IMPACT OF URINE DIVERSION ON BIOLOGICAL NUTRIENTS REMOVAL ACTIVATED SLUDGE WASTEWATER TREATMENT PLANT (BNRAS WWTP)

November 2011

Water Research Group

Department of Civil Engineering

University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

Rondebosch 7701

South Africa

THESIS PRESENTED FOR THE DEGREE OF MASTER IN WASTEWATER
BY:

ANDRE M.K.MBAYA

SUPERVISOR:

Prof. GEORGE EKAMA

RESEARCH SUPPORTED BY:

Water Research Commission (WRC)

DECLARATION

"I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own"

Signed by candidate

07 November 2011

ANDREM.K.MBAYA

DATE

ACKNOWLEDGEMENTS

- *GOD Almighty* and *His Holy Mother* for giving the aptitude to do the research and interceding for me always and especially in times of uncertainty and distress.

- *Professor G.A. Ekama* for assigning the urine separation project, for his countless knowledge, support, guidance, tips and sense of humour throughout the course of this Masters Degree.

- *Dr J. Wilsenach* for starting the urine separation project in its current context.

- *Mr J. Germanis* for arranging all the logistics around the urine separation project, which included the delivery of wastewater to the Water Research Laboratory (WRL) at UCT and the organisation of workshops.

- *Mr A. Simmers* for his work of running and maintaining the wastewater collection and storage systems at the Council for Scientific and Industrial Research (CSIR) and helping with wastewater delivery to the WRL at UCT.

- *Mr T. Lakay* for sharing his vast knowledge and experience, giving assistance in operating the laboratory units in the WRL at UCT.

- *Mr H. Mafungwa* for teaching the experimental tests, assisting with the daily work in the WRL as well as keeping all the equipment clean and running.

- All the *staff of block D at the CSIR* for properly using the no-mix toilets and without whom there would not have been wastewater for the experiment. Thanks to all the *cleaners* for always keeping the no-mix toilets tidy and respecting the given instructions.

- All the *librarians* for their help in the course of my theoretical research.

- *Parents* and *friends* for their interest in my work, encouragements and prayers.

The writer wishes to express his gratitude to *Dr V. Naidoo* who was the WRC chairperson of the committee on the urine separation project. Dr Naidoo is currently research manager at the WRC in the sector of water use and waste management.

Likewise, the writer wishes to thank the organizations which funded and/or assisted the project:

- *Water Research Commission* (WRC)
- *Water Research Group of the University of Cape Town* (WRG-UCT)
- *National Research Fund* (NRF)
- *Council for Scientific and Industrial Research* (CSIR)

Sincere thanks for giving permission of access to information go to:

Mr K. Samson	City of Cape Town WW Department (Manager)
Mr M. Toll	City of Cape Town WW Department (District Manager)

LIST OF ABBREVIATIONS

AE	Aerobic
AEML	Aerobic Mixed Liquor
AN	Anaerobic
ANML	Anaerobic Mixed Liquor
AS	Activated Sludge
Avg	Average
AX	Anoxic
AXML	Anoxic Mixed Liquor
BCFS	Biological-Chemical Phosphorus and Nitrogen Removal
BNRAS	Biological Nutrient Removal Activated Sludge
EBPR	Excess Biological Phosphorus Removal or Biological Excess Phosphorus Removal (**BEPR**)
CAS	Conventional Activated Sludge
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CSIR	Council for Scientific and Industrial Research
CSS	Combined Sewer System
DO	Dissolved Oxygen (mgO/ℓ)
DPAO	Denitrifying Phosphate Accumulating Organism
DSVI	Diluted Sludge Volume Index
E (or effl.)	Effluent

ECATU	Eastern Cape Appropriate Technology Unit
FAS	Ferrous Ammonium Sulphate
FE	Filtered Effluent
FI	Filtered Influent
FSA	Free and Saline Ammonia
GDP	Gross Domestic Product
GVA	Gross Value Added
Hh	Household
I	Influent
JHB	Johannesburg (NDEBPR system with Johannesburg configuration)
MLE	Modified Ludzack Ettinger
MLL	Minimum Living Level
n/a	Not Applicable
ND	Nitrification-Denitrification
NDEBPR	Nitrification-denitrification Excess Biological Phosphorus Removal or Nitrification-denitrification Biological Excess Phosphorus Removal (**NDBEPR**)
OHO	Ordinary Heterotrophic Organism
OPAO	Oxydizing Polyphosphate Accumulating Organism
OU	Oxygen Utilized
OUR	Oxygen Utilization Rate
/p.d	Per Person Per Day
PAO	Polyphosphate Accumulating Organism
PPP	Purchasing Power Parity

PS	Primary Sedimentation
PST	Primary Settling Tank
PT	Primary Treatment
Q_w	Waste flow rate (l/d)
RBCOD	Readily Biodegradable COD
ROEC	Reed’s Odourless Earth Closet
RWW	Raw Waste Water
SA	South Africa
SBCOD	Slowly Biodegradable COD
SCFA	Short Chain Fatty Acid
SRT	Solids Retention Time (or sludge age)
SSD	Sample Standard Deviation
SSP	Steady State Period
SSS	Separate Sewer System
SST	Secondary Settling Tank
ST	Secondary Treatment
SWW	Settled Waste Water
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
TSS	Total settleable solids (mg TSS/ℓ)
TT	Tertiary Treatment
UCT	University of Cape Town

UD	Urine Diversion
UE	Unfiltered Effluent
UWWM	Urban Wastewater Management
VFA	Volatile Fatty Acid
VIP	Ventilated Improved Pit
VSS	Volatile settleable solids (mgVSS/ℓ)
WAS	Waste Activated Sludge
WB	World Bank
WRC	Water Research Commission
WRL	Water Research Laboratory
WW	Wastewater
WWM	Wastewater Management
WWT	Wastewater Treatment
WWTPs	Wastewater Treatment Plants

LIST OF SYMBOLS

$\mathbf{b_{HT}}$	Specific endogenous mass loss rate of OHOs at temperature T (1/d)
$\mathbf{b_{GT}}$	Specific endogenous mass loss rate of PAOs at temperature T (1/d)
C	Carbon
d	day
˚C	Degrees Celsius
Δ	*Delta*. Indicates a change in parameter value
$\mathbf{f_{CV}}$	COD/VSS ratio (mgCOD/mgVSS) of the mixed liquor
$\mathbf{f_{EH}}$	Endogenous residue fraction of OHOs
$\mathbf{f_{EG}}$	Endogenous residue fraction of PAOs
$\mathbf{f_{i}}$	VSS/TSS ratio (mgVSS/mgTSS)of the mixed liquor
$\mathbf{f_{n}}$	Nitrogen to VSS ratio of the mixed liquor (mgN/mgVSS)
$\mathbf{f_{p}}$	Phosphorus to VSS ratio of the mixed liquor (mgP/mgVSS)
$\mathbf{f_{S'bs}}$	Fraction of the total COD that is biodegradable soluble or fraction of the total COD that is *readily* biodegradable
$\mathbf{f_{S'up}}$	Fraction of the total COD that is unbiodegradable particulate
$\mathbf{f_{S'us}}$	Fraction of the total COD that is unbiodegradable soluble
>	Greater than
<	Less than
~	Approximately equal to
ℓ	Litre
N	Nitrogen

