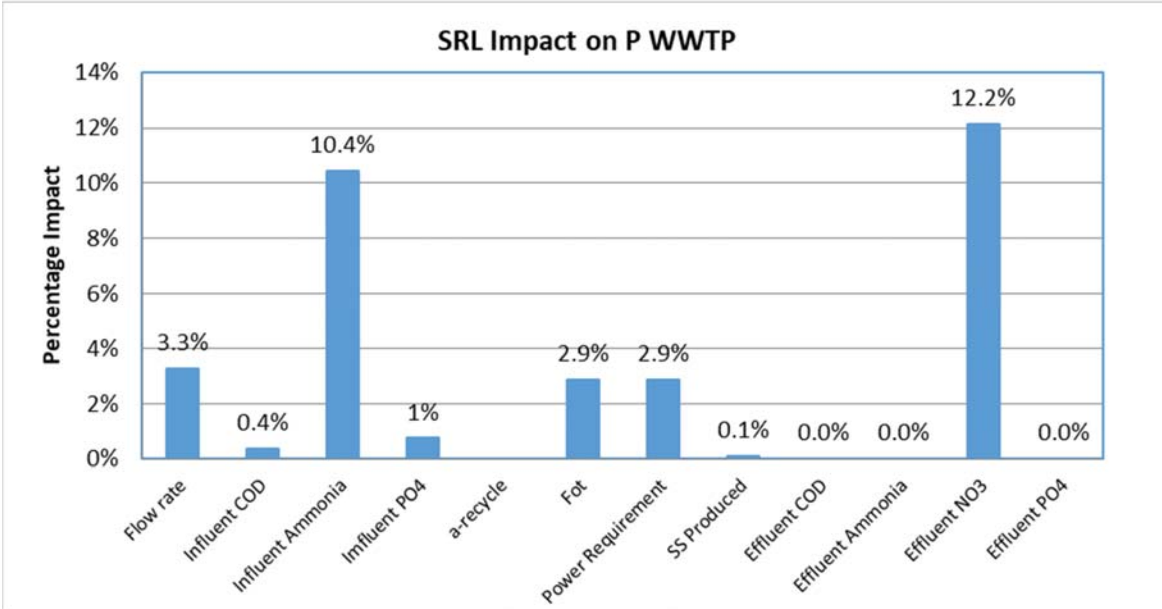

Figure 39: SRL Impact on ‘P’ WWTP at 0% side-stream treatment

CHAPTER 4: 'K' WWTP

The results of the impact of return sludge liquors at 'K' WWTP are presented in this section. The impact of the sludge return flows was determined on:

- Influent Characteristics
- Biological Treatment Capacity
- Biological Effluent Quality

4.1 Process Description

A description of the 'K' WWTP is indicated below as per information found in the operation and maintenance manuals. Table 10 and Table 11 give a summary of the unit operations and process data. A general process flow diagram of the works in indicated below in Figure 40, 'K' WWTP has a design capacity of 65 Mℓ/d.

Table 10: 'K' WWTP Unit Operations and Processes

Key Unit Operations and Processes	AS System
Primary Settling Tanks	Yes
Aerobic AS System	Yes
Secondary Settling Tanks	Yes
Gravity Thickeners	Yes
Dissolved Air Flotation	Yes
Anaerobic Digesters	Yes
Dewatering	Yes

The pertinent data for the above unit operations and processes is summarised in Table 11.

Table 11: 'K' WWTP Data Summary

Key Unit Operations and Processes	AS System
Primary Settling Tanks diameter	6 Units
BNR System Volume (m^3)	65 000
Secondary Settling Tank Diameter	8 Units
Dissolved Air Flotation	1
Anaerobic Digesters	4 × 2 000m^3 + 2 × 2 310m^3 (secondary digesters) + 5 380m^3

SRL treatment consists of

- All SRL from gravity thickener, DAF unit, secondary digester and mechanical dewatering are returned to upstream of the PSTs included in the AS treatment

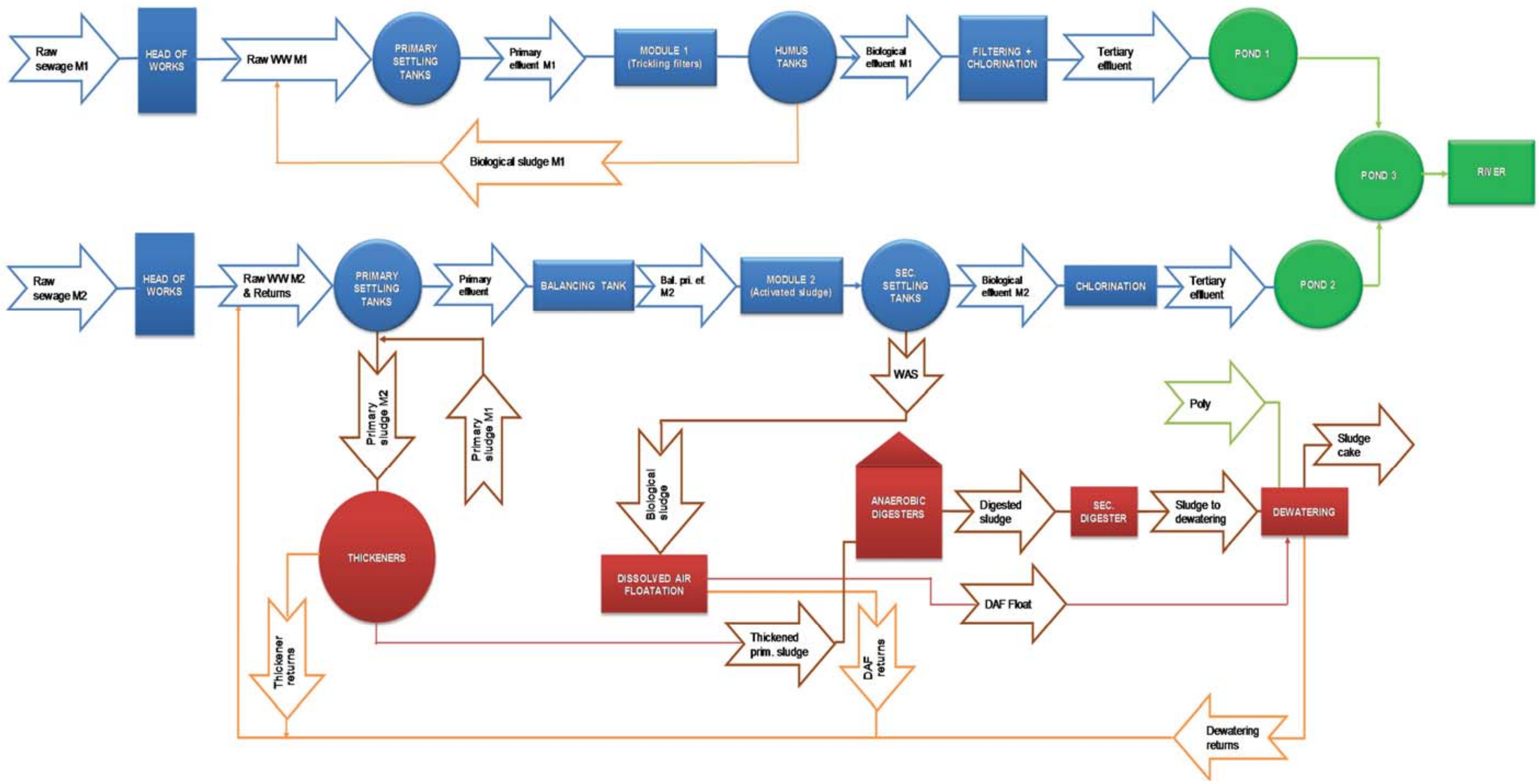

Figure 40: 'K' WWTP Process Flow Diagram

4.2 Impact of SRL on Influent Characteristics at 'K' WWTP

The influent characteristics impacted on by sludge return flows are:

- Influent Flow rate
- Influent COD Load
- Influent Ammonia Load
- Influent PO_4 Load

The impact of SRL on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

4.2.1 Influent Flow rate

The impact of percentage side-stream treatment on the flow rate is illustrated below in Figure 41. Without side-stream treatment, i.e. 0% side-stream treatment, means that 100% of return sludge liquors flow back to the AS system. The flow to the AS system decreases along with side-stream treatment causing the flow to decrease from 55 Mℓ/d to 52 Mℓ/d.

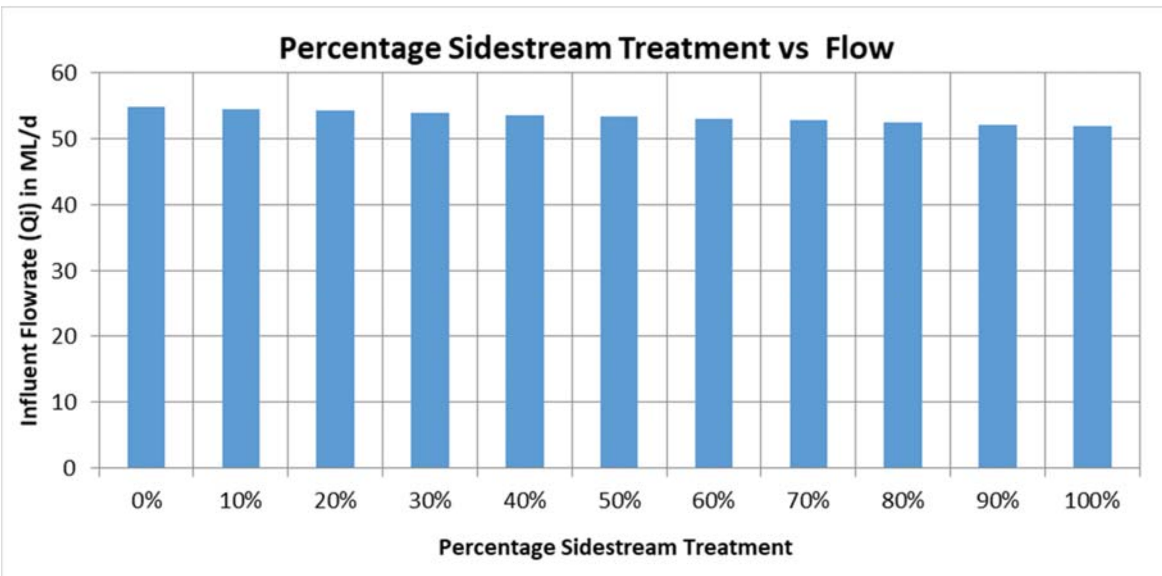

Figure 41: Impact of side-stream treatment on influent flow rate at 'K' WWTP

4.2.2 Influent COD Load

The impact of percentage side-stream treatment on the total influent COD load to the AS system is illustrated below in Figure 42. Influent COD load concentration to the AS system decreases from 31 236 kgCOD/d to 31 093 kgCOD/d.

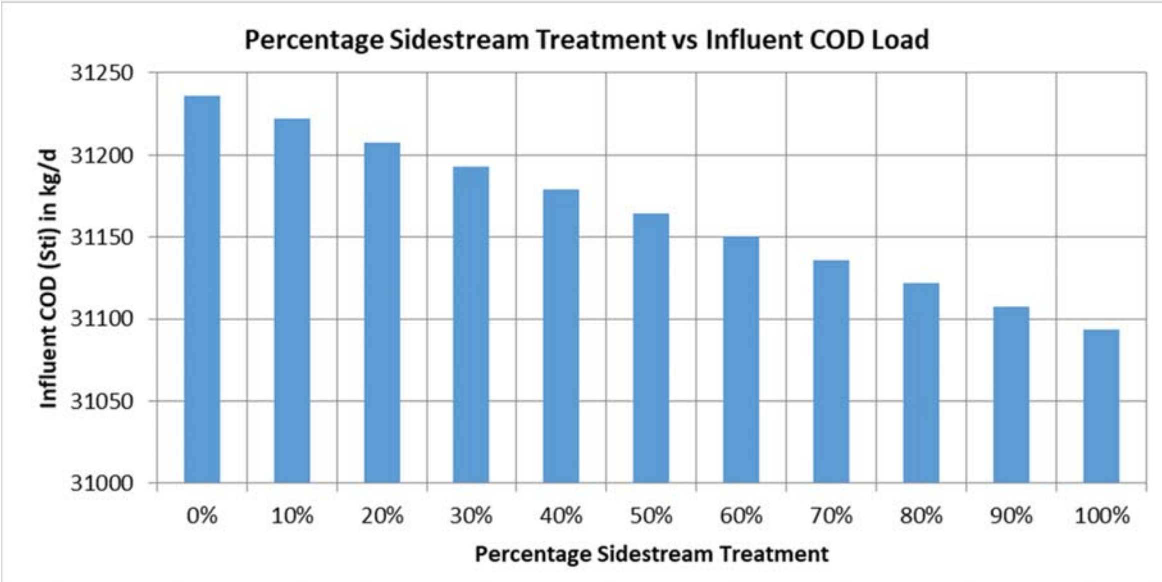

Figure 42: Impact of side-stream on influent COD at 'K' WWTP

4.2.3 Influent Ammonia Load

The impact of percentage side-stream treatment on the influent ammonia load to the activated sludge system is illustrated below in Figure 43. Influent ammonia load to AS system decreases from 1 525 kgN/d to 1 349 kgN/d.

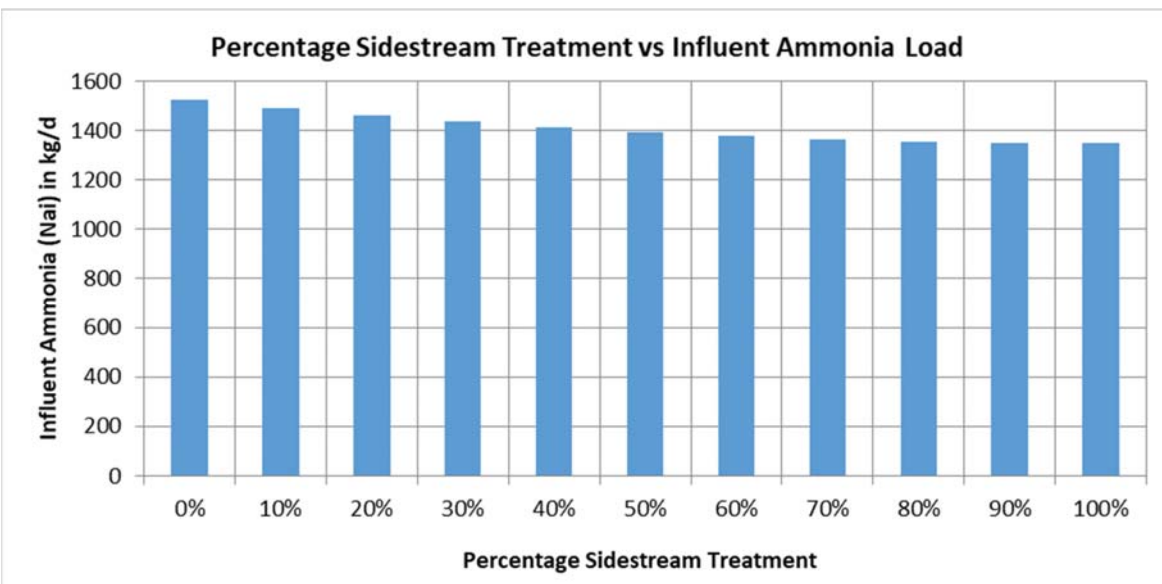

Figure 43: Impact of side-stream treatment on influent ammonia load at 'K' WWTP

4.2.4 Influent Phosphate Load

The impact of percentage side-stream treatment on influent phosphate load to the AS system is illustrated below in Figure 44. Influent phosphate load to the AS system increases from 178 kgP/d to 171 kgP/d.

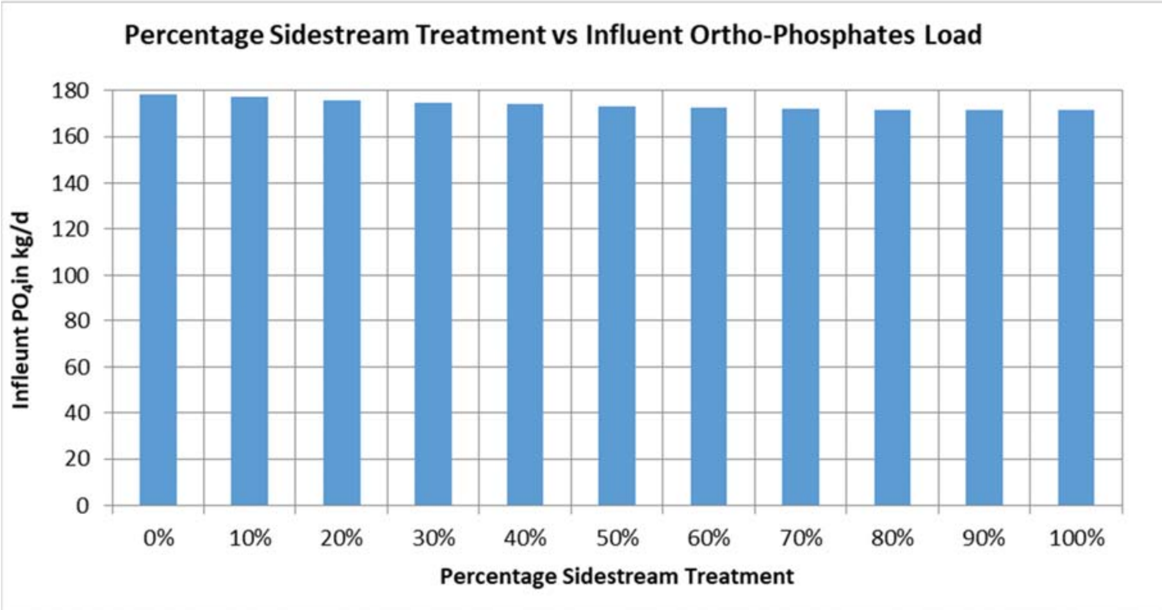

Figure 44: Impact of side-stream treatment on influent phosphate load at 'K' WWTP

4.3 Impact of SRL on Biological Treatment Capacity at 'K' WWTP

The biological treatment capacity parameters impacted on by sludge return flows are:

- Total oxygen demand
- Aeration power requirement
- Secondary sludge production

The impact of SRL on each of the above biological treatment capacity parameters is summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

4.3.1 Total Oxygen Demand

The impact of percentage side-stream treatment on the total oxygen demand (FOt) of the AS system is illustrated below in Figure 45. The FOt for each module decreases along with side-stream treatment capacity. The total oxygen demand for the AS system decreases from 27 614 kgO/d to 27 188 kgO/d.

The aeration power requirement for each module decreases along with side-stream treatment. Aeration power requirement decreases from 606 kW to 597 kW.

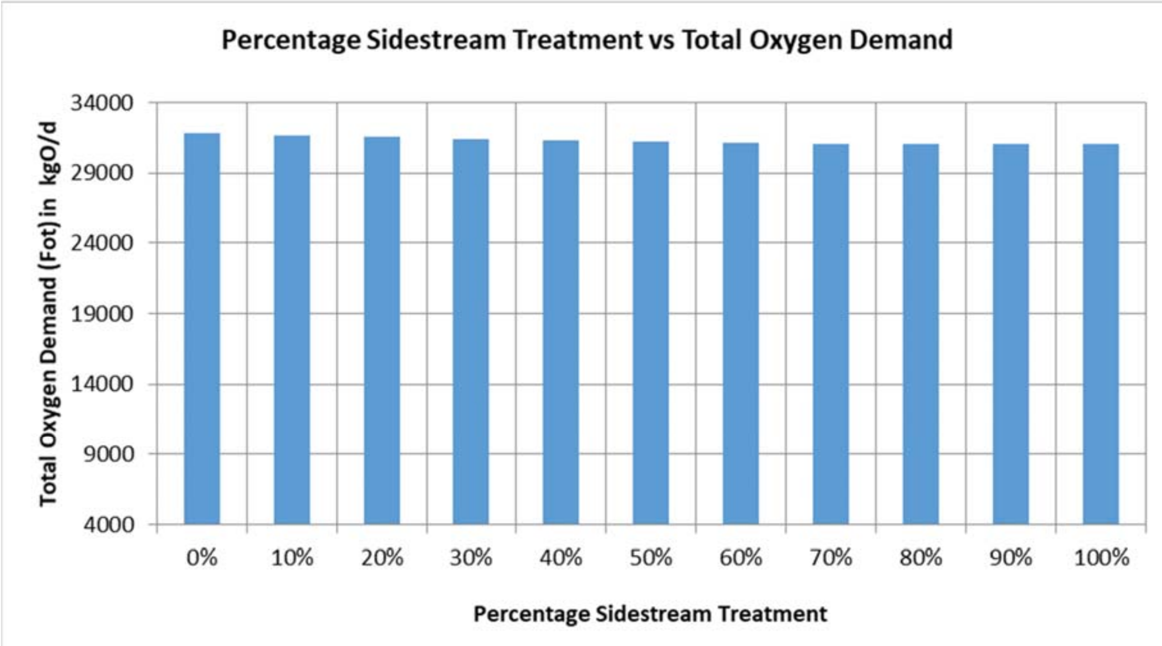

Figure 45: Impact of side-stream treatment on total oxygen demand at 'K' WWTP

4.3.2 Secondary Sludge Produced

The impact of percentage side-stream treatment on secondary sludge production from the AS system is illustrated below in Figure 46. The secondary sludge production decreases along with side-stream treatment from 4 918 kgTSS/d to 4 865 kgTSS/d.

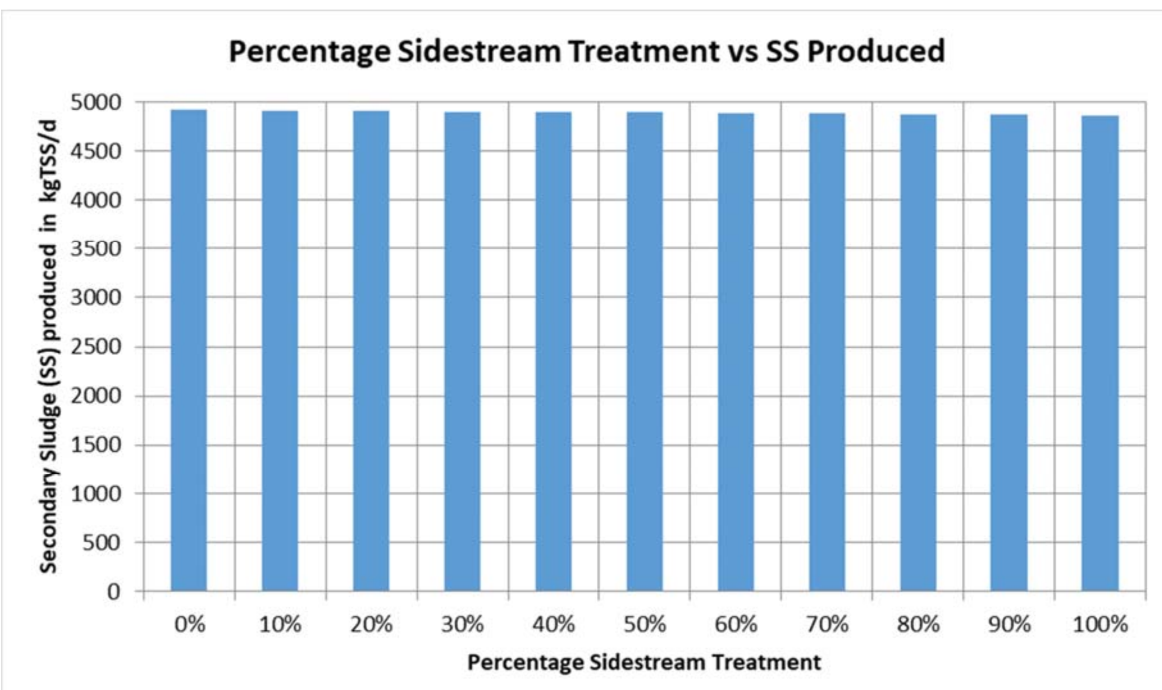

Figure 46: Impact of side-stream treatment on secondary sludge production at 'K' WWTP

4.4 Impact of SRL on Biological Effluent Quality at 'K' WWTP

The biological effluent quality parameters impacted on be sludge return flows are:

- COD concentration
- Ammonia concentration
- Phosphates concentration

The impact of SRL flows on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of sludge return flows on biological effluent quality for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

4.4.1 Effluent COD Concentration

The impact of percentage side-stream treatment on the effluent COD from the AS system is illustrated below in Figure 47. The effluent COD concentration for the AS system is 48 mg/ℓ.

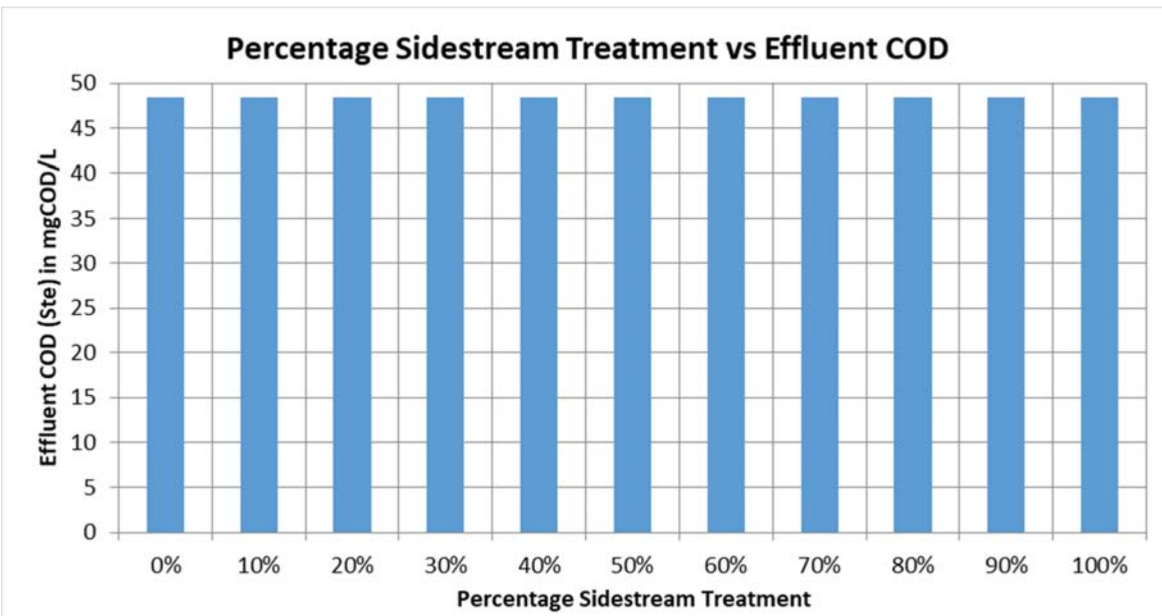

Figure 47: Impact of side-stream treatment on effluent COD at 'K' WWTP

4.4.2 Effluent Ammonia Concentration

The impact of percentage side-stream treatment on the effluent ammonia concentration from the SST is illustrated below in Figure 48. If aeration is limited, the effluent ammonia concentration from the AS system remains constant at 0.11 mgN/ℓ.

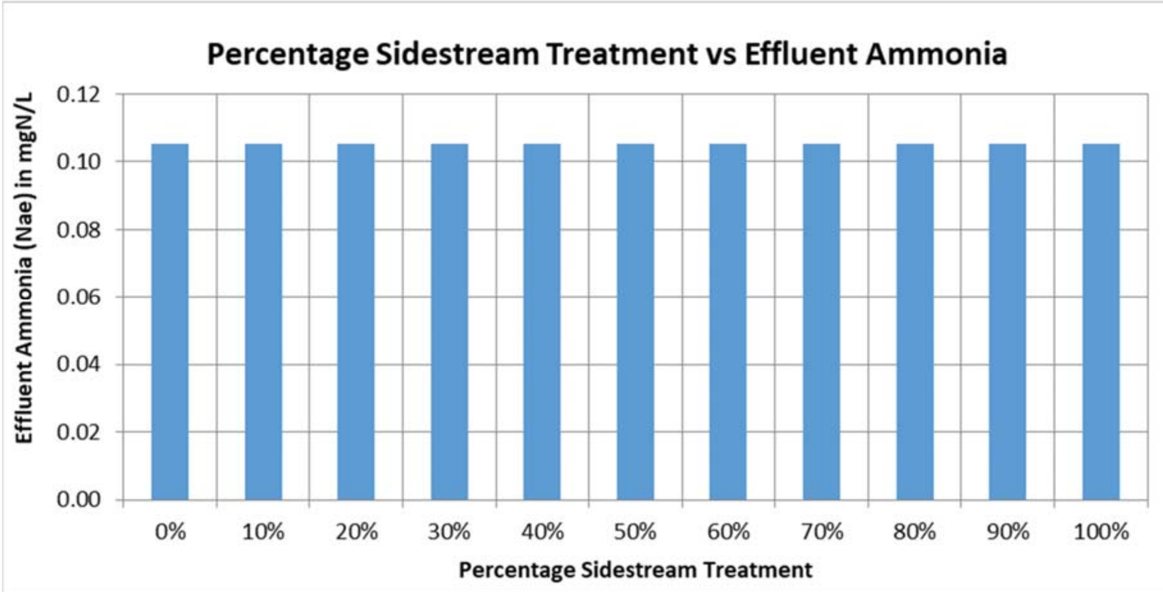

Figure 48: Impact of side-stream treatment on effluent ammonia at 'K' WWTP

4.4.3 Effluent Nitrate Concentration

The 'K' WWTW has no anoxic zone, hence has no capacity for denitrification, resulting in high effluent nitrates concentration. However, the effluent nitrate concentration decreases with decrease in nitrification capacity, when the aeration for conversion of ammonia to nitrates is not limited (see Figure 49 – the effluent nitrate concentration decreases from 35.8 mgN/ℓ to 34.4 mgN/ℓ).

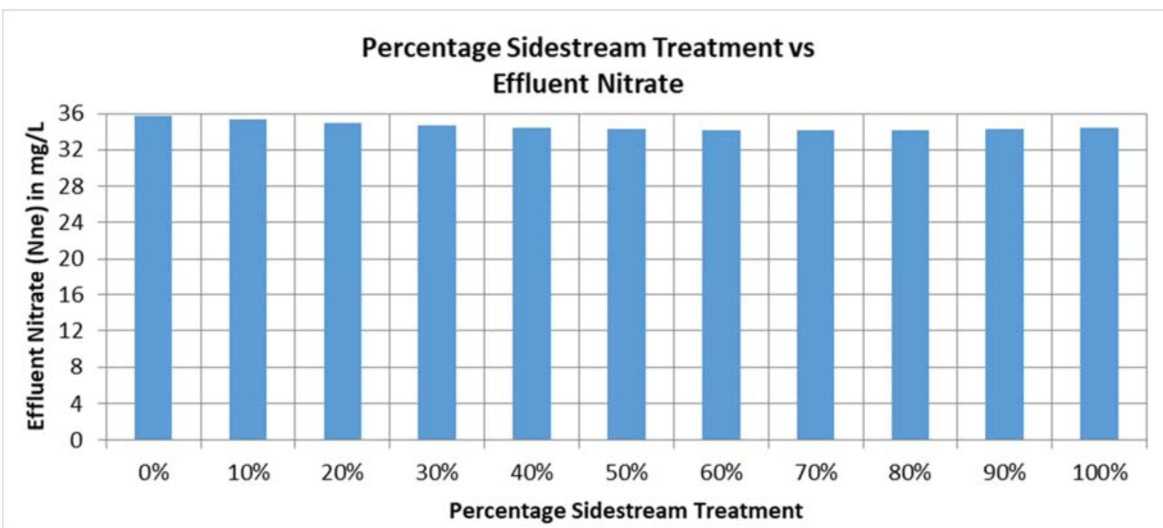

Figure 49: Impact of side-stream treatment on effluent nitrates at 'K' WWTP

4.4.4 Effluent Phosphates Concentration

The impact of percentage side-stream treatment on the effluent phosphate from the SST is illustrated in Figure 50. The effluent phosphate concentration from the AS system decreases marginally from 2.01 to 1.99 mg/ℓ. The presence of predicted effluent OP is due to Plant 'K' being fully aerated and not having the capacity for excess biological P removal (EBPR) – hence the influent OP is solely as nutrient requirement for biomass.

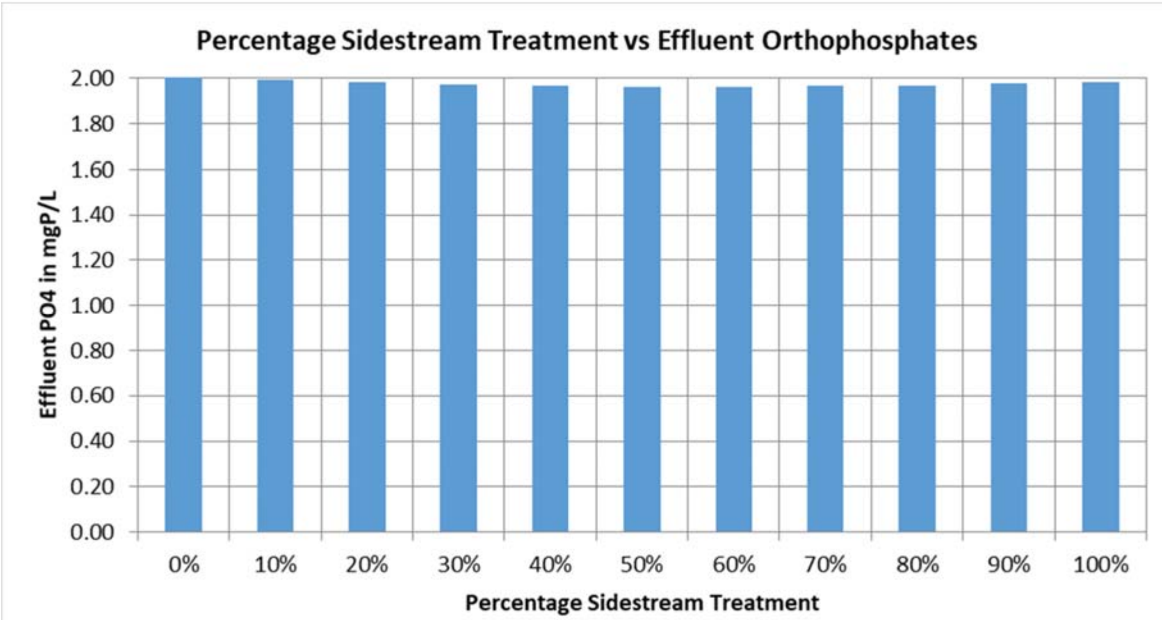

Figure 50: Impact of side-stream treatment on effluent phosphate at 'K' WWTP

4.5 Summary of Impacts of SRL Return Liquors at 'K' WWTP

Table 12 below summarises the percentage impact at a given percentage side-stream treatment starting at 0% side-stream treatment at 'K' WWTWP

Table 12: Percentage impact of SRL for given side-stream treatment at 'K' WWTP

Percentage Impact at given Percentage Side-stream Treatment at 'K' WWTP							
Parameter		0%	20%	40%	60%	80%	100%
Influent	Flow rate	5.7%	4.6%	3.4%	2.3%	1.1%	0.0%
	COD	0.5%	0.4%	0.3%	0.2%	0.1%	0.0%
	Ammonia	13.1%	8.4%	4.7%	2.1%	0.5%	0.0%
	PO_4	4.2%	2.7%	1.5%	0.7%	0.2%	0.0%
	Total Oxygen Demand	2.6%	1.7%	0.9%	0.4%	0.1%	0.0%
	Aeration Power Requirement	2.6%	1.7%	0.9%	0.4%	0.1%	0.0%
	SS Produced	1.1%	0.9%	0.6%	0.4%	0.2%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	4.0%	1.7%	0.1%	0.0%	0.0%	0.0%
	PO_4	1.2%	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 51 below shows the SRL impact on 'K' WWTP at 0% side-stream treatment. The major impact was observed for influent ammonia load were the impact was 13.1%.