$\mathbf{N_{obs}}$	Organic Nitrogen Biodegradable Soluble
$\mathbf{NO_2}$	Nitrite
$\mathbf{NO_3}$	Nitrate
$\mathbf{NO_x}$	Nitrite and nitrate
P	Phosphorus
$\mathbf{P_{obs}}$	Organic Phosphate Biodegradable Soluble
SRT	Solid Retention Time (Sludge Age)
$\mathbf{S_{bs}}$	Biodegradable Soluble Organics
$\mathbf{S_{bp}}$	Biodegradable Particulate Organics
$\mathbf{S_{us}}$	Unbiodegradable Soluble Organics
$\mathbf{S_{up}}$	Unbiodegradable Particulate Organics
$\mathbf{S_{ti}}$	Total Influent Organics

Note: Only symbols used in the text are included in this list. The symbols used in equations are defined in the appropriate sections.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYNOPSIS

1. MOTIVATION

Urine contains most nutrients – 80% nitrogen (N) & 50% phosphorus (P) - of the total wastewater (WW) although it represents a mere 1% of its volume. Separation of urine from main WW stream can be a way to:

a) Improve the effluent quality from WW treatment plants (WWTPs) in terms of N & P as well as micropollutants such as estrogens, medicine residues and pharmaceutical products. If N & P are not removed from WW to low concentrations they can cause eutrophication of receiving water bodies. Likewise, micropollutants which are also called endocrine disruptors or environmental estrogens, are proven to be responsible for severe disruption in the environment affecting the gender of fish and reptiles at WWTP discharges and believed to be detrimental to human health. Because urine contains most nutrients and micropollutants, diverting urine from WW will reduce the loads of such substances on WWTPs with the aim of environmental protection.

b) Save water with*urine separation toilet* also called *no-mix toilet*, which offers the significant advantage of using up to 90 % less flush water/p.d than ordinary toilet.

c) Close the loop of nutrients by recycling them to agriculture. Through proper handling, source separated urine can be used as a soil conditioner in agriculture and in so doing returns the macro-nutrients N & P to the earth.

d) Recover P from diverted urine. P bearing ore is a non-renewable resource so there is a drive for P recovery from WW for reuse. The low dilution factor associated with the no-mix toilet makes it easier to chemically recover P e.g. through *struvite* precipitation.

e) Possibly simplify Biological Nutrient Removal Activated SludgeWastewater Treatment Plants (BNR AS WWTPs) because N removal through nitrification-denitrification is the BNRAS size governing bioprocess via the sludge age (SRT).

The concept of urine separation is fairly recent having been experimented in fringe projects in both developed and developing countries like Holland, Germany, Sweden, Australia, Ethiopia or South Africa in the late 1990s. Whereas in developed economies the aim of urine separation isgenerally to protect the environment; save water; recycle nutrients and possibly recover P, in the developing world,the primary and often single aim for doing urine separation is nutrient recycle to agriculture. Reasons for this are 1) given the large number of poor people in developing countries, the potential use of urine as a fertilizer is considered a way to alleviate poverty because people can use urine as a soil conditioner to grow vegetables and fruits for subsistence and/or for selling; and 2) most developing economies do not have WW treatment systems and therefore environmental protection is not a concern i.e. the concept of environmental sustainability is generally quasi-inexistant;Besides, *dry* as opposed to *wet* no-mix toilet is the widely found technology for urine separation in developing countriessuch as *South Africa*because they were initially designed to remedy problems associated with the composting process of human wastes (composting toilet). In general, the focus of urine separation worldwide has been on the diverted urine, but seldom on the remaining WW components and the advantages of treating these separately from urine.

While studying the impacts of urine separation on treatment plants, Wilsenach (2006) experimentedwiththe modeling on a pilot-scale BCFS process (Biological and Chemical Phosphorous Removal) WWTP. The first phase of the project consisted of separating urine in increments and analyzing the impacts of treating the remaining wastes on the treatment plant.The results showed a 70% decrease in total effluent N content with increasing urine separation up to 60% and nearly 100% P removal without urine separation. At greater urine separation, the model showed no improvement in effluent quality due to the magnitude of the Monod affinity constants in the kinetic equations and therefore the system became redundant (Wilsenach, 2006:52). An additional finding was that urine separation increased the treatment capacity of the plant by 50 %.The predicted effluent N and P concentrations only decreased below the affinity constant limit concentrations once nutrient limitation took place.Nonetheless, the analysis of the impacts of urine separation on WWTP such as BNRAS plant is lacking. Do the Monod affinity constants also set the limit of technology – LOT - in such real WWTP? There are assumptions onthe significant improvements urine separation can bring to BNRAS treatment work viz. 1) increase in WW treatment plant capacity; 2) Improvement in effluent quality; and 3) Reduction inenergy consumption

Therefore, this experimental investigation was started to study the impacts urine separated WW can have on *BNRAS WWTPs*with a*UCT* and a *JHB configuration.*

2. OBJECTIVES AND AIMS OF RESEARCH

The objective of this research was to:

Investigate the impact of urine diversion on a laboratory scale BNRAS WWTPhaving a UCT configuration, operated at 20 day SRT (T= 20^{o}C) and receiving a mixture of grey and brown WW.

During the course of the research, effluent nitrate concentrations (<1 mgNO$_3$-N/ℓ) and nitrification batch tests on sludge harvested from the aerobic (AE) reactor revealed the absence of nitrification in the UCT system treating a 50/50 (by volume) grey and brown WW mix, i.e. nearly all N was used for biological growth and no nitrate was produced. The P removal in the UCT system proceeded via the normal excess biological phosphorus removal (EBPR). Subsequent to these observations made in running the UCT system,the Johannesburg (JHB) system was set up and started after 224d steady-state-operation of the UCT system. The rationale for operating the JHB system was to achieve 1) better P removal at the short SRT, without interference of nitrification (which was confirmed to not be taking place in the long SRT UCT system). The P removal was protected by placing an AX reactor upstream of the AN reactor which prevented any nitrate to be recycled to AN reactor in the event it did nitrify; and 2) smaller system volume due to the low SRT (¼ of the UCT system's SRT). The JHB systemreceived the same volume of grey and brown WW mix.Hence, a second objective of the research was identified:

Protect or possibly improve the P removal within the JHB system operated at a SRT of 5 days (T= 20^{o}C) and monitor the effluent COD, N and P concentrations thereof.

The JHB system was then run simultaneously with the UCT system for asteady state period (SSP) of 154 days.Throughout the experiment, the grey and brown water were collected separately from the kitchen and from two no-mix toilets in one office block (D-block) at the CSIR, in Stellenbosch, in the Western Cape Province of SA (± 60 Km). Fifteen (15) people frequented block D of the CSIR during working hours. These WW components were stored for about 1 week in the empty freezer in the compressor room by B-block (of the CSIR) before being shipped to the UCT waterresearch laboratory (WRL) for the experiment.

3. INVESTIGATION OF THE IMPACTS OF URINE SEPARATION ON THE BNRAS UCT AND JHB SYSTEMS

3.1 SYSTEMS OPERATED

The research approach adopted for the experimental investigation was to first run a BNRAS system with the UCT configuration at a long SRT for a fixed SSP of nearly 224 days. Once it became apparent that nitrification did not take place in the UCT system at 20d SRT (and 20℃), the JHB system was started up at 5d SRT due to the significantly better N and P removal performance of this system at the short SRT. Then both systems were run simultaneously for a further period of 198 days. The UCT system was selected because it offers the advantage that the nitrification-denitrification (ND) process can occur independently of the biological excess phosphorus removal (BEPR) process. The UCT system was run at a long SRT of 20 days to induce nitrification. Its performance was evaluated by comparaison with the performance of the conventional activated sludge UCT system (identified here as CAS UCT system) operated by Ramphao et al. (2004). The CAS UCT was fed normal (real) WW from Mitchell's Plain WWTP and had similar design and operating parameters to the UCT system.