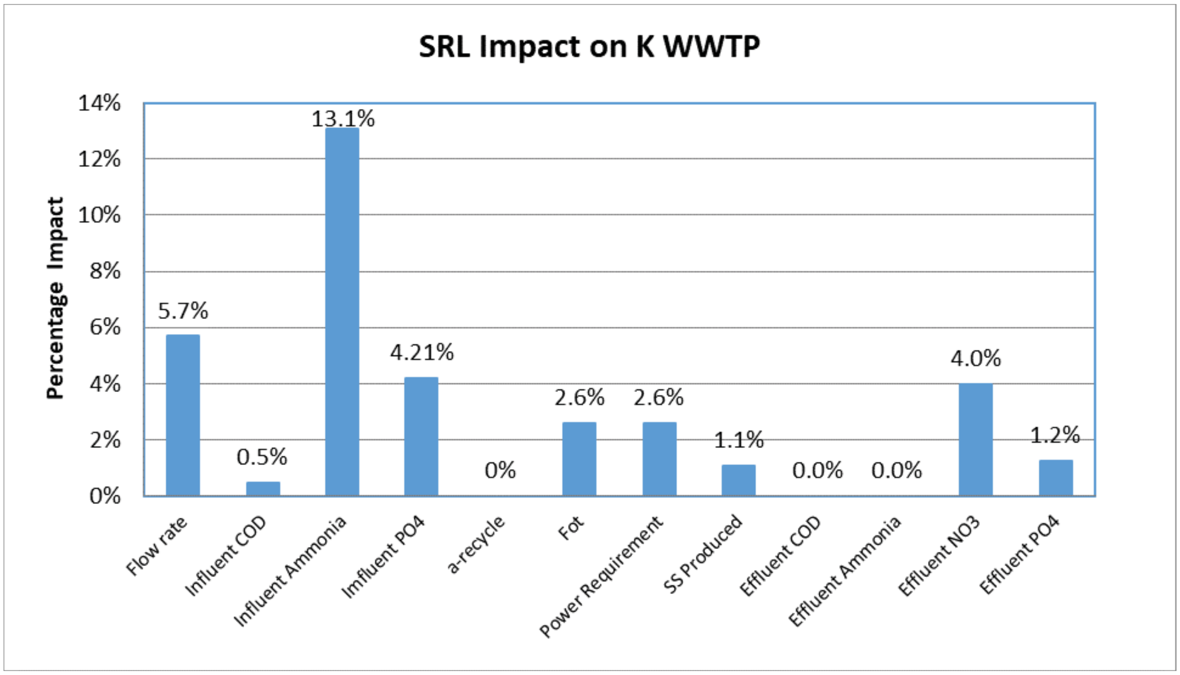

Figure 51: SRL Impact on 'K' WWTP at 0% side-stream treatment

CHAPTER 5: 'C' WWTP

The results of the impact of SRL at 'C' WWTP are presented in this section. The impact of the sludge return flows was determined on:

- Influent Characteristics
- Biological Treatment Capacity
- Biological Effluent Quality

5.1 Process Description

A description of the 'C' WWTP is indicated below as per information found in the operation and maintenance manuals. Plant 'C' has a 5-Stage Bardenpho configuration. Table 13 and Table 14 give a summary of the unit operations and process data. A general process flow diagram of the works in indicated below in Figure 52. 'C' WWTP has a design capacity of 198 Mℓ/d.

Table 13: 'C' WWTP Unit Operations and Process

Key Unit Operations and Processes	Module
Primary Settling Tanks	Yes
BNR System	Yes
Secondary Settling Tanks	Yes
Gravity Thickeners	Yes
Dissolved Air Flotation	Yes
Anaerobic Digesters	Yes
Dewatering	Yes

The pertinent data for the above unit operations and processes is summarised in Table 14.

Table 14: 'C' WWTP Data

Key Unit Operations and Processes	AS System
Primary Settling Tanks diameter	8 × 23 m
Diameter (m)	25
BNR System Volume (m^3)	29 696
Secondary Settling Tank Diameter	22 × 26 m + 4 × 31m
Gravity Thickeners	3 Units
DAF Units Diameter of ea. Unit (m)	2 Units
Anaerobic Digesters	6 × 5 380 m^3

SLR:

- Return liquors from gravity thickening and dissolved air flotation process operations are blended and recycled to the beginning of the biological reactors
- The filtrate from the sludge drying beds is discharged into ponds and not returned to the treatment works

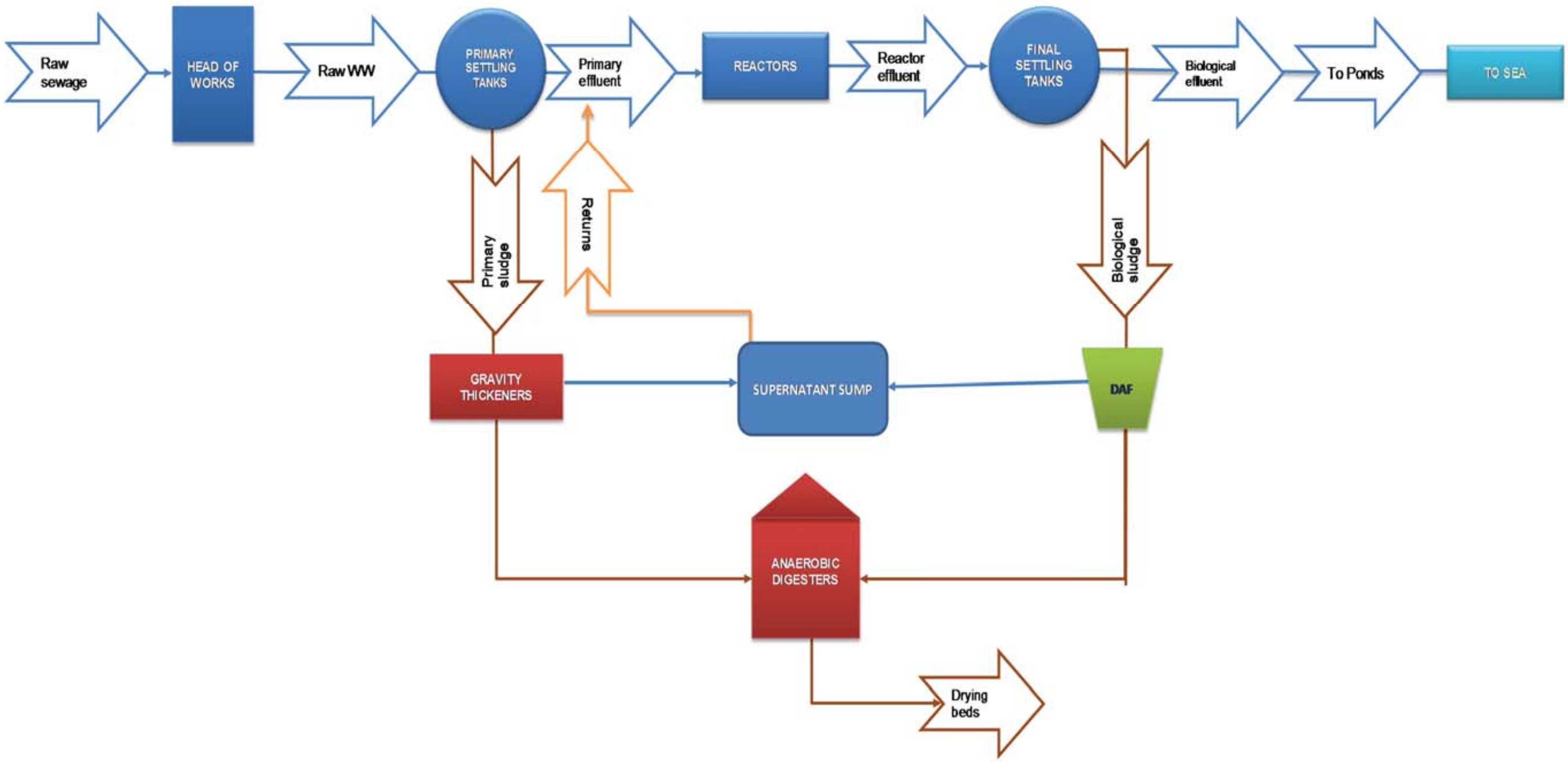

Figure 52: 'C' WWTP Process Flow Diagram

5.2 *Impact of SRL on Influent Characteristics at 'C' WWTP*

The influent characteristics impacted on by SRL are:

- Influent flow rate
- Influent COD Load
- Influent Ammonia Load
- Influent PO_4 Load

The impact of SRL on each of the above influent characteristics is summarised in this section. Figure 53 to Figure 56 illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

5.2.1 *Influent Flow rate*

The impact of percentage side-stream treatment on the flow rate is illustrated below in Figure 53. Without side-stream treatment, i.e. 0% side-stream treatment, 100% of SRL flows back to the activated sludge system. The flow to the AS system decreases along with side-stream treatment from 206 Mℓ/d to 198 Mℓ/d.

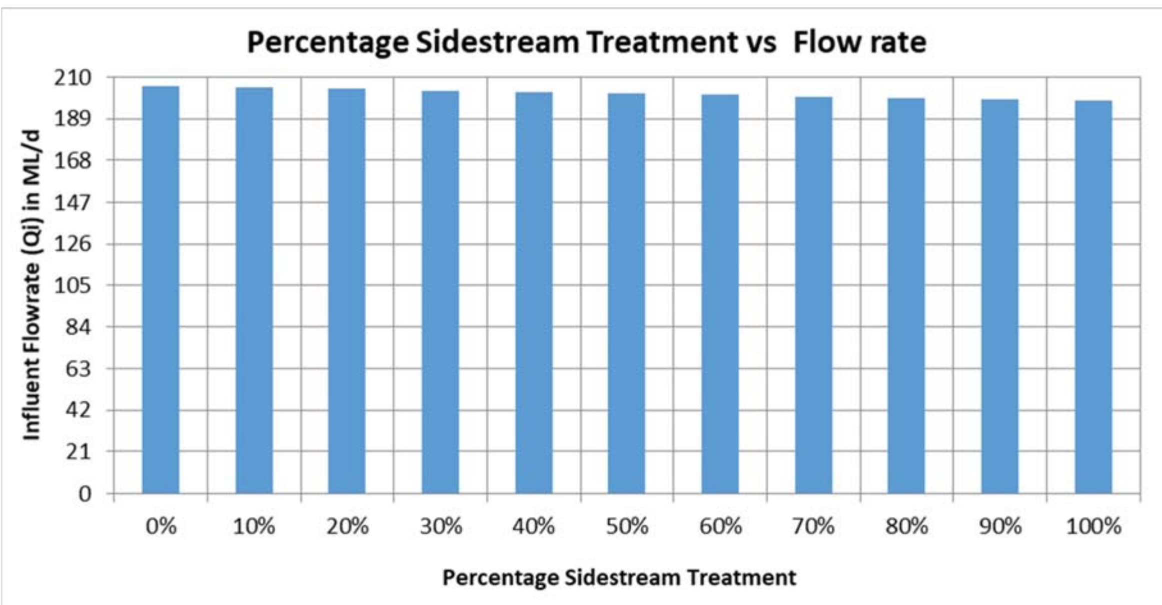

Figure 53: Impact of side-stream treatment on influent flow at 'C' WWTP

5.2.2 *Influent COD Load*

The impact of percentage side-stream treatment on the total influent COD load to the AS system is illustrated below in Figure 54. Influent COD load to the plant increases from 84 911 kgCOD/d to 84 348 kgCOD/d. This trend is similar to the model predictions for the other plants.

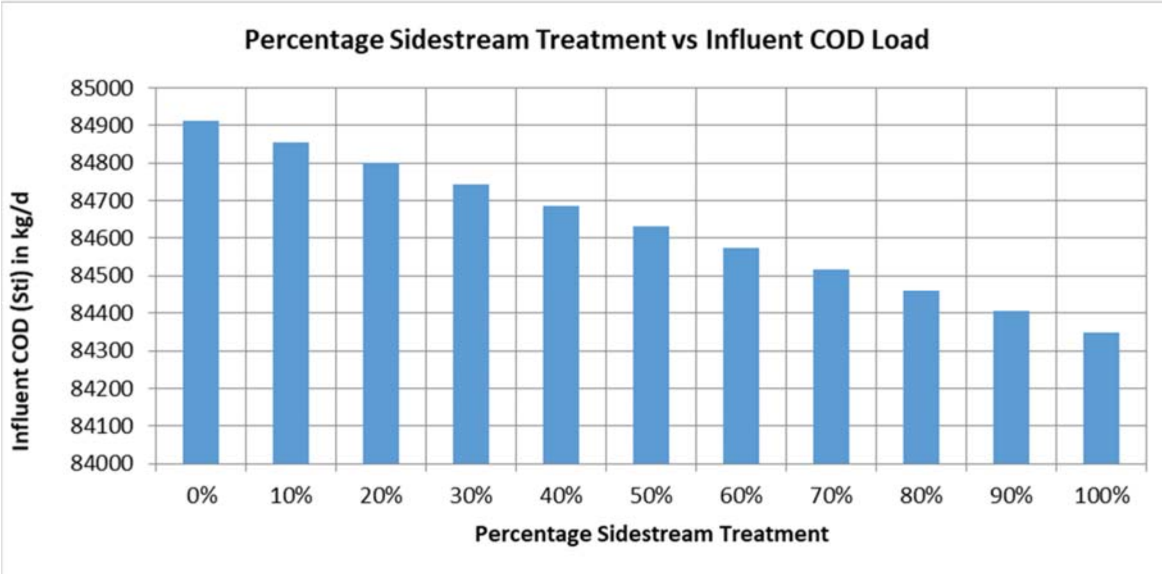

Figure 54: Impact of side-stream treatment on influent COD Load at 'C' WWTP

5.2.3 Influent Ammonia Load

The impact of percentage side-stream treatment on the influent ammonia load to the activated sludge system is illustrated below in Figure 55. Influent ammonia load to the AS system decreases from 7 875 kgN/d to 6 613 kgN/d.

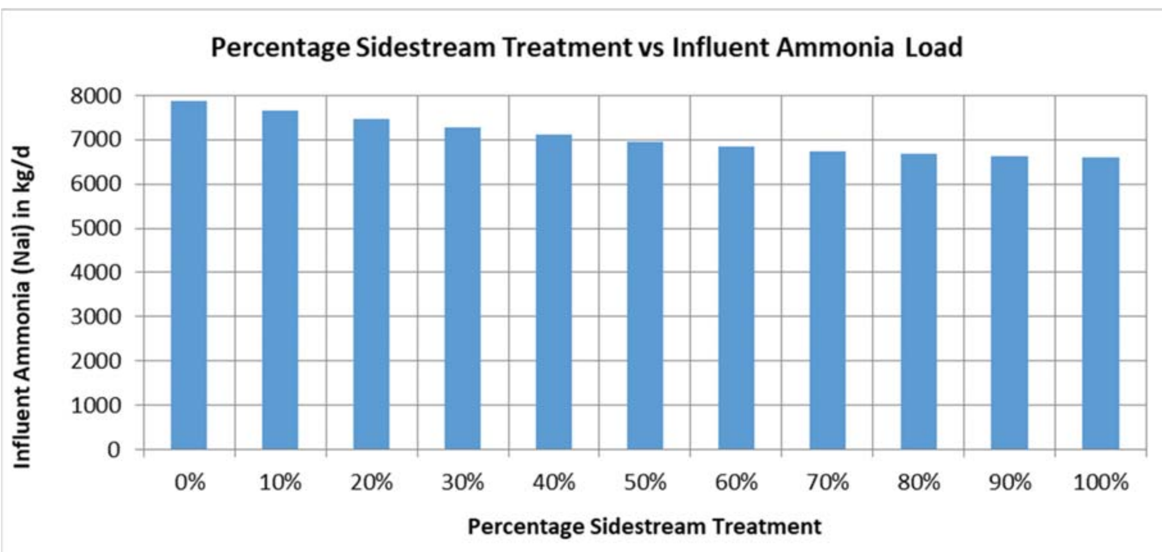

Figure 55: Impact of side-stream treatment on influent ammonia load at 'C' WWTP

5.2.4 Influent Phosphate Load

The impact of percentage side-stream treatment on the influent orthophosphate load to the AS system is illustrated below in Figure 56. Influent orthophosphate load to the AS system decreases from 1 614 kgP/d to 705 kgP/d.

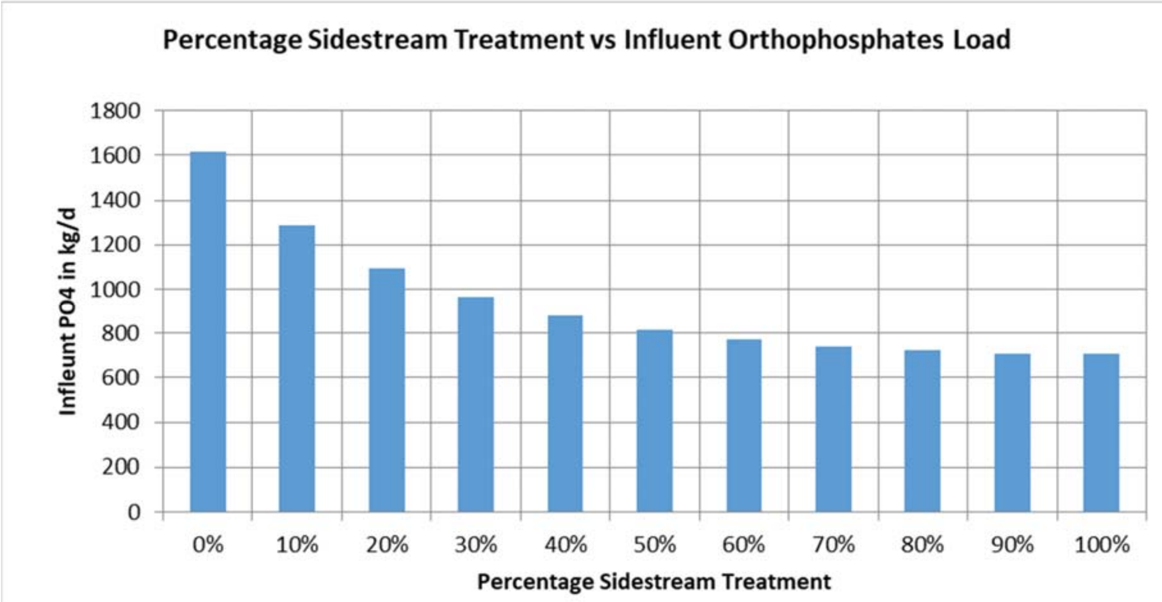

Figure 56: Impact of side-stream treatment on influent phosphate load at 'C' WWTW

5.3 Impact of SLR on Biological Treatment Capacity at 'C' WWTP

The biological treatment capacity parameters impacted on by SRL flows are:

- A-recycle
- Total oxygen demand
- Secondary sludge production

The impact of SRL on each of the above biological treatment capacity parameters is summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

5.3.1 A-recycle

The impact of percentage side-stream treatment on the a-recycle of the AS system is illustrated below in Figure 57. The a-recycle ratio flow to the anoxic reactors increases along with side-stream treatment from 0.15 to 0.64.

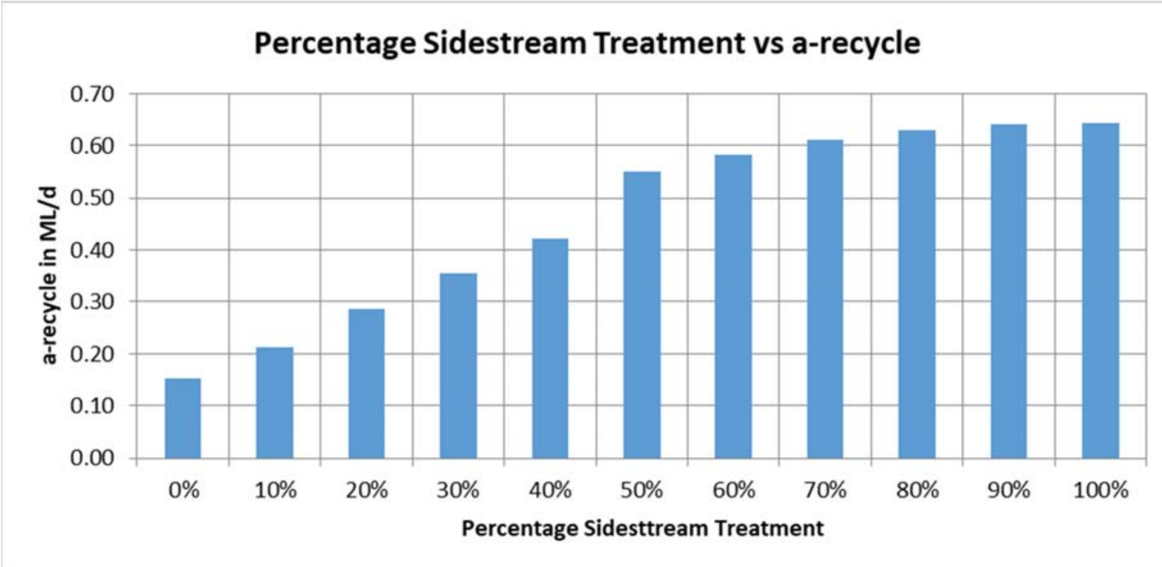

Figure 57: Impact of side-stream treatment on a-recycle at 'C' WWTP

5.3.2 Total Oxygen Demand

The impact of percentage side-stream treatment on the total oxygen demand (FOt) for the AS system is illustrated in Figure 58. The FOt for the AS system decreases along with side-stream treatment capacity from 64 599 kgO/d to 61 815 kgO/d.

Aeration power requirement for the AS system decreases along with side-stream treatment, seen in the decrease from 1 418 kW to 1 357 kW.

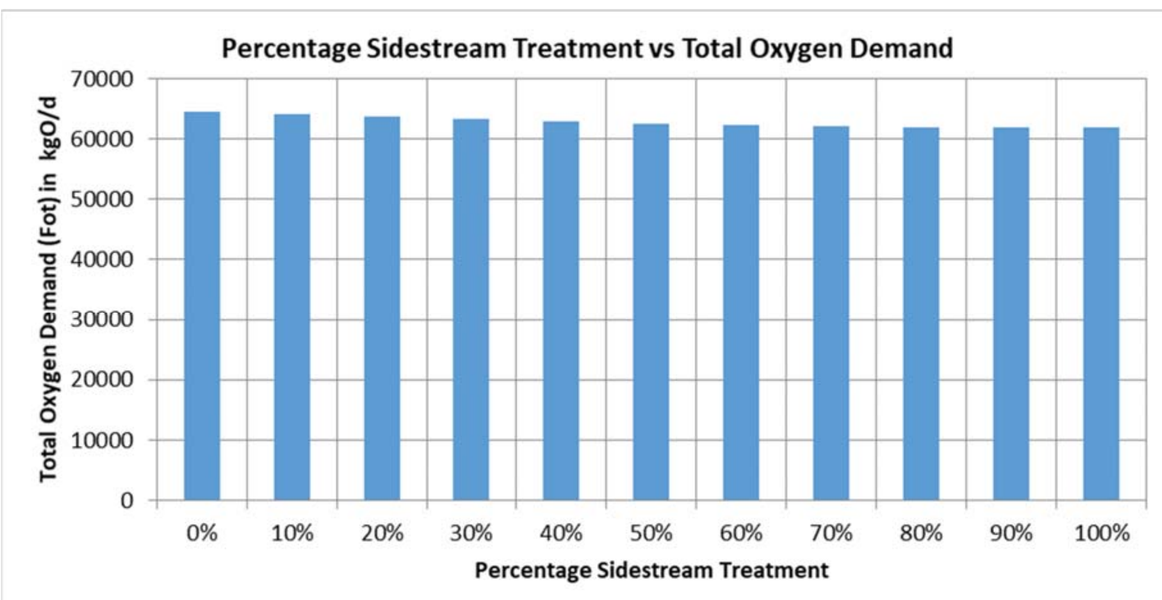

Figure 58: Impact of side-stream treatment on total oxygen demand at 'C' WWTP

5.3.3 Secondary Sludge Produced

The impact of percentage side-stream treatment on secondary sludge production from the AS system is illustrated in Figure 59. Secondary sludge production in the AS system decreases along with side-stream treatment 27 731 kgTSS/d to 24 502 kgTSS/d.

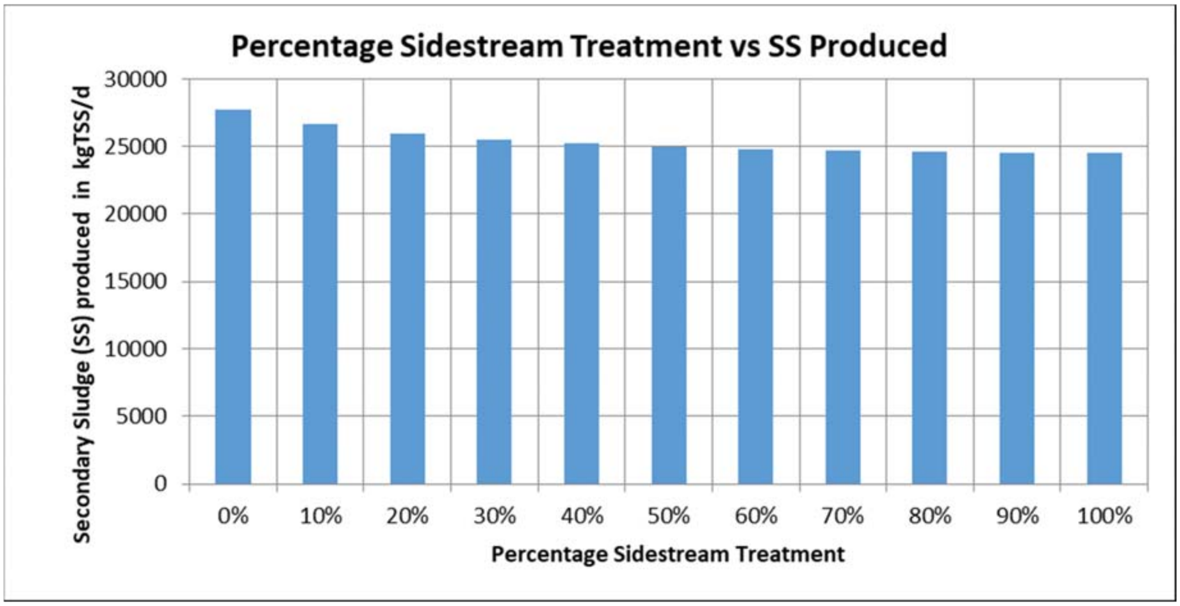

Figure 59: Impact of side-stream treatment on secondary sludge production at 'C' WWTP

5.4 Impact of SLR on Biological Effluent Quality at 'C' WWTP

The biological effluent quality parameters impacted on be sludge return flows are:

- COD Concentration
- Ammonia Concentration
- Nitrate Concentration
- Phosphates Concentration

The impact of SRL on each of the above biological effluent parameters are summarised in this section. Figures below illustrate the impact of sludge returns for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

5.4.1 Effluent COD Concentration

The impact of percentage side-stream treatment on the effluent COD from the AS system is illustrated below in Figure 60. The effluent COD concentration from the AS system remains constant at 75 mgCOD/ℓ.

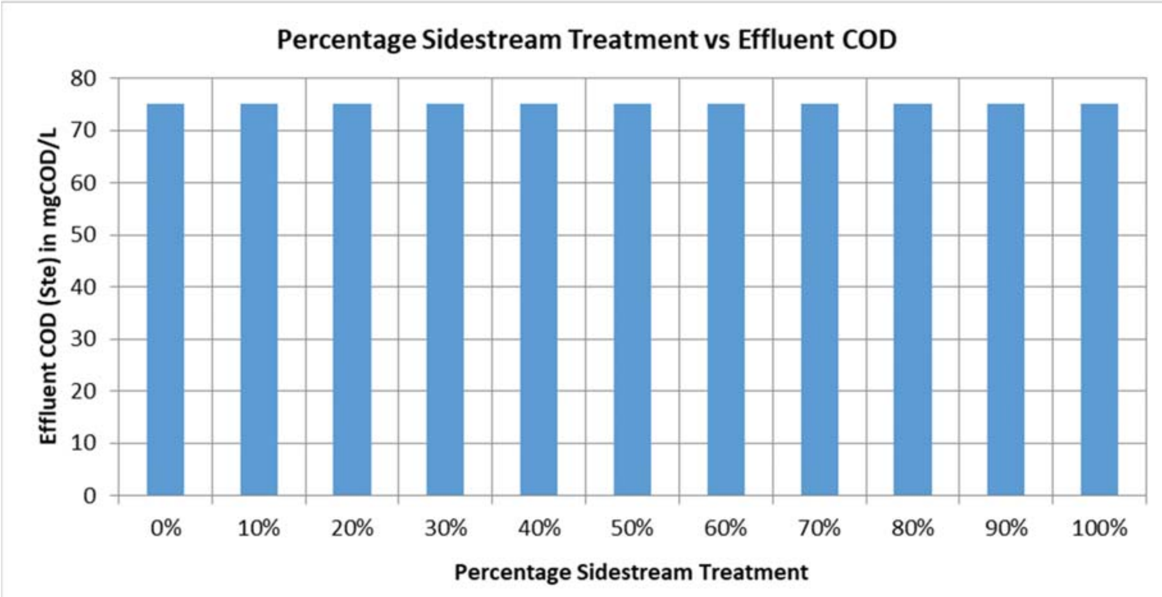

Figure 60: Impact of side-stream treatment on effluent COD at 'C' WWTP

5.4.2 Effluent Ammonia Concentration

The impact of percentage side-stream treatment on the effluent ammonia from the AS system is illustrated below in Figure 61. The effluent ammonia concentration remains constant 0.42 mgN/ℓ.

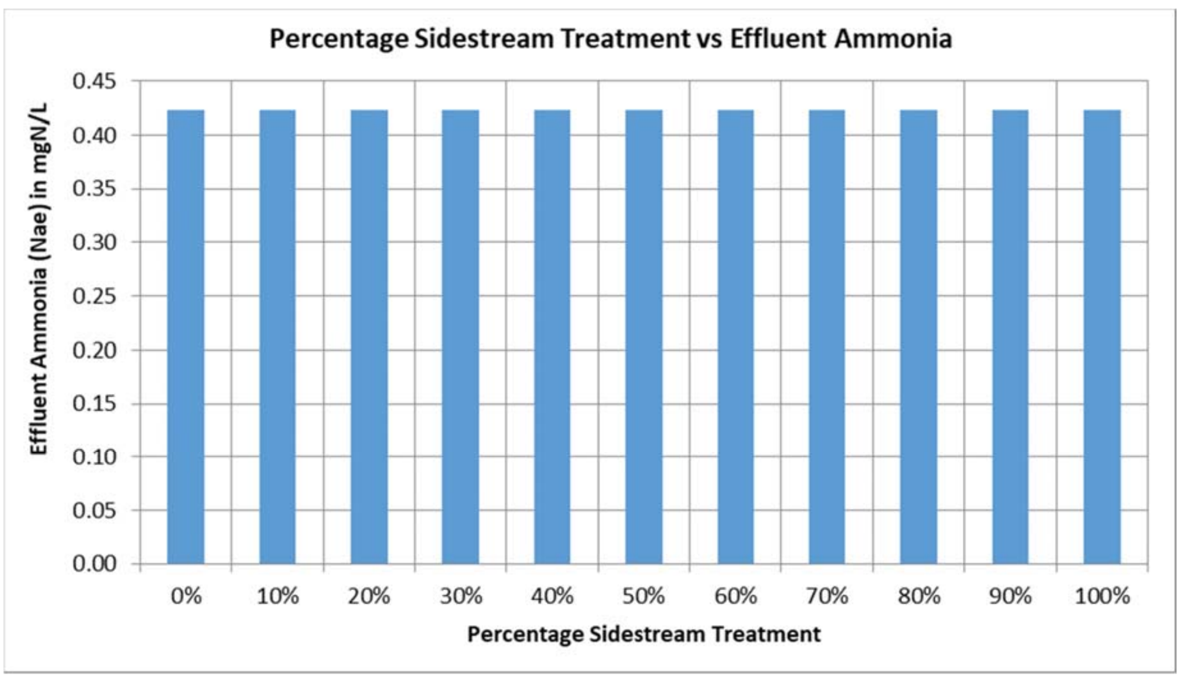

Figure 61: Impact of side-stream treatment on effluent ammonia (with limited aeration capacity) at 'C' WWTP

5.4.3 Effluent Nitrate Concentration

The effluent nitrate concentration decreases with decrease in nitrification capacity. Figure 62 illustrates the effluent nitrate concentration decreases marginally from around 8.5 mgN/ℓ to 6.9 mgN/ℓ.