3.2 SYSTEMS SET-UP

The UCT and JHB systems were *3-reactor-configuration* systems consisting of anaerobic (AN), anoxic (AX) and aerobic (AE) reactors that were operated in the constant temperature WRL of 20°C at the University of Cape Town.The UCT system was set-up to have the same design parameters as the CAS UCT for evaluation purpose viz. Influent flow of 15 ℓ/d; recycles r = 1:1, a = 2:1 and s = 1:1 and SRT of 20 days. The design parameters for the UCT, JHB and CAS UCT are listed in **Table 1.**The UCT and JHB systems were operated at 20d and 5d SRT respectively by wasting the required fixed amount of mixed liquor from the aerobic reactor daily and taking account of sample volumes.

Table 1: UCT, JHB and CAS UCT systems' design parameters.

System parameter	UCT	JHB	Conventional UCT
Sludge age (days)	*20*	*5*	*20*
$f_{m,anaerobic}$, Volume (ℓ)	*0.200 [1]/ 7*	*0.250[1]/ 4.4*	*0.126 [1]/ 5.6*
$f_{m,anoxic}$, Volume (ℓ)	*0.400 [1]/ 10*	*0.500[1]/ 1.1*	*0.279 [1]/ 6.2*
$f_{m,aerobic}$, Volume (ℓ)	*0.400 [1]/ 15*	*0.250[1]/ 8*	*0.595 [1]/ 13.2*
a-recycle (AE to AX)	*1:2*	*n/a*	*1:2*
r-recycle (AX to AN)	*1:1*	*n/a*	*1:1*
s-sludge recycle (SST to AX)	*1:1*	*1:1*	*1:1*
Hydraulic retention time (day)	*2.13*	*0.90*	*1.4*
MLVSS (AE) (mg/ℓ)	*2600[2]*	*2100[2}*	*3600[2}*
MLTSS (AE) (mg/ℓ)	*3250[2}*	*2650[2}*	*4950[2}*
$f_{S'us}$	*0.05*	*0.05*	*0.05*
$f_{S'up}$	*0.13*	*0.13*	*0.13*
$f_{S'bs}$	*0.27*	*0.27*	*0.27*
Influent flow (ℓ/d)	*15*	*15*	*15*
Feed COD (mg/ℓ)	*1000*	*1000*	*1000*

$f_{m,anaerobic}$, $f_{m,anoxic}$&$f_{m,aerobic}$ are anaerobic, anoxic and aerobic mass fraction respectively; [1] for the given a-, r- or s-recycle ratios; [2] predicted using processes and modeling of NDBEPR BNR (Wentzel et al., 1992).

3.3 SYSTEMS' FEED

Given that incremental urine separation would be unnecessary unless complete separation brought significant improvement to WW treatment, it was decided to mix only grey and brown water. This corresponded to a scenario of 100 % urine separation. The grey and brown WW were imported from the pilot-scale no-mix toilet and kitchen of one office block at the CSIR (D-block) and stored in the cold room (4°C) of the WRL at UCT for 10 days before it was discarded and a new batch stored. In order to estimate the volumes of grey and brown water to mix, the changes in TKN/COD and TP/COD ratios were calculated at different mixing proportions. The grey and brown WW had COD (mgCOD/ℓ), TKN (mgN/ℓ) and TP (mgP/ℓ) concentrations around 1800, 45 and 5 and 7000, 260 and 90 respectively. From the ratios, the brown water contained about 50% more N and P per COD. Because the per capita generation of grey and brown water varies quite widely, it was decided, for consistency, to mix equal volumes of grey and brown water. So the grey and brown water were mixed 50/50 by volume and diluted with tap water to the target COD of 1000 mgCOD/ℓ. Both systems were then fed the same mix of grey and brown water. Daily, after thoroughly mixing the stainless steel tank contents, the required volume of grey and brown water was collected through a fine (1mm) mesh (to prevent blockages of the UCT or JHB system interconnecting tubes), and tap water added. In this way 15.2ℓ was prepared, a 200mℓ sample taken and 15.0ℓ transferred to the influent feed drum. The feed volume was doubled when the JHB system operation was commenced. The feed drum was gently mixed (20 rpm) to minimize settlement of particulates. 15ℓ were pumped into each system over 23.5 to 24 hours at the end of which, the particulates not pumped into the system were collected in a small volume of effluent (200mℓ) and added to the AN reactor.

The experimental investigation used 16 and 9 WW batches for the UCT and JHB system respectively. When both systems were run simultaneously, one was tested fully while the other had the effluent concentrations, solids (TSS, VSS and ISS) and DSVI only, measured, for monitoring and simplification purposes. In this way, 90 % and 80 % of total WW batches were selected for the UCT and JHB system respectively because these WW batches represented SSP.

3.4 SYSTEMS’ OPERATION

From the experimental investigations of the UCT and JHB systems, some major operating problems were encounteredand appropriate precautions were taken:

- Unclear (particulates filled) UCT system effluent possibly caused by the presence of foam in the AE reactor. The layer of foam was approximately 1 cm thick. The foam may have causedparticulates in the effluent which resembled bread crumbs. This problem persisted for the last 5 months of operation often with intermediate days when the effluent was clear. This was attributed to the detergents used for cleaning or other chemicals regularly used or discarded in the kitchen sink or no-mix toilets of D-block at the CSIR and which ended in the grey or brown water storage containers.

- Unclear JHB system effluent. The low sludge TSS concentration of the JHB system (given the low SRT of 5 days) had also poor flocculation property such that the effluent generally looked cloudy with dispersed (DS) or suspended solids (SS). Unlike the UCT system, the AE reactor of the JHB system had no foam.

- Frequent pipe clogging followed by reactor overflows in both systems. This was often caused by large particulates (~1cm wide) present in the mixed liquor whichwere black in colour or resembled red chillies skin. This required sieving the reactors' contents and waiting 1 - 3 days (depending on the estimated amount of sludge loss) for the system to regain steady state before sampling again.

- Toilet paper sieved out to avoid clogging in the UCT and JHB systems' pipes. This was done daily before feeding.

3.5. SYSTEMS' RESPONSE

3.5.1 NDEBPR UCT system

From the SSP biological treatment of grey and brown water mix it was found that:

a) The nitrification-denitrification (ND) process was no longer required in the UCT system (20d SRT)from the low nitrate concentrations measured in the effluent as well as in the nitrification batch tests (all < 1 mgNO_3-N/ℓ). This implied that the overall reactor volume of the system could be reduced significantlygiventhat nitrification is the BNR size governing factor via the SRT.

b) The N content of the AS f_n(mg N/mgVSS) including OHOs and PAOs was lower (being 0.093)than the experimental value of 0.10 which has been accepted in steady state models and kinetic simulation models. The low $f_n$led to poor N balance (53 – 89 %, avg of 71 %).This was not interpreted as a sign of N deficiency in the system because the average (of WW batches)influent TKN/CODratio of 0.056 was twice the maximum expected for complete N removal through sludge production at 20d SRT of 0.023 and 0.016 for RWW and SWW respectively. After investigation, it was found that with no nitrification at such long SRT, the VSS concentration of the sludge was the most sensitive factor affecting the N balance.A graph of *N balance vs % increase in*f_n indicated that an average of 0.135 mgN/mgVSS (equivalent to 55% increase in f_n)yielded 100 ± 2 % N balance for all WW batches. Why this measured f_n ratio yielded an N balance of only 53 – 89 % with the absence of nitrification and denitrification but high influent TKN/COD ratio, is not clear.