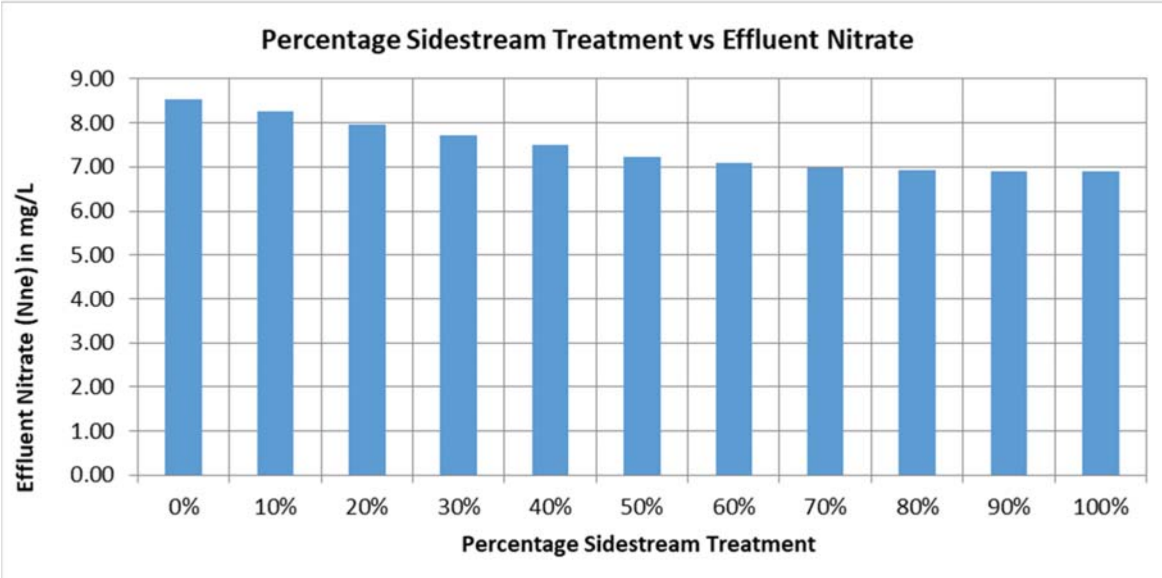

Figure 62: Impact of side-stream treatment on effluent nitrate concentration at 'C' WWTP

Figure 63 shows the estimated readily biodegradable COD load to the anoxic zone that could be used to increase the denitrification potential of the plant to ensure minimum effluent nitrate concentrations (the trend observed is with decreasing SRL to the AS system).

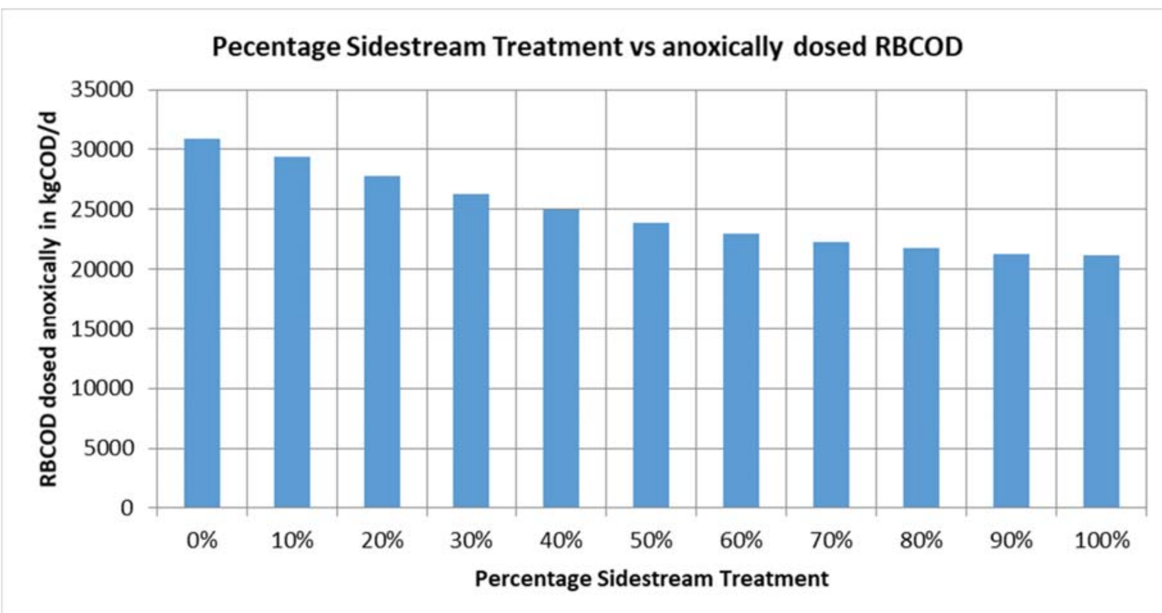

Figure 63: Impact of side-stream treatment on requirements of readily biodegradable organics to be dosed in anoxic zone for reduction of effluent nitrates to minimum concentration at 'C' WWTP

5.4.4 Effluent Phosphorus Concentration

The effluent phosphate concentration from the AS system remains constant at 0.00 mg/ℓ.

5.5 *Summary of Impacts of SRL on 'C' WWTP AS System*

Table 15 below summarises the percentage impact at a given percentage side-stream treatment at 'C' WWTP.

Table 15: Percentage impact for selected side-stream treatment at 'C' WWTP

Percentage Impact at given Percentage Side-stream Treatment at 'C' WWTP							
Parameter		0%	20%	40%	60%	80%	100%
Influent	Flow rate	3.8%	3.0%	2.3%	1.5%	0.8%	0.0%
	COD	0.67%	0.53%	0.40%	0.27%	0.13%	0.00%
	Ammonia	19.1%	12.9%	7.4%	3.3%	0.8%	0.0%
	PO_4	129.0%	55.0%	24.5%	9.5%	2.2%	0.0%
Biological Reactor	a-recycle	-76.1%	-55.5%	-34.5%	-9.1%	-2.1%	0.0%
	Total Oxygen Demand	1.7%	3.1%	1.8%	0.8%	0.2%	0.0%
	Aeration Power Requirement	4.5%	3.1%	1.8%	0.8%	0.2%	0.0%
	SS Produced	13.2%	6.0%	2.9%	1.3%	0.4%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	5.7%	5.3%	4.4%	3.2%	1.7%	0.0%
	PO_4 (Average)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 64 below shows the SRL impact on 'C' WWTP at 0% side-stream treatment. The major impact was observed for influent phosphate load were the impact was 129%.

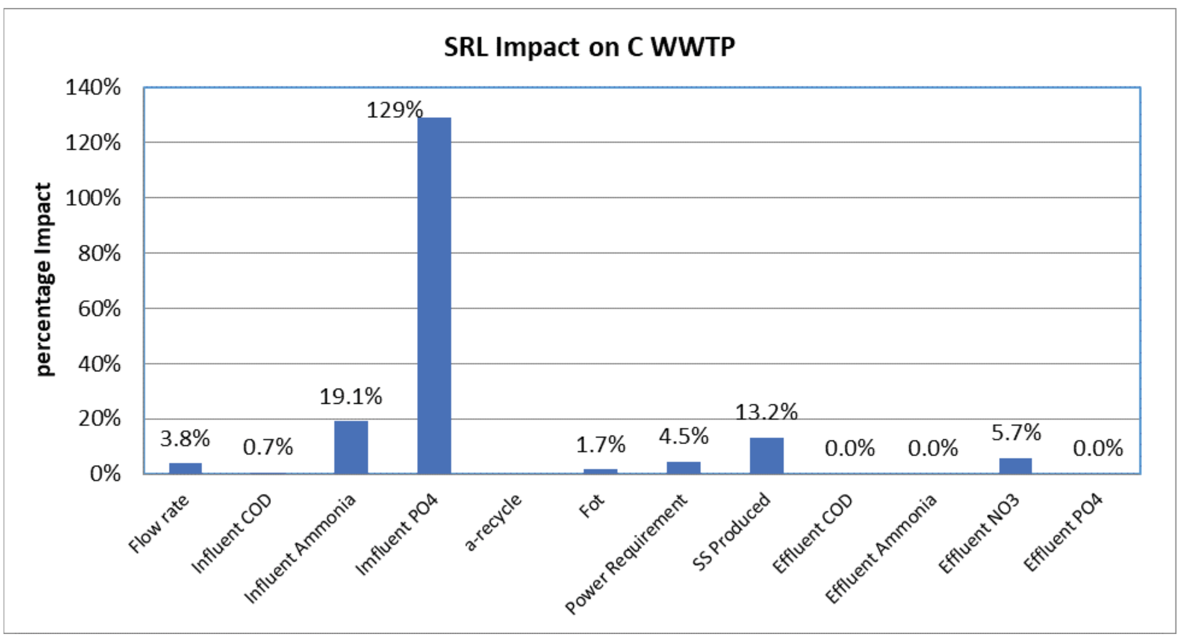

Figure 64: SRL Impact on 'C' WWTW at 0% side-stream treatment

CHAPTER 6: 'D' WWTP

The results of the impact of return sludge liquors at 'D' WWTP are presented in this section. The impact of the sludge return flows was determined on:

- Influent Characteristics
- Biological Treatment Capacity
- Biological Effluent Quality

6.1 Process Description

A description of the 'D' WWTP is indicated below as per information found in the operation and maintenance manuals. Table 16 and Table 17 give a summary of the unit operations and process data. The general process flow diagram of the works in indicated below in Figure 65. 'D' WWTP has a design flow capacity of 4.25 Mℓ/d.

Table 16: 'D' WWTP Unit Operations and Processes

Key Unit Operations and Processes	AS System
Primary Settling Tanks	Yes
BNR System	Yes
Secondary Settling Tanks	Yes
Dissolved Air Flotation	Yes
Anaerobic Digesters	Yes
Dewatering	Yes

The pertinent data for the above unit operations and processes is summarised in Table 17.

Table 17: 'D' WWTP Data

Key Unit Operations and Processes	AS System
Diameter (m)	25
Volume (m^3)	5 940
Diameter	30
Diameter of ea. Unit (m)	10
Volume of each unit (m^3)	424
Anaerobic Digesters	4

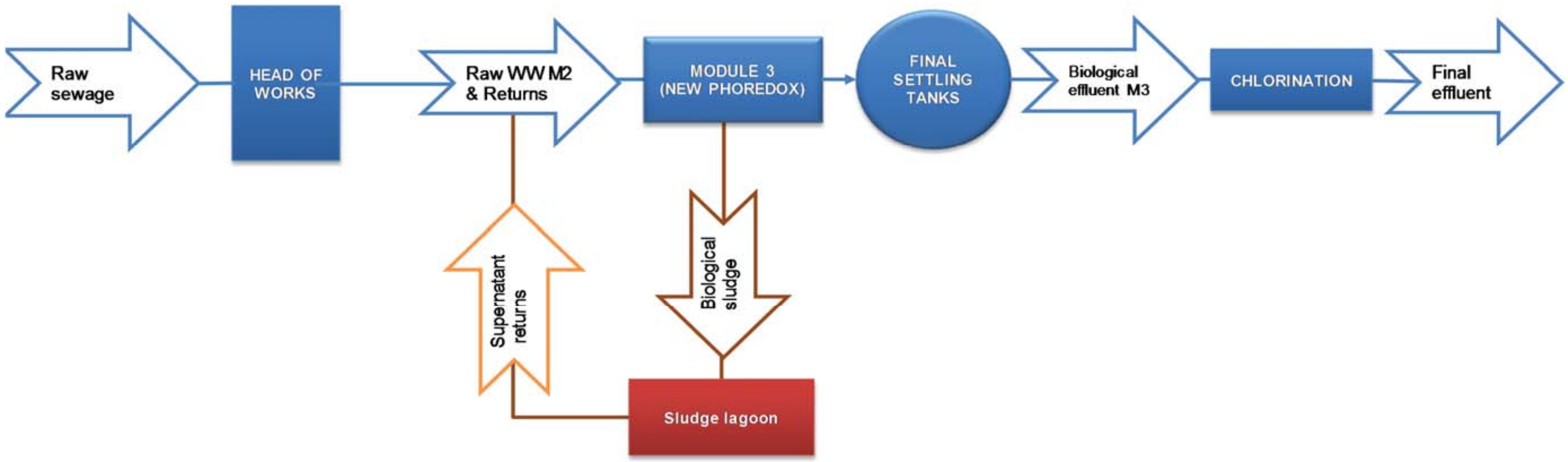

Figure 65: 'D' WWTP Process Flow Diagram

6.2 *Influent Characteristics*

The influent characteristics impacted on by sludge return flows are:

- Influent Flow rate
- Influent COD Load
- Influent Ammonia Load
- Influent PO_4 Load

The impact of sludge return flows on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of SRL for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

6.2.1 *Influent Flow rate*

The impact of percentage side-stream treatment on the flow rate is illustrated below in Figure 66. Without side-stream treatment, i.e. 0% side-stream treatment, means that 100% of SRL flow back to the AS system. The flow to the AS system decreases along with side-stream treatment from 4.10 Mℓ/d to 4.02 Mℓ/d.

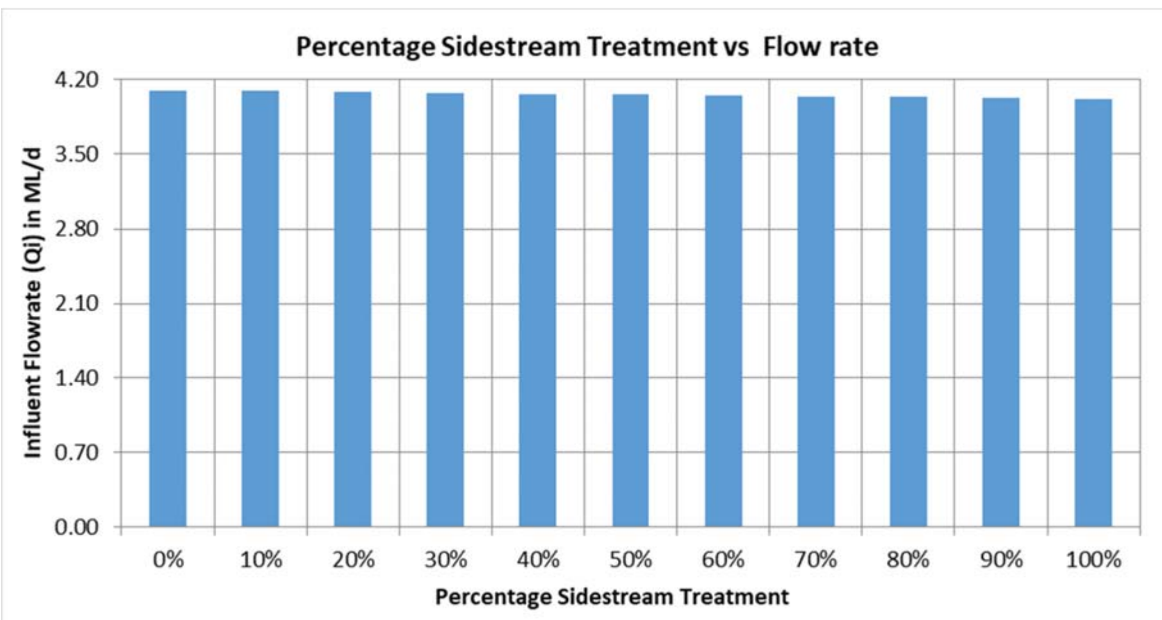

Figure 66: Impact of side-stream treatment on influent flow at 'D' WWTP

6.2.2 *Influent COD*

The impact of percentage side-stream treatment on the total influent COD load to the AS system is illustrated below in Figure 67. Influent COD load to the AS system decreases from 1 884 kgCOD/ℓ to 1 881 kgCOD/ℓ.

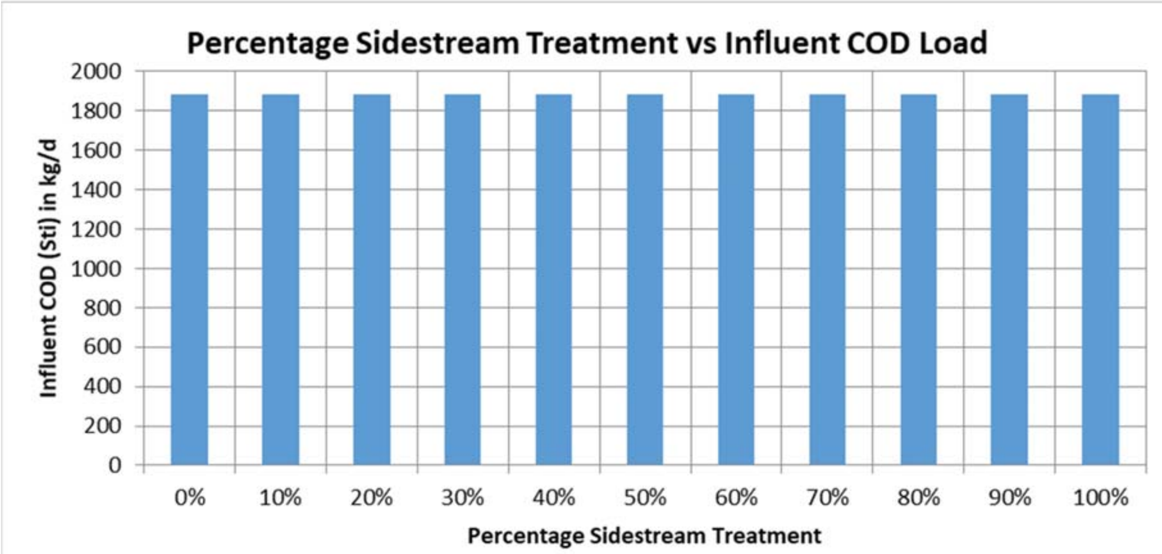

Figure 67: Impact of side-stream treatment on COD Load at 'D' WWTP

6.2.3 *Influent Ammonia Load*

The impact of percentage side-stream treatment on the influent ammonia load to the activated sludge system is illustrated below in Figure 68. The influent ammonia load to the AS system remains constant at 169 kgN/d to 169 kgN/d.