c) The mixed liquor contained 116.4 mgCOD/ℓ of influent unutilized BPO (or 30 % of the total influent BPO) which, with a low N/VSSand COD/VSS yielded the lower than usual composite mixed liquor f_n of 0.093 mgN/mgVSS and f_{CV} of 1.25 mgCOD/mgVSS. This unutilized influent BPO was calculated from the nitrification batch tests done the AEML of the UCT system.

d) The P removal within the UCT system proceeded normally with consistent P release and P uptake in the anaerobic (AN) and aerobic (AE) reactor respectively. There was also anoxic (AX) P release (54 % of the sum of release in AN and AX reactors) which was a further indication of no nitrification in the UCT system. The P removal was 15.6 mgP/ℓ for 1000 mgCOD/ℓ influent (or ~ 0.063 mgP/mgRBCOD for RBCOD of 277.4 mg/ℓ). This is only 2/3 rds of that usually observed with real WW (20 mgP/ℓ or ~0.10 mgP/mgRBCOD).While the influent RBCOD was significantly high to induce greater EBPR than observed, this was not the case. Aerobic batch tests were conducted on the effluent using aerobic sludge from the membrane system which is a fully nitrifying system treating normal (real) WW from Mitchell's Plain WWPT. The results of the tests revealed the presence of significant RBCOD (unutilized BSO or S_{bse})(60 %) which exited in the effluentof the UCT system. The percentage number isa ratio ofthe measured 0.45 µm membrane filtered effluent COD concentration.The parameter P removal/influent RBCOD arose because with real WW most of the influent RBCOD was converted to VFA and taken up by PAOs and so the difference between filtered influent and effluent COD is a reasonable approximation for the influent RBCOD concentration. In this investigation, neither the P removal/mg RBCOD nor the measurement method to approximate the influent RBCOD concentration were valid due to the incomplete utilization of BSO, not only in the AN reactor but also in the AE reactor. The P release and P uptake were therefore better measures for observing EBPR in this investigation.

e) The COD, N and TP removal efficiencies of the UCT system were good (all greater than 83%) and so was the overall effluent quality. While the effluent concentrations were comparatively lower than the general limits specified by the water act of 1998 (Act 36, for plants discharging no more than 2000 m^3 of effluent in a water resource), they were not as good as expected from a scenario of complete urine separation.

f) Influent WW characteristics were the main cause for the irregularities observed in running the UCT system.This was not attributed to the BNRAS set up because similar units (with identical design parameters) were satisfactorily operated in the past such as the Conventional Activated Sludge (CAS) UCT system of Ramphao (Ramphao et al., 2004). Rather, the characteristics of the grey and brownWW collected caused acclimatization problems for microorganisms (OHOs and possibly PAOs). The WW streams collected were not sufficiently representative of real domestic or municipal WW because it came from a single office block where only 15 staff members of a specific socio-economic group worked.The organic types and characteristics of grey and brown water fed to the system changed almost weekly depending on the batch of WW collected in the recent week which also depended on the recent diet of the small community generating the WW.

3.5.1.1 Importance of nitrification

In running the UCT system at 20 day SRT and 20°C operating temperature, it was found and subsequently concluded that nitrification was not important. Six factors pointed to the evidence of no nitrification in the UCT system

i. Low aerobic reactor and effluent nitrite (NO_2) and nitrate (NO_3)

The recorded NO_2& NO_3 in the effluent were on averageequal to the concentrations in the AE reactor for all WW batches as the clarifier was mostly clear of sludge which minimized denitrification there. The aerobic and effluent nitrite and nitrate were on average 0.15 mgNO_2-N/ℓ& 0.24 mgNO_3-N/ℓ and 0.15 mgNO_2-N/ℓ & 0.32 mgNO_3-N/ℓ respectively. These low NO_2 and NO_3concentrations indicated the absence of nitrification in the AS of the UCT system. Such low NO_2& NO_3 concentrations are probably spurious (should be zero) due to background colour effects in the autoanalyser.

ii. No nitrate generation in nitrification batch tests

The results of five batch tests on sludge harvested from the AE reactor conducted a month apart show that there was no correlation between the decrease in ammonia and the respective increase in OUR. The results showed an ammonia decrease over time by 9 mgFSA-N/(ℓ) at an average ammonia utilization rate of 0.4 mgFSA-N/(ℓ.h) whereas the nitrate generation was negligible, 0.55 mgNO_3-N/(ℓ) at an average production rate of 0.02 mgNO_3-N/(ℓ.h) i.e. only 1/20th of the decrease in ammonia. The increase in OUR wasless than 30% of that expected from the ammonia decrease. The poor nitrate generated in nitrification batch tests confirmed the absence of nitrification in the UCT system. The observed decrease in FSA and increase in OUR was probably a response of the OHOsto the sudden availability of excess ammonia for growth.

iii. No decrease in Alkalinity

Because 7.14 mg/ℓ as $CaCO_3$ are needed per mg FSA-N nitrified, a decrease in Alkalinity between the influent and the aerobic mixed liquor would be a sign of nitrate being produced. However, the UCT system showed no decrease in the average Alkalinity for the WW batches i.e. it remained unchanged at 81 mg$CaCO_3$/ℓ. The no-decrease in Alkalinity provided further evidence that there was no nitrification in the UCT system.

iv. Anoxic P release

The UCT system indicated consistent anoxic P release throughout the experiment. This could only happen if no external electron acceptor – nitrate in this case – enters the AX reactor such that the OHOs are not capable of using the SBCOD for denitrification. The PAOs also present in the AX reactor take up the VFAs produced from RBCOD which continues in the AX reactor as if it is an AN reactor.

v. Uncorrected measured OUR yields good COD balance

The COD mass balances were good (98 - 110 %) for 90 % of WW batches (11 out of 12 batches) as a result of the measured OUR_m. Because for BNR systems with ND, the OUR measured in the AE reactor (OUR_m) is the sum of the nitrification OUR (OUR_n) and carbonaceous OUR (OUR_c) minus the equivalent OUR recovered by denitrification (OUR_d), If there is no ND in the BNR system, then OUR_n and OUR_d are zero and the measured $OUR_m = OUR_c$. This provided further evidence that there was no nitrification-denitrification (ND) in the UCT system.

vi. Low nitrogen fraction of the sludge f_n (mgN/mgVSS)

The average f_n (mgN/mgVSS) obtained for all WW batches was 0.093 which is less than the experimental 0.10 derived from steady state and kinetic simulation models (See **Section 3.5.1**above).

3.5.1.2 Mass balances, removal efficiencies and effluent quality

COD, Total Nitrogen (TKN) and Total Phosphorus (TP) mass balances as well as removal efficiencies were calculated from the experimental data. Mass balances between 90 – 110 % indicated good and reliable data.**Table 2** lists the average influent and effluent concentrations, the mass balances as well as the removal efficiencies.

Table 2: Overall average influent and effluent COD, TKN and TP concentrations and mass balances as well as the average removal efficiencies for the UCT system at 20d SRT.

PARAMETER	Unit	Influent	Effluent	Efficiency	Mass Balance
COD	**mgCOD/ℓ**	*1020.9*	*108.2*[1] *(85.4*[2]*)*	*90%*	*105%*
TKN	**mgN/ℓ**	*55.4*	*6.4*[1] *(4.4*[2]*)*	*88%*	*71%*
FSA	**mgNH_3-N /ℓ**	*24.7*	*3.5*	*85%*	–
TP	**mgPO_4-P/ℓ**	*19.0*	*2.7*[1] *(2.1*[2]*)*	*84%*	*74%*
Ortho P	**mgPO_4-P/ℓ**	–	*2.0*	–	–
NO_2/NO_3	**mgNO_2-(NO_3-) N/ℓ**	*0.0*	*0.1 / 0.3*	*n/a*	*n/a*

[1]Unfiltered sample; [2] 0.45 µm membrane filtered sample; avg values include B1-B9, B11 & B13 which represented SSP.

- Of the avg COD balance of 105%, the largest share was from the carbonaceous oxygen demand (FO_c) at 57%, then the COD in the WAS (FS_{tws}) at 39% and the COD in the effluent (FS_{teffl}) at 10%. Because there was no nitrification-denitrification in the UCT system, both FO_n and FO_d were zero.

- It is unclear why the N deficit (Uncc) to balance N at 100% was as high as 30%. However, of the 71% avg N balance, the N in the WAS (FN_{tws}) represented 63%, followed by the N in the effluent (FN_{teffl}) at 16%. Because there was no nitrification-denitrification in the UCT system the average share of the N denitrified (FNO_{xd}) wasonly 2%.

- It is not clear why the P deficit (Uncc) to balance P at 100% was approximately 30%. Nonetheless, of the 74% avg P balance, the P in the WAS (FP_{tws}) represented 60%, followed by the P in the effluent (FP_{teffl}) at 14%.

*Note:*The UCT system yielded better COD balance than the comparativeCAS UCT system operated by Ramphao et al.(2004) and to which normal (real) WW from Mitchell's Plain WWTP was fed. However, the UCT system produced on average 20 % lower N balance than the comparative CAS UCT system. No data was available on the P balance performance of the CAS UCT system.

- All removal efficiencies were good (all greater than 83%). However, they were less when compared to the CAS UCT which yielded 94% and 97% COD and N removal respectively. Unlike the CAS UCT system, the UCT system produced 20% higher P removal.The low P removal in the comparative CAS UCT system was because additional P was dosed to the influent which was not done in this investigation.

- The effluent NO_2, NO_3 and OrthoP were all lower than those obtained for the comparative CAS UCT system and also lower by 99%, 98% and 80% respectively than the general limits specified by the National Water Act (Act 36 of 1998).

- The effluent FSA and unbiodegradable soluble COD (BSO or S_{bse}) were higher than obtained for the comparative CAS UCT system by 25 % and 35 % respectively and also higher than the limits of the Water Act. However, aerobic batch tests were done on the effluent of the UCT (and JHB) system to determine the residual biodegradable soluble COD (S_{bse}), organic N (N_{obse}) and organic P (P_{obse}) The results of the tests revealed that the 0.45µm membrane filtered effluent concentrations of **Table 2** (above) contained 60 % S_{bse} , 25 % N_{obse} and no P_{obse}which exited in the effluent (see **Table 4** below).

3.5.2JHB vs UCT system over the same WW batches

From the SSP biological treatment of grey and brown water mix it was found that the overall performance of the JHB systemwas notas good as that of the UCT system over the same WW batches. The following was observed:

a) f_n value was good at 0.097 mgN/mgVSS but 3 % less than the experimental value of 0.10 derived from steady state and kinetic simulation models. This f_n value was 5 % higher than that obtained for the UCT system over the same WW batches and also led to better N balance of 110 – 126 %, average of 115 %(For the UCT system over the same WW batches, the f_n = 0.092 mgN/mgVSS and the N balance was between 53 – 76 %).With the absence of nitrification and denitrification and the fact that most of N exits the system as N in WAS (avg FN_{tws} = 79 %), indicated that the measured f_n value was reliable but a little too high for 100 % N balance.This indicated that at the short sludge age of 5 days the increased flux of OHOs wasted from the system (gVSS/d) did not result in N deficiency for sludge growth, and the available N from the incoming WW was sufficient for the production of cell mass. The JHB system N balance based on 0.45µm membrane filtered effluent N ranged between 100 and 114 % (average of 106 %).Why the measured f_n of the UCT system over the same WW batches yieldeda poor N balance (53 – 76 %) is not clear.

b) P removal within the JHB system proceeded normally with P release and P uptake in the AN and AE reactorrespectively even though it did fluctuate from time to time where P uptake was observed in the AN reactor for 30 % of WW batches. However, the JHB system showed consistent P uptake exclusively to the AE reactor for the entire period of measurement (a situation of anaerobic P release and aerobic P uptake was consistent in the UCT system over the same WW batches).The P removal was low at 11.3 mgP/ℓ for 1000 mgCOD/ℓ influent (or ~ 0.093 mgP/mgRBCOD for a RBCOD of 184.4 mg/ℓ). This is less than 2/3 rds of that usually observed with real WW (20 mgP/ℓ or ~0.10 mgP/mgRBCOD). The performance of the UCT system over the same WW batches was17.7 mgP/ℓ for 1000 mgCOD/ℓ influent (or 0.080 mgP/mgRBCOD for a RBCOD of 217.0 mg/ℓ). Investigation with aerobic batch tests on the filtered effluent from the JHB system indicated thatnearly 70 % S_{bse} (or unutilized BSO) exited in the effluent(see **Table 4**below). *Note:*the percentage number is a ratio of the measured0.45 µm membrane filteredeffluent average COD concentration.The loss of S_{bse} (RBCOD) reduced the P removal (*mg P/ℓ*) by 10.1 mP/ℓ and 3.9 mP/ℓ for the JHB and UCT system respectively. Alternatively, had all the RBCOD been fermented and taken up by PAOs within the WAS systems, the P removal for both BNR systems would have been 100 % thus yielding the low effluent concentrations of 0.1 mg PO_4-P/ℓ possible with N & P loads from urine separation.

c) The JHB system contained greater concentrations of unutilized influent BPOthan the UCT system which decreased the concentration of OHOs and therefore also the hydrolysis of influent RBCOD (BSO) to VFA in the AN reactor thereby yielding lower than observed EBPR.The high concentration of unutilized influent BPO was caused by the influent WW characteristics (see **Section 3.5.1**above) and exacerbated here by the low SRT of the JHB system (5 days).

d) N and P removal efficiencies of the JHB system were relatively poor at 53 % for TP, 58 % for TKN and 80 % for COD(the removal efficiencies were on average 30 % higher for the UCT system over the same WW batches, see **Table 3**). The effluent concentrations far exceeded those of the UCT system and so also the standard limits set by the water act (Act 36 of 1998).

e) The influent WW characteristics were the cause of the overall poor performance of the JHB system which was possibly exacerbated by the low SRT of 5 days (see also **Section 3.5.1**).

3.5.2.1 Importance of nitrification

Because the rationale for setting up the JHB system was the observed *absence of nitrification*in the UCT system, no nitrification batch tests were conducted on the JHB system AEML. Therefore, the observations mentioned in point **3.5.1.1** above on the UCT system over the same WW batches applied also to the JHB system.

3.5.2.2 Mass balances, removal efficiencies and effluent quality

COD, Total Nitrogen (TKN) and Total Phosphorus (TP) mass balances as well as removal efficiencies were calculated from the experimental data. Mass balances between 90 – 110 % indicated good and reliable data. **Table 3** lists the average influent and effluent concentrations, the mass balances as well as the removal efficiencies for the JHB and UCT systems over the same WW batches.