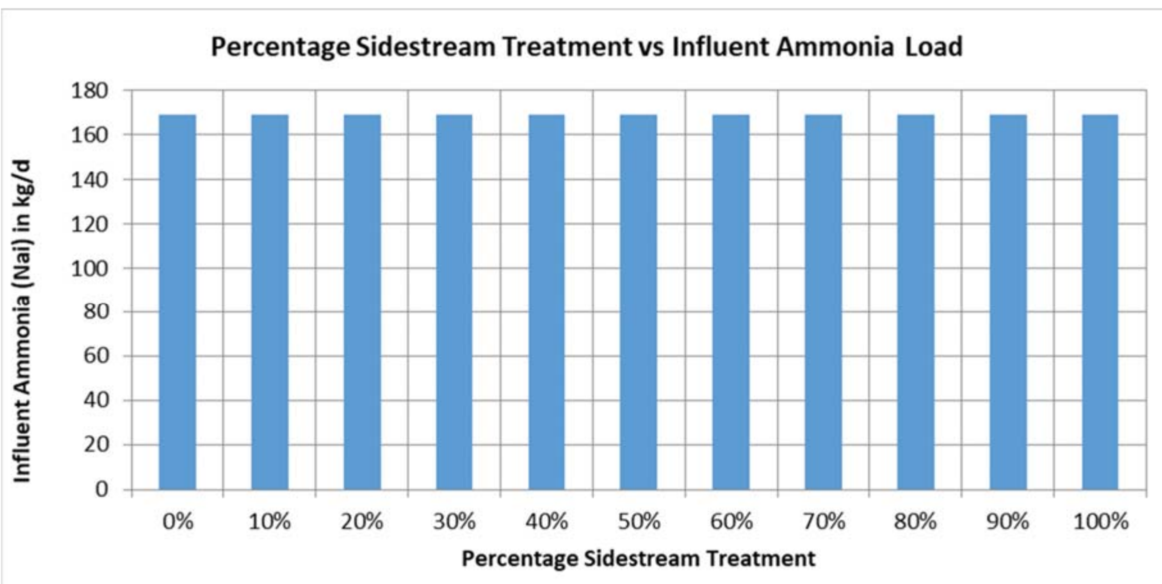

Figure 68: Impact of side-stream on influent ammonia load at 'D' WWTP

6.2.4 *Influent Phosphate Load*

The impact of percentage side-stream treatment on influent phosphate load to the AS system is illustrated below in Figure 69. Influent orthophosphate load to the AS system is constant at 17 kgP/d to 17 kgP/d.

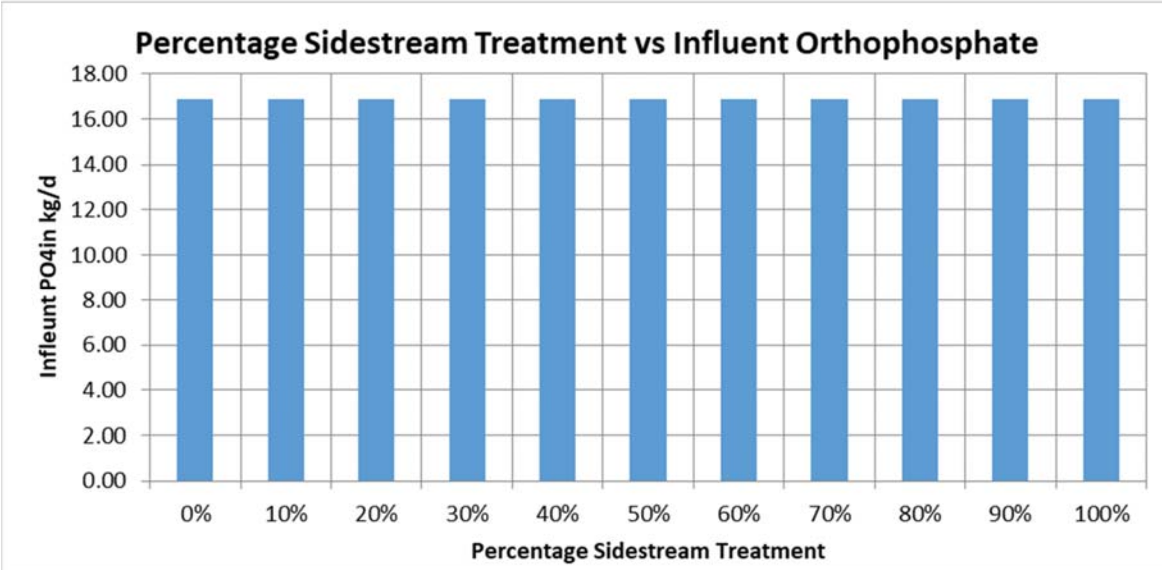

Figure 69: Impact of side-stream treatment on influent phosphate load at 'D' WWTP

6.3 Impact of SRL on Biological Treatment Capacity at 'D' WWTP

The biological treatment capacity parameters impacted on by sludge return flows are:

- A-recycle
- Total oxygen Demand
- Secondary sludge production

The impact of SRL on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of SRL for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

6.3.1 A-recycle

The impact of percentage side-stream treatment on the a-recycle for the AS system is illustrated below in Figure 70. The a-recycle ratio for the AS system decreases from 0.06 Mℓ/d to 0.04 Mℓ/d.

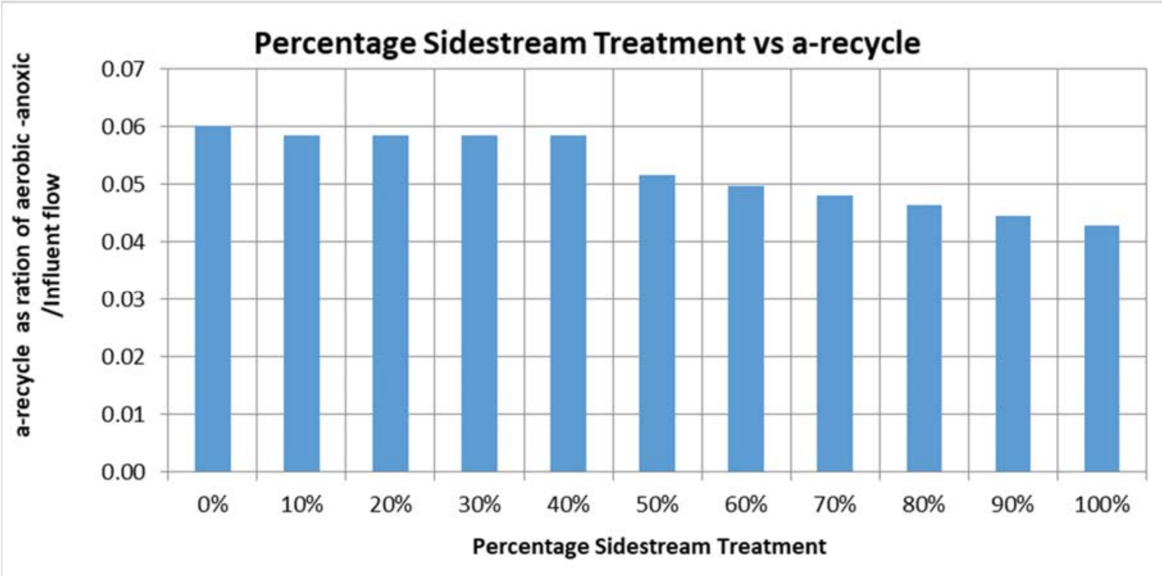

Figure 70: Impact of side-stream treatment on a-recycle at 'D' WWTP

6.3.2 Total Oxygen Demand

The impact of percentage side-stream treatment on the total oxygen demand (FOt) of the AS system is illustrated below in Figure 71. The FOt for the AS system decreases marginally along with side-stream treatment capacity from 1 501 kgO/d to 1 502 kgO/d.

Aeration power requirement for the AS system remains constant at about 33 kW.

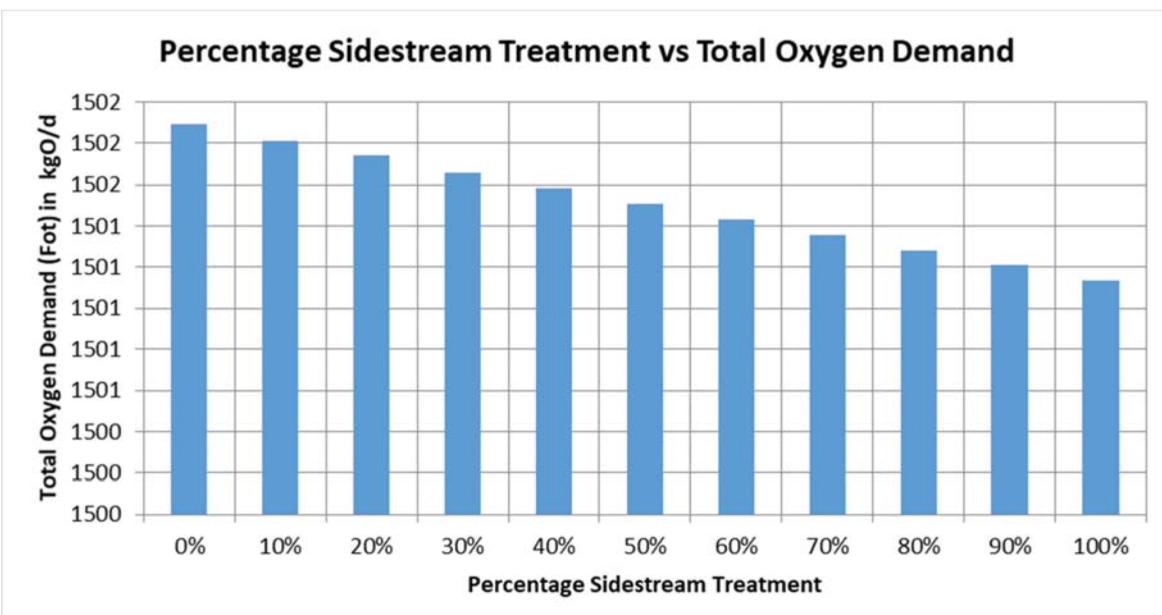

Figure 71: Impact of side-stream treatment on total oxygen demand at 'D' WWTP

6.3.3 *Secondary Sludge Produced*

The impact of percentage side-stream treatment on secondary sludge production in the AS system is illustrated below in Figure 72. Secondary sludge production in the AS system decreases marginally along with side-stream treatment from 764 kgTSS/d to 760 kgTSS/d.

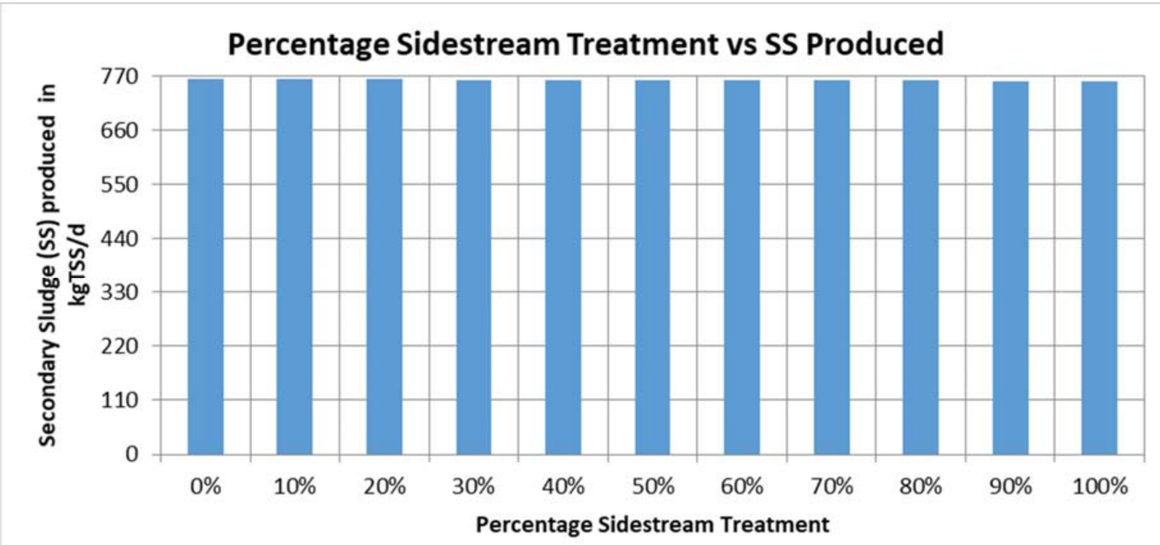

Figure 72: Impact of side-stream treatment on secondary sludge production at 'D' WWTP

6.4 ***Biological Effluent Quality***

The biological effluent quality parameters impacted on be sludge return flows are:

- COD Concentration
- Ammonia Concentration
- Nitrate Concentration
- Phosphate Concentration

The impact of SRL on each of the above influent characteristics is summarised in this section. Figures below illustrate the impact of sludge return flows on biological effluent quality for a given percentage side-stream treatment (0% to 100% side-stream treatment) prior to return to the main water line.

6.4.1 *Effluent COD Concentration*

The impact of percentage side-stream treatment on the effluent COD from the AS system is illustrated below in Figure 73.

The effluent COD concentration from the AS system is constant at 33 mgCOD/ℓ.

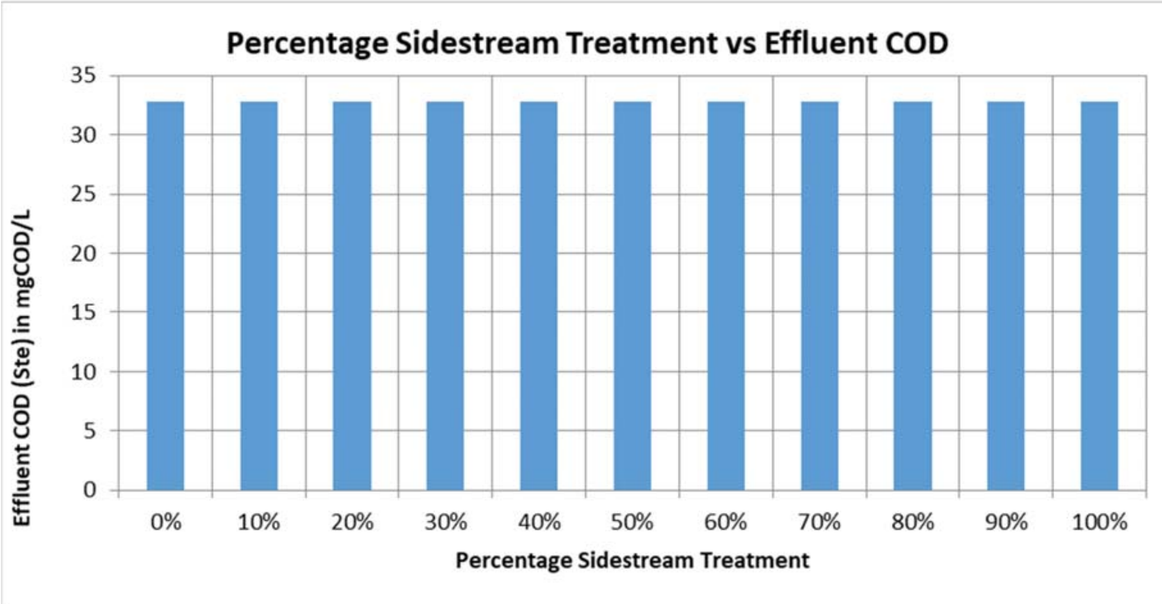

Figure 73: Impact of side-stream treatment on effluent COD concentration at 'D' WWTP

6.4.2 *Effluent Ammonia Concentration*

The impact of percentage side-stream treatment on the effluent ammonia from the AS system is illustrated below in Figure 74. The effluent ammonia concentration from the AS system remains constant at 0.18 mgN/ℓ.

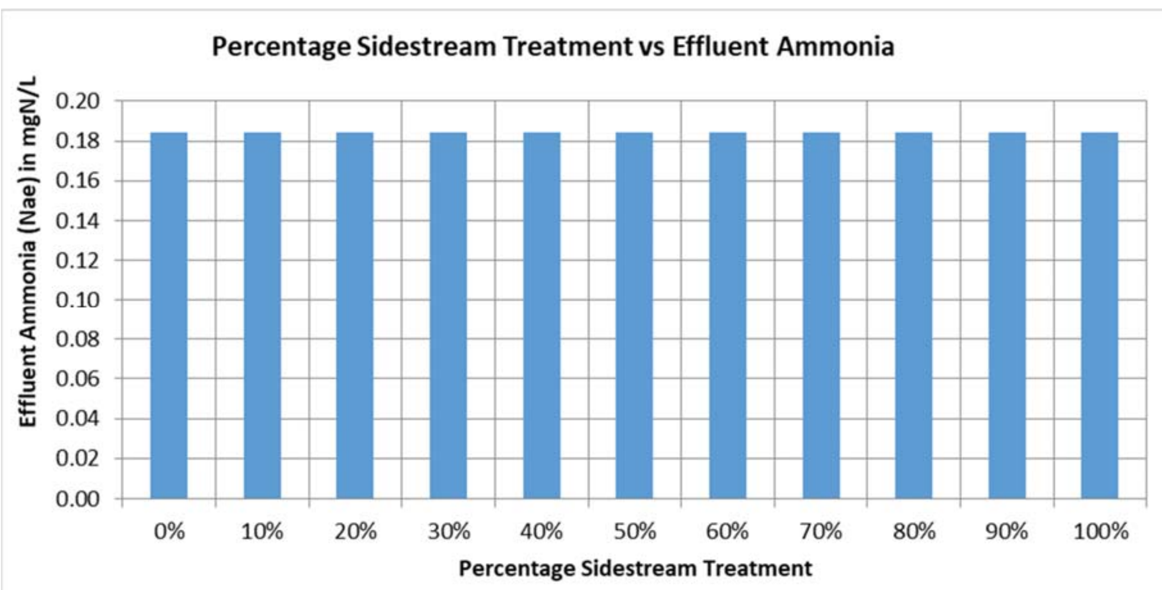

Figure 74: Impact of side-stream treatment on effluent ammonia concentration at 'D' WWTP

6.4.3 *Effluent Nitrate Concentration*

The effluent nitrate concentration increases with increase in nitrification capacity (see Figure 75, the increase is marginal, from around 13.6 mgN/ℓ to 13.9 mgN/ℓ).

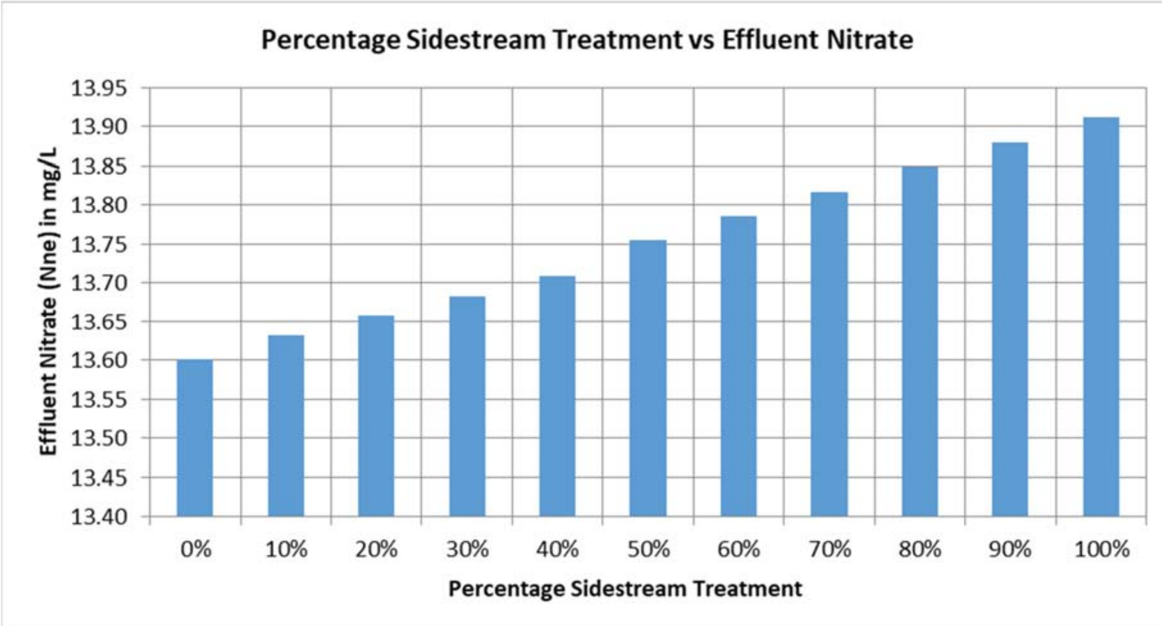

Figure 75: Impact of side-stream treatment on effluent nitrate when aeration is not limited at 'D' WWTP

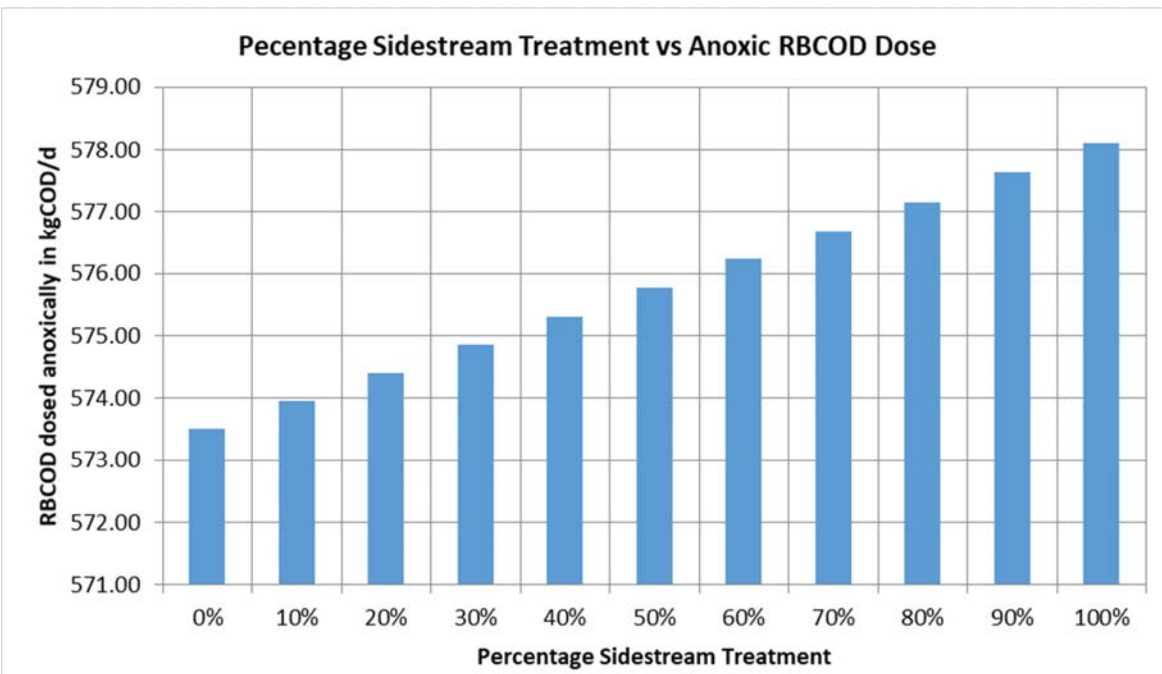

Figure 76: Impact of side-stream treatment on required RBO for use in anoxic zone, for NO_3 removal at 'D' WWTP

6.4.4 *Effluent Ortho-Phosphates Concentration*

The impact of percentage side-stream treatment on the effluent TP from the SST is illustrated below in. The effluent phosphate concentration from the AS system remains constant at 0.00 mg/ℓ.

6.5 *Summary of Impacts of SRL on Influent Characteristics at 'D' WWTP*

Table 18 below summarises the percentage impact at a given percentage side-stream treatment at 'D' WWTP.

Table 18: Percentage impact of SRL for given side-stream treatment at 'D' WWTP

Percentage Impact at given Percentage Side-stream Treatment at 'D' WWTP							
Parameter		0%	20%	40%	60%	80%	100%
Influent	Flow rate	1.9%	1.6%	1.2%	0.8%	0.4%	0.0%
	COD	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	PO4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biological Reactor	a-recycle	40.4%	36.3%	36.3%	16.2%	8.2%	0.0%
	Total Oxygen Demand	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
	Aeration Power Requirement	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
	SS Produced	1.1%	0.4%	0.3%	0.2%	0.1%	0.0%
Effluent	COD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Ammonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NO_3	-2.2%	-1.8%	-1.5%	-0.9%	-0.5%	0.0%
	PO4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 77 below shows the SRL impact on 'D' WWTP at 0% side-stream treatment. The highest impact was observed for a-recycle at 40%.

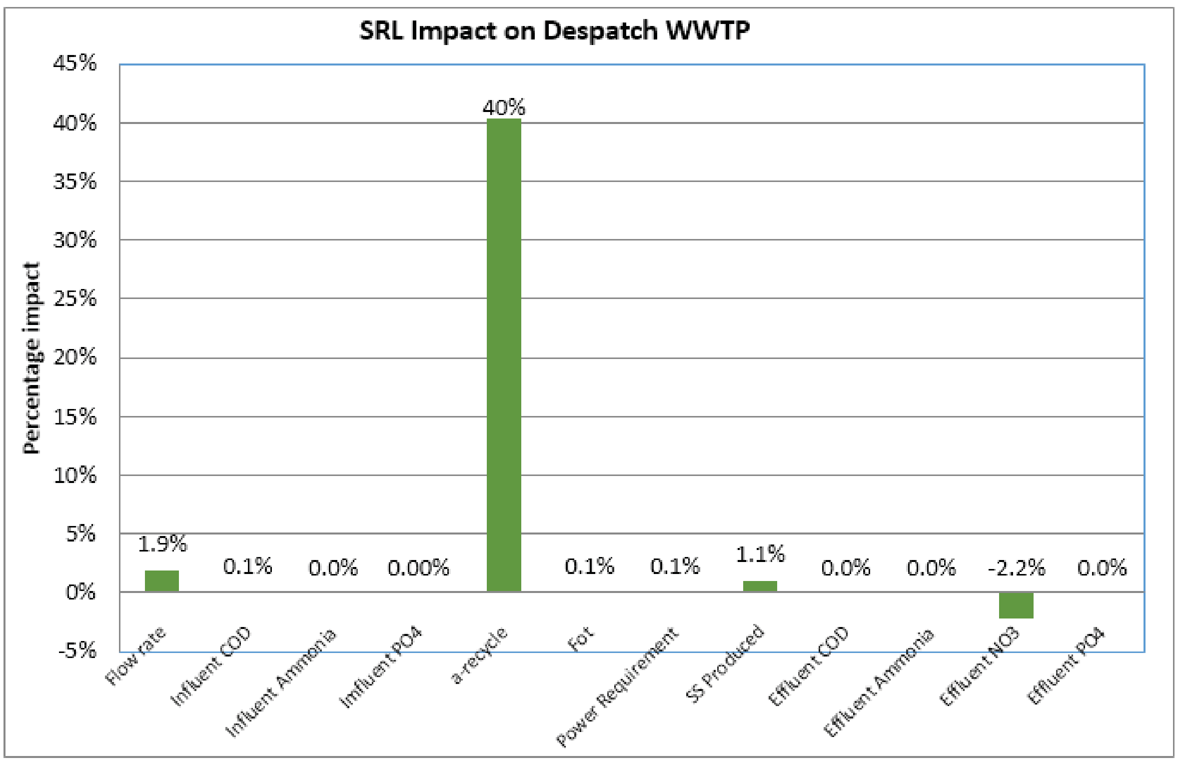

Figure 77: SRL impact on 'D' WWTP at 0% side-stream-treatment

WATER RESEARCH COMMISSION REPORT TT800-19

APPENDIX 3

PLANT PERFORMANCE EVALUATION TOOL

USER MANUAL

PPET

Plant performance evaluation tool

USER MANUAL

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Acronyms and abbreviations

AD	Anaerobic Digester
BABE	Bio-Augmentation Batch Enhanced
BNR	Biological Nutrient Removal
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
DSVI	Diluted Sludge Volume Index
EQI	Effluent Quality Index
JHB	Johannesburg
MLE	Modified Ludzack-Ettinger
OCI	Operational Cost Index
PPET	Plant Performance Evaluation Tool
PS	Primary Sludge
SRT	Sludge Retention Time
TSS	Total Settleable Solids
UCT	University of Cape Town
$V_{aerobic}$	Volume of the Aerobic Reactor (m^3)
$V_{anaerobic}$	Volume of Anaerobic Reactor (m^3)
V_{anoxic}	Volume of Anoxic Reactor (m^3)
WAS	Waste Activated Sludge
WW	Wastewater
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

This user manual is one of three deliverables that were submitted at the end of a study on the impact return dewatering liquor on the overall plant performance in the South African context; the other deliverables being a Plant Performance Evaluation Tool (PPET) and a Detailed Report. PPET was developed with the aim of converting complex plant-wide steady-state models into simple evaluation tools with the intent of evaluating the plant performance (i.e. effluent quality and cost).

The main objectives of PPET are to:

- Evaluate the impact of return dewatering liquor on the overall plant performance (cost and effluent);
- Provide a recommendation for a suitable side-stream treatment process for best effluent quality and lowered operational costs; and
- Educate the user about treatment processes and how different decisions affect the overall plant performance.

<u>Due to the complex processes running in the background, PPET requires a strong computer with a fast CPU for it to function.</u>

2. USER MANUAL

2.1 Home

Upon opening PPET, the home page is displayed. A brief introduction to the tool is provided.

- Please click on the Start button to proceed with this tool.

- By Clicking on the Start button, you will be taken to the Input Parameters tab.

2.2 Input parameters

This page entails entering all raw and settled wastewater (WW) inputs. It has been colour-coded such that the user can easily follow the instructions given. It is recommended that a value within the given range should be chosen, where input parameters are not known.

- A reset button has been provided for clearing all inputs, if needed.

Step 1: General input

Please enter the "blue" values (either for raw or settled wastewater) for the different parameters as shown in *Table **1***. Please select a value within the given range of the parameter, in the case that the input value of a parameter is not known.

Table 1: General inputs

General Input					
Parameter	**Abbreviation**	**Value @ 20 °C**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Design Sludge Age, SRT	SRT	10	10	15 to 25	d
factor of safety	Sf	1.25	1.25	1.1 to 1.5	Constant
Number of Anaerobic Reactors in Series	N_{ana}	2	2	-	-
Population	Popn	5000	5000	-	-
Energy cost		62.03	62.03	-	c/kWh
System Temperature	Design Temp	18	18	15 to 25	°C
Aeration power	P_O2	1.2	1.2	-	kgO_2/kWh
Diluted Sludge Volume Index	DSVI	160	160	150 to 250	mL/g
peak factor (PWWF/ADWF)	fq	2.0	2.0	2 to 4	-

Note:

- Sludge retention time (SRT) is the length of time (in days) that sludge remains in the reactor. It is given by:

$$\mathrm{SRT} = \frac{\text{Total reactor volume}}{\text{Waste flowrate}}$$

- There are different tests that are used to measure sludge settleability.
    - The traditional test for measuring sludge settleability is **Sludge Settleability Test (SVI)**, however, it does not provide the best measurement due to variation in the test results with respect to sludge concentration and stirring effects, the dependency of the test on the cylinder diameter and depth, etc.
    - **Diluted Sludge Volume Index (DSVI)**, is an improved test for measuring sludge settleability. It is the volume (ml) occupied by 1 g of sludge after 30 minutes settling in a one-litre measuring cylinder. DSVI falls within the 150 to 250 ml/l range.

Step 2: Biological Reactor Sizing

Please enter the blue parameters as shown in *Table **2***.

Table 2: Biological reactor sizing parameters

Biological Reactor Sizing Parameters					
Parameter	**Abbreviation**	**Input**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Anoxic Vol.	V_ax	2376	2376	-	m^3
Anaerobic Vol.	V_an	1010	1010	-	m^3
Total Aerobic	V_aer	2554	2554	-	m^3
Aerobic fract.	f_Xaer	0.43	0.43	0 to 1	-
Anoxic fract.	f_Xd	0.4	0.4	0 to 1	-
Anaerobic fract.	f_Xana	0.17	0.17	0 to 1	-
SST Area	AST	1414	1414	-	m^2
anoxic to anaerobic recycle ratio	r_recy	1.00	1.00	0.5 to 5	:1 w.r.t influent flow
mixed liquor recylce ratio	a_recy	4.00	4.00	1 to 10	:1 w.r.t influent flow
Sludge underflow recylce ratio	S_recy	1.00	1.00	1 to 11	:1 w.r.t influent flow
Fraction of influent flowrate (Qi) to Module 1	f_Qi_Mod 1	0.24	0.24	0 to 1	-

- The anaerobic (f_{xana}), anoxic (f_{xd}) and aerobic mass fractions (f_{xaer}) can be calculated using the formulae below:

$$f_{xana} = \frac{V_{anaerobic}}{\text{Total volume}}$$

$$f_{xd} = \frac{V_{anoxic}}{\text{Total volume}}$$

$$f_{xaer} = \frac{V_{aerobic}}{\text{Total volume}}$$

Where:

$V_{anaerobic}$ = Volume of anaerobic reactor (m^3)

V_{anoxic} = Volume of anoxic reactor (m^3)

$V_{aerobic}$ = Volume of the aerobic reactor (m^3)

The sum of the different mass fractions should equal to 1.

- a-recy stands for the recycle ratio from the aerobic reactor to the anoxic reactor. The other recycle ratios (i.e. the r and s) have been assumed to be equal to 1.

Step 3: Anaerobic Digestion (AD)

The primary sludge (PS) and waste activated sludge (WAS) are treated in the anaerobic digester (AD) to reduce the fraction of active biodegradable organics in them before disposal.

➢ Please enter the blue parameters as shown in Table 3.

Table 3: Anaerobic digestion inputs

Anaerobic Digestion (AD)					
Parameter	Abbreviation	Input		Range	Unit
		Raw WW	Settled WW		
Fraction of primary sludge fed to AD	f_QPS_AD	1	1	0 or 1	-
Fraction of secondary waste fed to AD	f_QW_AD	1	1	0 or 1	-
Thickening effect on Primary Sludge (PS)	f_PS	100%	100%	0 to 100	%
Required Sludge Age for Anaerobic Digestion (AD)	Rs_AD_min	60	60	-	Days
Selected Total Suspended Solids (TSS) Concentration	AD_TSS	50000	50000	-	mg/l
pH		8.0	8.0	See Step 3	-
Alkalinity		500	500	See Step 3	mg $CaCO_3$/l
Volatile fatty acids	VFA	0.00	0.00	See Step 3	mg/l

Note:

It is recommended that the pH, alkalinity and VFA concentration of WAS and PS sludge should be measured. Figure 1 shows typical values for treating WAS or PS separately.

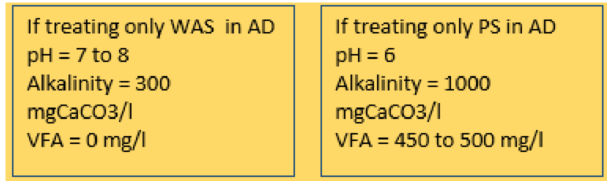


Figure 1: Typical values of pH, alkalinity and VFA concentration.