- Given that there was no nitrification-denitrification and given the short SRT of 5 days the largest share of the COD balance was from the WAS (FS_{tws}) at 59 %, then the carbonaceous oxygen demand (FO_c) at 35 % and the COD in the effluent (FS_{teffl}) at 10 %. Both FO_n and FO_d were zero. The situation was similar for the UCT system over the same WW batches i.e. FO_c = 57 %; FS_{tws} = 39 % and FS_{teffl} = 10 %.

- Of the 115 % N balance, the N in the WAS (FN_{tws}) represented 79 %, followed by the N in the effluent (FN_{teffl}) at 34 %. The share of N denitrified (FNO_{xd}) was 2 %. The share of COD in the effluent is so high because of the high concentration of solids 70.5 mgTSS/ℓ (dispersed and suspended) in the mixed liquor of the JHB system. The situation for the UCT system over the same WW batches was FN_{tws} = 63 %; FN_{teffl} = 16 %; FNO_{xd} = 2 % and 29.8 mgTSS/ℓ for 81 % avg N balance.

- Of the 106 % P balance, the P in the WAS (FP_{tws}) represented 69 % and the P in the effluent (FP_{teffl}) 37 %. The situation for the UCT system over the same WW batches was FP_{tws} = 60 % and FP_{teffl} = 23 % for 83 % avg P balance.

Table 3: Overall average influent and effluent COD, TKN and TP concentrations and mass balances as well as average removal efficiencies for the JHB system at 5d SRT and for the UCT system at 20d SRT over the same WW batches.

PARAMETER	**JHB system**				**UCT system**		
	Inf.	**Effl.**	**Eff.**	**Mss Bal.**	**Effl.**	**Eff.**	**Mss Bal.**
COD (mg/ ℓ)	*1014.0*	*200.2*[1] *(125.1*[2]*)*	*80%*	*104%*	*117.3*[1] *(89.2*[2]*)*	*88%*	*107%*
TKN (mg N/ℓ)	*59.6*	*25.7*[1] *(19.0*[2]*)*	*58%*	*115%*	*9.1*[1] *(6.0*[2]*)*	*85%*	*82%*
FSA (mg NH_3-N /ℓ)	*30.8*	*15.1*	*54%*	—	*4.8*	*83%*	—
TP (mgP/ℓ)	*21.5*	*10.2*[1]*(8.5*[2]*)*	*53%*	*106%*	*3.9*[1] *(3.2*[2]*)*	*82 %*	*83%*
Ortho P (mg PO_4-P/ℓ)	—	*8.5*	—	—	*3.2*	—	—
NO_2/NO_3 (mg NO_2-(NO_3-) N/ℓ)	*0.0*	*0.3 / 0.4*	*n/a*	*n/a*	*0.1 / 0.2*	*n/a*	*n/a*
SS (mg SS/ℓ)	—	*70.5*	*n/a*	*n/a*	*29.8*	*29.8*	*n/a*
pH	*5.5 - 6.5*	*6.0 - 7.5*	*n/a*	*n/a*	*6.0 – 7.5*	*n/a*	*n/a*

[1]Unfiltered sample; [2] 0.45 µm membrane filtered sample; values represent the averages for B8, B10, B12, B14 & B15 which represented SSP.

- All removal efficiencies, except for the COD, were poorbeing caused by the high concentration of solids in the effluent.The removal efficiencies for the UCT system over the same WW batches were on average 30 % higher (see **Table 3**).

- The effluent NO_2, NO_3 and OrthoP were higher than those obtained for the UCT system over the same WW batches but still acceptable when compared to the general limits specified by the National Water Act (Act 36 of 1998). They were lower than the general limits by 98 %, 98 % and 15 % respectively.

- The effluent unbiodegradable soluble COD, TKN, TP, effluent FSA and total solids (TSS) averaged at values much higher than obtained for the UCT system over the same WW batches and therefore also higher than the general limits e.g. the soluble effluent COD, FSA and total solids were higher than the general limits by 42 %, 80 % and 65 % respectively.Aerobic batch tests were done on the effluent of the JHB system to determine the residual biodegradable soluble COD (S_{bse}), organic N (N_{obse}) and organic P (P_{obse}). The results of the tests revealed that the 0.45µm membrane filtered effluent COD concentration of **Table 3** (above) contained 70 % S_{bse}, 95 % N_{obse} but no P_{obse}which exited in the effluent (see **Table 4** below). These represented 40 % more S_{bse} and 50 % more N_{obse} than the UCT system over the same WW batches.

Table 4: Results from aerobic batch tests done on effluent samples from the UCT and JHB systems

PARAMETER	**UCT System (20d-SRT)**	**JHB System (5d-SRT)**
	BT[1] Effluent[2]	**BT[1]Effluent[2]**
S_{use} (mgCOD/ℓ)	*34.9*	*36.6*
TKN_{se} (mgN/ℓ)	*2.1*	*4.8*
FSA (mgN/ℓ)	*1.4*	*4.6*
TP_{se} (mgP/ℓ)	*1.6*	*1.3*
OrthoP (mgP/ℓ)	*1.5*	*1.3*
NO_3 (mgN/ℓ)	*0.7*	*0.7*

[1]0.45µm membrane filtered concentrations at the end of the batch test;[2]From **Table 2** or **Table 3**for the JHB and UCT systems over the same WW batches.

4. CLOSURE

The overall performance of the UCT system was equivalent and better in some instances than the performance of a previously-run UCT system, identified here as CAS UCT system (Ramphao et al., 2004). This system was fed normal (real) WW from Mitchell's Plain WWTP and had similar design parameters as the UCT system in this investigation. Although the effluent quality met the general limits specified by the Water Act (Act 36 of 1998), it was not what was expected from a scenario of 100 % urine separation. From nitrification batch tests conducted on the AEML and aerobic batch tests done on the effluent of the UCT system, it was found that 30 % of influent BPO were unutilized,60 % of BSO and 25 % N_{obse}exited in the effluent. These were caused by the difficulty of microorganisms (OHOs and possibly PAOs) to adapt to the characteristics of the influent grey-brown water mix, which were constantly changing.

In general, the JHB system performed poorly when compared to the UCT system over the same WW batches which was also assigned to the influent grey-brown WW characteristics. In the JHB system, this was exacerbated by the short SRT of 5 days. Aerobic batch tests conducted on the effluentof the JHB system showed that 70 % of BSO exited the system. Also, it was found that the JHB system contained more unutilized BPO than the UCT system over the same WW batches. In terms of P removal, the loss of S_{bse} (RBCOD) reduced the P removal by 10.1 mP/ℓand 3.9 mP/ℓ for the JHBand UCT system respectively. Alternatively, had all the RBCOD been fermented and taken up by PAOs within the AS systems, the P removals would have been 100 % thus yielding the low effluent concentrations of 0.1 mg PO_4-P/ℓ possible with reduced N & P loads from urine separation.

This research has demonstrated that urine separation can bring significant improvements to WWTPs. In fact, operating a UCT system type of BNRAS at 20 day SRT (and 20°C), the nitrification-denitrification process (ND) is no longer required. This can subsequently reduce the overall reactor volume per mass of COD load on the plant (a *reduction of 50 %*is possible as shown in this investigation) or alternatively more WW can be treated for the same overall reactor volume. Also, using a no-mix toilet reduces the hydraulic load on the WWTP because urine separation toilets can save up to 90 % in water.

Good effluent quality e.g. 0.1 mgP/ℓ are related to reducing the load of N and P on the treatment plant. However, proper consideration must be given to the quality of the grey and brown water treated. These must at best represent real domestic or municipal WW i.e. they must be collected from a large enough population which must also be diverse.In this experiment the grey and brown WW were generated from a too small a pool of people (15) of a specific socio-economic group whose diet was constantly changing i.e. on a weekly basis which also corresponded to a new batch of WW fed to the lab-scale BNR systems. This may have caused acclimatization problems to microorganisms (OHOs and possibly PAOs) . In addition, the grey and brown water were mixed in a 1:1 ratio unlike in real domestic WW where the ratio of grey to brown water is 3:1.

Because of the irregularities accountered in the experimental investigation, the evaluations of the results of both systems by comparison with predictions of the models for BNRAS systems were not possible.

5. RECOMMENDATIONS FOR FURTHER STUDY

Improved performance of the JHB system is possible if the following is considered:

- A larger urine separation set up. The influent WW (grey and brown water) characteristics must at best represent the overall population which, in this context is real domestic or municipal WW i.e. the grey and brown WW must be collected from a larger and socio-economically more diverse group of people.This may require the installation of no-mix toilets in places such as shopping malls or airports.

- A larger BNR system set up. A lab- or possibly pilot-scale JHB system (e.g. 2000 m^3 in volume) can be operated at the same SRT of 5 days which will treat grey and brown water collected from a large and more diverse population. *Note:* Further precautions must be considered when operating the new system such as toilet paper which is biodegradable COD must be part of the treated WW or the use of excessive detergents in cleaning no-mix toilets must be avoided because they can be detrimental to the microorganisms in the AS.

- An extensive analysis of the results. Measurements on the JHB system must be evaluated by comparison with predictions of the models for BNRAS systems. Also, the separated and brown water samples must be analysed for micropollutants such as hormones, environmental estrogens and pharmaceutical residues which was not done in this investigation.

Chapter I : INTRODUCTION

1.1 MOTIVATIONS AND AIMS

Considerations of WW environmental sustainability demand that the N, P and endocrine disruptors burden on surface water be reduced to conserve surface water quality, especially in view of rapidly increasing water demand for food production and urban use as more and more people become urbanized and connected to the water supply and sanitation networks and increase their quality of life and demand for food (Economist, 2010:6; Ekama, 2010). To sustain this growth will require greater recycle and re-use of available water which in turn demands better effluent quality of used water. One way this can be achieved is through separation of urine at source. Urine contains most nutrients – 80% nitrogen (N) & 50% phosphorus (P) - of the total WW although it represents a mere 1% of its volume. The principles of cleaner production and resource recovery already applied in industrial waste management would point to not diluting the small flow of concentrated urine into the large WW flow and rather treat it separately as a concentrate and recover the nutrients from it (Wilsenach and van Loosdrecht, 2003:103; Wilsenach, 2006:18). Source separation of urine not only offers improved conservation of water quality but also water quantity. Various studies by Larsen and Gujer (1996), Jonsson et al., (1997), Wilsenach and van Loosdrecht (2003), and others show that source separation of urine with separate treatment and nutrient recovery can bring significant surface water benefits (quality improvement and quantity savings) and unlock greater treatment capacity at existing WWTPs, all aspects aligned with greater sustainability of urban water and sanitation systems.

1.2 SCOPE OF RESEARCH

The concept of urine separation is fairly recent having been experimented in fringe projects in both developed and developing countries like Holland, Germany, Sweden, Australia, Ethiopia or South Africa in the late 1990s. Whereas in developed economies the aim of urine separation is generally to protect the environment; save water; recycle nutrients and possibly recover P, in the developing world, the primary and often single aim for doing urine separation is nutrient recycle to agriculture. In general, the focus of urine separation worldwide has been on the diverted urine, but seldom on the remaining WW components and the advantages of treating these separately from urine.

While investigating the impacts of urine separation on treatment plants, Wilsenach (2006) experimented with the modeling on a pilot-scale BCFS process (Biological and Chemical Phosphorous Removal) WWTP. The first phase of the project consisted of separating urine in increments and analyzing the impacts of treating the remaining wastes on the treatment plant. The results showed a 70 % decrease in total effluent N content with increasing urine separation up to 60 % and nearly 100 % P removal without urine separation. At greater urine separation, the model showed no improvement in effluent quality due to the magnitude of the Monod affinity constants in the kinetic equations and therefore the system became redundant (Wilsenach, 2006:52). An additional finding was that urine separation increased the treatment capacity of the plant by 50 %. The predicted effluent N and P concentrations only decreased below the affinity constant limit concentrations once nutrient limitation took place. Nonetheless, the analysis of the impacts of urine separation on WWTP such as BNRAS plant is lacking. Do the Monod affinity constants also set the limit of technology – LOT - in such real WWTP? There are assumptions on the significant improvements urine separated WW can bring to BNRAS treatment work viz. 1) increased WWTP capacity. Treating urine separated WW will reduce the N & P loads on the treatment plant thereby making the nitrification-denitrification (ND) process redundant. Because the ND process is a BNRAS size gorverning factor via the sludge age (SRT), this 80 % and 50 % reduction in N and P load respectively on the treatment plant will also lead to a reduction in the overall size of the plant or alternatively more WW can be treated for the same organic load (on the plant); 2) improvements in effluent qualityN and P as well as micropollutants; and 3) reductionin energy consumption. The energy required in WW treatment is mostly for aeration (largest share of energy) and mechanical operation (e.g. reactor mixers) which will be reduced if the ND process is no longer required.

Therefore, this experimental investigation was started to study the impacts urine separation can have on *BNRAS WWTPs*with a *UCT* and a *JHB configuration.*

1.3 OBJECTIVES AND RESEARCH APPROACH

The objectives of this research are to:

Investigate the impacts of urine separatedwastewater on BNRAS WWTPs with a University of Cape Town (UCT) Biological Nutrient Removal process (BNR) operated at a SRT of 20 days (T= 20°C) and receiving a mixture of grey and brown WW.

The UCT system will be operated at a long SRT of 20 days – to induce nitrification - for a fixed SSP of at least 200 daysand it will receive a mix of grey andbrown water. During this time the performance of the system will be evaluatedby organic-, N- and P-related measurements on samples harvested from the system. Focus will be on nitrification, P removal as well as the effluent concentrations.Nitrification batch tests or else may be conducted when necessary in order to vindicate the observations.In the instance of no nitrification within the UCT system, an EBPR system such as the Johannesburg (JHB) system will be set up and operated at a sludge age much shorter than 20 days and run simultaneously with the UCT system for a further SSP of at least 200 days. The rationale for operating the JHB system is to achieve 1) better P removal at the short SRT, without interference of nitrification (which will be confirmed to not be taking place in the long SRT UCT system) and 2) smaller system volume due to the low SRT.

Consequently, the second objective of the research will be:

Protect the P removal within the JHB system operated at a SRT of 5 days (T= 20°C) and monitor the effluent COD, N and P concentrations thereof.

A small (by volume) AX reactor may be provided just upstream of AN reactor in order to preserve or protect the P removal within the system from any nitrate in case it does nitrify.