Step 4: Effluent Quality Criteria

➢ Please enter the plant's effluent quality criteria as shown in Table 4.

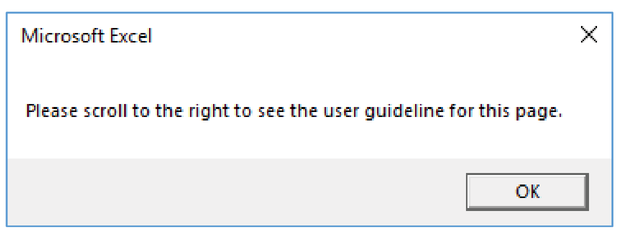
Table 4: Effluent quality criteria inputs

Effluent Quality Criteria				
Parameter	**Abbreviation**	Special limit	Default	unit
Chemical Oxygen Demand	COD	30	30	mgCOD/l
Free and Saline Ammonia	FSA	2	2	mgN/l
Ortho-Phosphate	OP	2.5	2.5	mgP/l
Nitrates	NO_3	1.5	1.5	mgN/
Total Suspended Solids	TSS	10	10	mgTSS/l

Note:

- If no special permission has been granted with respect to having a different effluent criterion, use the defaults special limit values.

➢ Please click on the Data Reconciliation tab to go to the next step.



2.3 Data Reconciliation

This section requires adding influent measurements that have been made on a yearly, monthly basis or diurnally. The data provided is used to estimate the missing influent measurements through the interpolation and fitting processes (see steps 2 and 3 below). Once this process is complete, the generated influent measurements are combined to characterise the wastewater.

This tool is limited to not more than one-year plant data.

Step 1: Please click on the reset button to empty the data cell, then enter the available plant measurements.

Note:

- **<u>All measurements inputs should have a flow rate measurement.</u>**
- Flowrate and COD are the most important measurements. It is recommended that many successive blanks of COD measurements should be avoided as much as possible to avoid skewed results from the interpolation and fitting processes.
- It is recommended that a considerable amount of data should be entered for more accurate influent wastewater characterisation. The richer the influent data measurements, the more accurate the wastewater characterisation will be.

<u>Please note that Excel will be frozen during the execution of steps 2 to 4.</u>

Step 2: Please click on the “INTERPOLATE” button.

Note:

- This process takes several minutes to complete.
- The interpolation process is for interpolating values to fill in the missing gaps in the measurements.

Step 3: Please click on the “FIT” button.

Note:

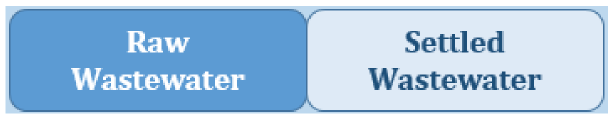
- This process takes about **<u>2 hours</u>** to complete.
- The fitting process is used for calculating the actual values where the interpolated COD and influent flowrate values were estimated.

After the fitting process is complete, you will be taken to the plant configuration tab.

2.4 Plant Configuration

This section consists of selecting the biological nutrient removal plant layout and the type of influent wastewater.

Step 1: Please select between Raw or Settled Wastewater by click on either of the buttons. By selecting the Settled Wastewater, the button will be highlighted as shown below.



Step 2: Please click on one of the buttons to select the biological nutrient removal layout of your choice.

Four configurations have been given. Figure 2 shows the selection of the UCT layout.

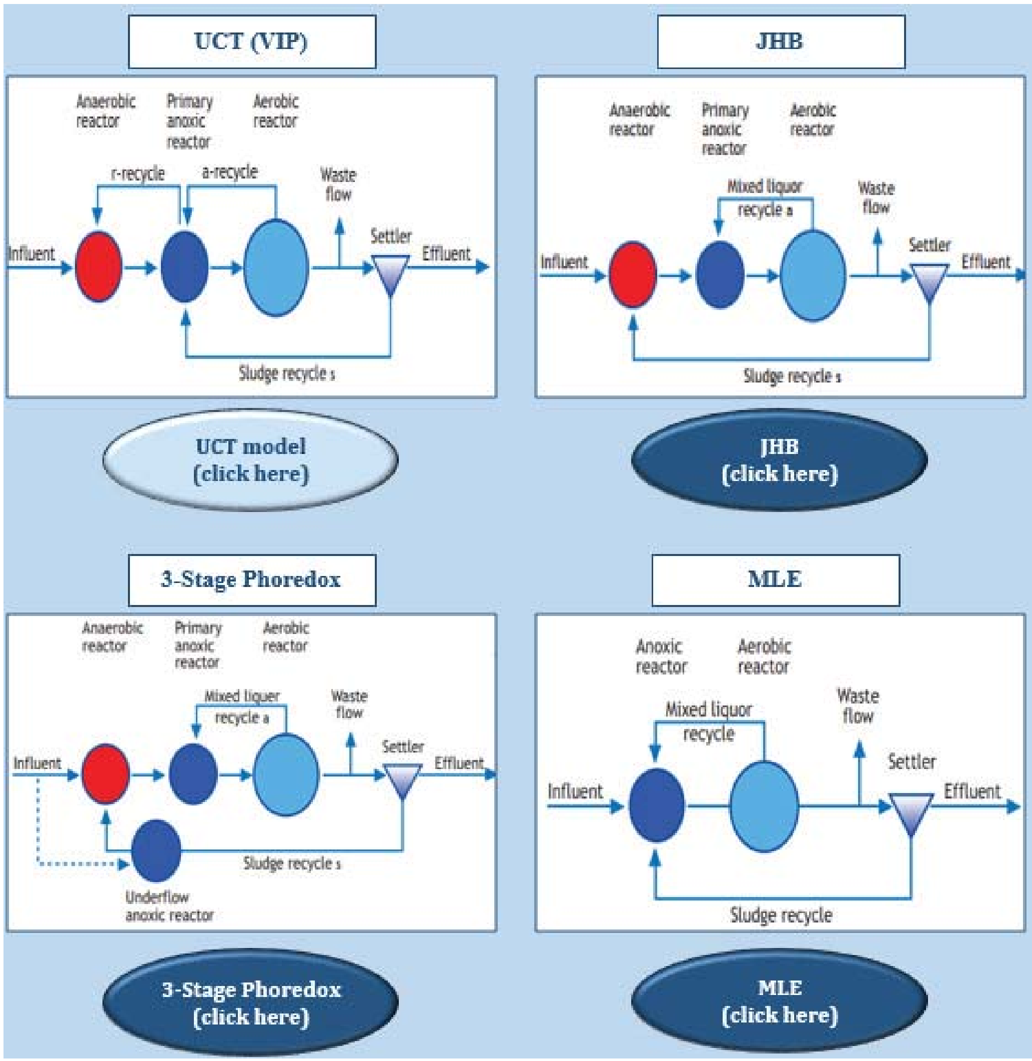


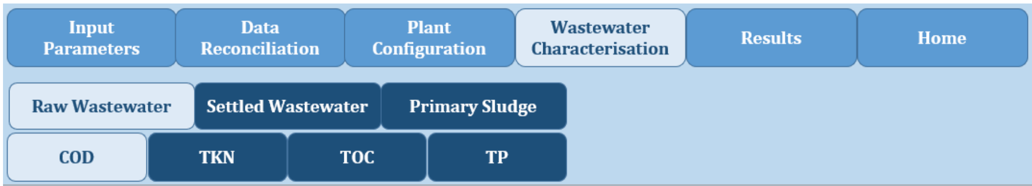
Figure 2: Plant Configuration

By click on any of the buttons, in this case, the UCT layout, the model will take several minutes to run after which you will be taken to the Wastewater Characterisation tab.

2.5 Wastewater Characterisation

The main aim of this page is for educational purposes. The resulting influent wastewater characteristics are used as inputs for the biological nutrient removal models.

Detailed wastewater characterisation (COD, TKN, TOC and TP) is provided under this tab.



The buttons have been colour-coded to make this page easier to navigate. Click on the different button combinations to look at different results.

For example, to view the raw wastewater characterisation of COD, Click on the Raw Wastewater button, then the COD button. The raw and COD button will be highlighted as shown below.

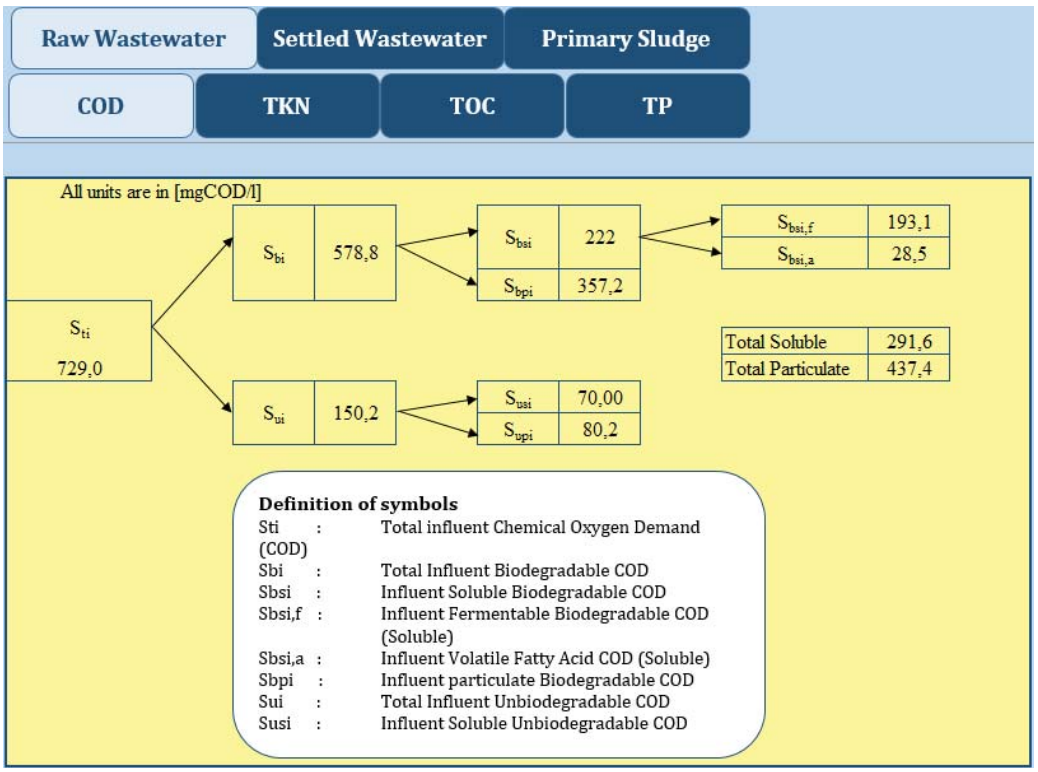


Figure 3: Raw wastewater COD characterisation

2.6 Results

Data from a South African wastewater treatment plant has been used for this demonstration. Several results, based on the inputs, for different biological reactor layouts (i.e. UCT, JHB, MLE and 3-Stage Phoredox) have been summarised.

Figure 4 shows the results' interface once the UCT model has completed running. To view, any of the results click on the buttons.

Figure 4: Interface for the results section

Please choose which results to view by clicking on the respective button.

For example, by clicking on the Biological Reactor button the results will be displayed as shown in *Table **5***, and the results will be displayed.

Table 5: Biological reactor results

Biological Reactor | Dewatering Liquor | Effluent Quality | Plant Performance | Recommendation

Parameter	Units	No side-stream treatment	Struvite precipitation	BABE process
Minimum sludge age for nitrification	days	8,35	8,35	8,24
Carbonaceous Oxygen demand	KgO/d	7459	7459	7459
Nitrification oxygen demand	KgO/d	5265	4812	4771
Peak oxygen demand	KgO/d	9766	9552	9501
Aeration Power Requirements	kW	488	478	475
Secondary Sludge produced	kgTSS/d	7647	6784	7561
PolyP produced in WAS (excess P removal)		301	42	283

Note:

- **Effluent Quality**

  The effluent quality results highlighted in red (see *Table **6***) are those that exceed the effluent quality limit (see *Table **4***).

Table 6: Effluent quality results

Biological Reactor | Dewatering Liquor | Effluent Quality | Plant Performance | Recommendation

Parameter	Units	No side-stream treatment	Struvite precipitation	BABE process
Effluent COD concentration	mgCOD/l	70,00	70,00	70,00
Effluent Ammonia	mgN/l	2,20	2,20	2,20
Effluent NO_3 conc (denitrification)	mgN/l	5,10	4,75	4,76
PO4	mgP/l	0,89	0,91	1,07

- **Plant Performance**
  - The plant performance was evaluated based on two indices, namely the Effluent Quality Index (EQI) and the Operational Cost Index (OCI).
  - The impact of returning dewatering liquor at the different percentage on the EQI and OCI has been summarized in several graphs as shown in Figure 5.

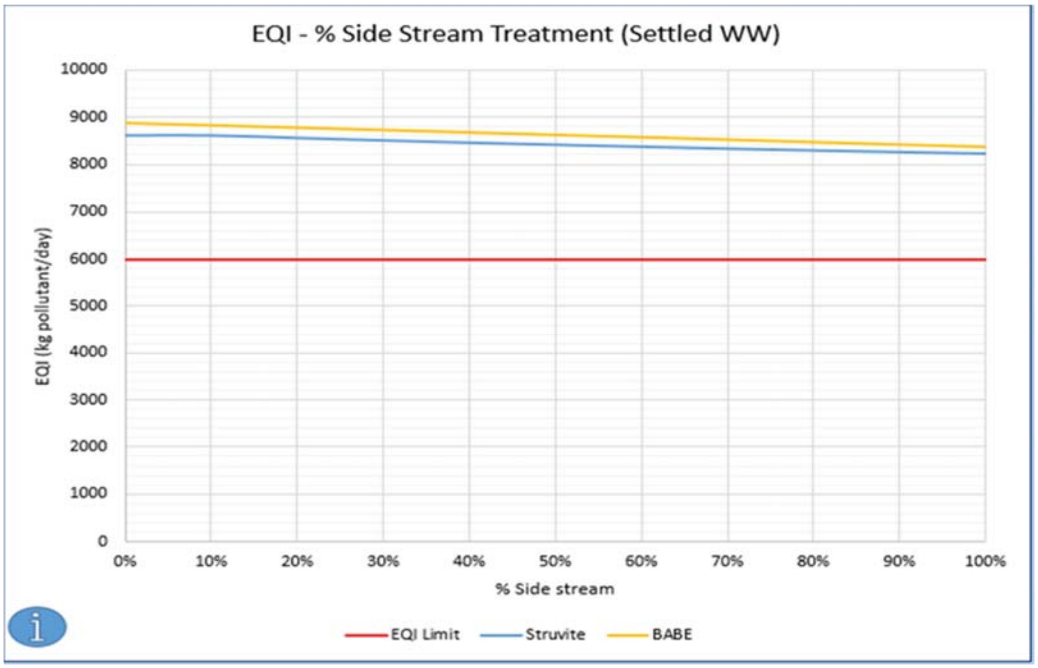
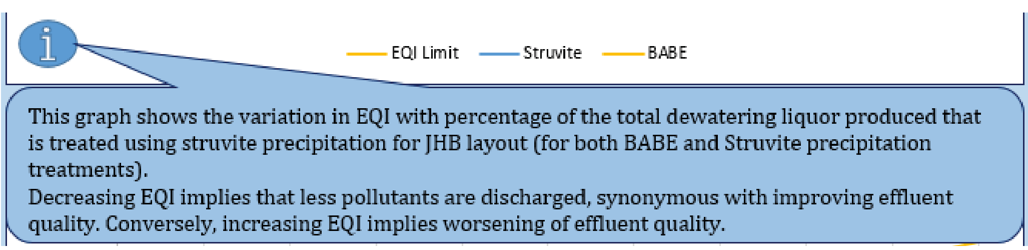


Figure 5: Example EQI graph

Please click on the info  button for more information about interpreting the graph.



3. TOOL DEMO

PPET will be used primarily for evaluating the impact of the return liquors on the effluent quality and operational cost of the plant. The tool's results are estimates and are not to be used as the final figures. For a demonstration, the impact of return dewatering liquors on the wastewater treatment plant was analysed using three South African wastewater treatment plants. Table 7 summarises the plant's information.

Table 7: Plant information

Parameter	Plant A	Plant B	Plant C	Unit
Reactor Layout	UCT	3-Stage Phoredox	JHB	-
Raw WW Flowrate	40.00	23.6	4.02	Ml/d
Settled WW Flowrate	39.6	23.36	4.02	Ml/d
Primary Sludge Flowrate	0.4	0.24	0.0	Ml/d
Influent COD Load	17 386.0	17 736.0	1 886.0	kgCOD/d
Influent TKN Load	1915.0	1 539.0	218.9	kgN/d
Influent TP Load	515.7	533.5	36.7	kgP/d
Volume of anaerobic reactor	1 010.0	6 656.0	405.0	m^3
Volume of anoxic reactor	2376.0	15 660.0	1 158.0	m^3
Volume of aerobic reactor	2554.0	16 835.0	4 225.0	m^3

It was found that there is an added benefit of better effluent quality when a side-stream process is used. The high the percentage of dewatering liquor treated in the side-stream process before being returned to the reactor, the better the effluent quality. Struvite precipitation process achieved lower phosphorus concentration while the BABE process led to lower nitrate concentration in the effluent. The operational cost varied for the different plants based on their influent characteristics and operational parameters. For more information about the tool's results please refer to section 5.6 of the Detailed Report.