1.4 SPECIFIC TASKS

1.4.1Task 1: Determine the required volume of grey and brown water

In order to estimate correct volumes of grey and brown water to mix, the changes in TKN/COD and TP/COD ratios will be calculated at different mixing proportions. This will be done because there is a minimum N and P requirements for heterotrophic growth which is also determined by the sludge age.The shorter the sludge age, the higher the minimum N & P requirements for sludge growth and increase when rawWW is treated.COD, TKN and TP average concentrations for initial grey and brown water will be used in the calculation. From the different mixing proportions, the variations in the resulting TKN/COD and TP/COD ratios will be studied and compared with the minimum required for complete N take up for sludge growth at 20 days and no nitrification,to prevent an N deficiency in the AS. The grey and brown water will be mixed to the optimum ratio decided upon and diluted with tap water to the target COD of 1000 mg COD/ℓ.

1.4.2 Task 2: Operate the UCT and JHB systems

Operate under controlled laboratory conditions two systems namely the BNRAS UCT system for a SSP of at least 200 days prior to the JHB system. Then operate theNDEBPR JHB system simultaneously with the UCT system for a further SSP of at least 200 days. All the engineering parameters will be measured on the systems and with these the usual consistency cheks such as COD, N and P mass balances will be made. When operated concurrently, a particular system will be tested fully every second week or so while the other system will have the effluent concentrations, settleable solids (TSS, VSS and ISS) and DSVI only tested, for monitoring and simplification purposes.

1.4.3 Task 3: Evaluate the performance of the UCT and JHB systems

From the measurements on the two parallel systems, the COD, N and P removals and performance of the two systems will be evaluated. The evaluation will be done by comparison with one another, withWRL previously run system such asthe Conventional Activated Sludge UCT system(CAS UCT system of Ramphao et al., 2004) and by comparison with the predictions of the models for BNR activated sludge systems.

Chapter II : LITERATURE REVIEW

INTRODUCTION

The concept of urine separation is primarily aimed at environmental protection and secondly at closed-loop nutrients – Nitrogen "N" and Phosphorus "P" – being returned to the earth. In recent years, dwindling quality of P reserves have triggered the drive for P-recovery from WW for reuse. Increasing population growth and urbanisation as more and more people get connected to urban water facilities require that effluent from WW treatment plants be of a quality good enough for direct reuse. The technology of no-mix toilet - for urine separation - can address these concerns satisfactorily because 1) urine contains most nutrients i.e. 80% N and 50% P but represents <1% of total domestic WW volume and 2) no-mix toilets use up to 90 % less water than a normal flush toilet.

This chapter presents the findings from literature on the subject of urine separation. Section 1 gives a brief *history of conventional WW*collection and treatment as it is known today. Section 2 summarises the *concept of sustainability* because today's new developments are all assessed in terms of their technical, social, economic, institutional and environmental sustainability. Section 3 places *urine and other liquid wastes* in the broad concept of municipal or urban WW management. Section 4 describes *urban WW management in South African* cities with due attention to informal settlements because it is for these poor sub-urban areas that the first urine separation projects in the country were designed and developed. Section 5 brings forth the *arguments in favour of urine separation* as well as those against conventional sanitation worldwide. Section 6 revisits the concept of sustainability by proposing a *general method for the evaluation of WW treatment* projects. Section 7 summarises the *objectives, hypothesis and key questions* of the research.

Each of the above sections ends with a short summary.

2.1 DEVELOPMENT OF SANITATION AND URBAN WATER DRAINAGE FROM 1850 UNTIL TODAY

As household occupants, we drink a very small fraction of the water that is supplied to our house. The large portion (more than 75%) of supplied drinking water ends up as waste in the sewerage system (network of sewer pipes) (Armitage et al., 2007:438). Sewer pipes represent the modern way of transporting household liquid wastes – also called wastewater (WW). Before the industrial revolution of the mid 19th century, Europe did not have a proper means of managing its WW or stormwater even though prior to the medieval age, the Greek and the Roman civilisations boasted urban WW management systems. These first systems were capable of draining wastes away from areas of potential harmfuleffects on human health. The fall of the great civilisations have also seen the neglect and fall of these first urban sewerage systems which already incorporated primary treatment - sedimentation and subsequently discharge of effluent - as a means of protecting urban people (Lofrano and Brown, 2010:5257). During the medieval age in Europe, household wastes were simply discarded out of house windows onto the streets thus creating conditions for water-borne pathogens responsible for water-borne diseases. But it also caused a potential danger to the environment (Lofrano and Brown, 2010:5260). The frequent resurgence of lethal water-borne diseases such as cholera, typhoid fever and dysentery stimulated scientists and engineers to solve these problems. This led to the design of the first combined sewer system so called because it transported both WW and stormwater into a single drain. However efficient this design was, it did not solve the problem of diseases because the wastes were not treated but merely transported and discharged to the nearest water stream. In fact, the understanding at the time was that *dilution* of WW was the remedy to water-borne diseases (Wilsenach, 2006:3; Lofrano and Brown, 2010:5259). Although local communities were asked to draw their daily water upstream of the discharge point, the act of discharging WW into nearby water courses simply carried the potential danger of water-borne diseases from one place to the other. Soon, with population growth such practice created terrible water supply and environmental threats. Thanks to the work of scientists such as Louis Pasteur – in the 1880s - who discovered and understood that pathogens were the cause of epidemics. Thereafter, throughout the 20th century, Europe experienced a shift in the practice of WW management and urban drainage from transport and discharge to transport, treatment and discharge. In its early days however, treatment of WW and stormwater merely consisted of self-purification processes such as sedimentation and septic tank degradation (Wilsenach, 2006:3-6; Lofrano and Brown, 2010:5258-5260).

Wilsenach (2006:4) states that in this day and age, most of European cities boast advancedWW treatment plants which necessitate the construction of a series of physical, chemical and biological unit processes. The author's geographic area of concern is Europe and specifically the Netherlands. But what about the state of WW treatment in Africa, the majority of whose countries are identified as developing economies? The world's population is expected to increase to 8.5 billion in 2025 from 6 billion in 2006, but with most of the growth concentrated in the urban environments of developing countries (Wilsenach, 2006:6). In a similar way, the Economist (2010) states that African cities are growing faster than in any other continent. For that reason, particular attention should be directed to the state of WW treatment in African cities where most sewage is discharged without treatment into receiving waters (Wilsenach, 2006:25; Lofrano and Brown, 2010:5263). The focus on WW treatment in Africa and particularly in *South African cities* is taken as the first valuable contribution of this research.

The objectives of WW treatment which is an integral part of conventional WW management have been identified to be 1) removal of organic material (proteins, carbohydrates, fats or lipids) to reduce deoxygenation; 2) reduction of ammonia (NH_3) – the generally available form of N – to minimise its toxicity; and 3) removal of nutrients N and P to reduce eutrophication. With today's state-of-the-art nitrification-denitrification excess biological phosphate removal activated sludge (NDEBPRAS) systems such as the UCT system, good effluent qualities are obtainable e.g. Chemical Oxygen Demand (COD) < 50 mg/ℓ; N_{tot} or Total Kjeldahl Nitrogen (TKN) < 10 mg/ℓ; NH_3< 1 mg/ℓ and TP (P_{tot}) (PO_4) < 1.0 mg/ℓ. Activated Sludge (AS) covers a variety of physical mechanisms and biological processes that are based on the bacterial degradation of organic materials and/or removal of nutrients in aerated or non-aerated conditions. There is increased flocculation in the process as bacteria grow and particulates get enmeshed in the sludge mass. This way, most harmful bacteria are removed in the treatment and disinfection of WW does not form part of the treatment (Wilsenach, 2006:4; Lofrano and Brown, 2010:5260). Therefore, conventional systems have been successful because: 1) they have helped eradicate water-borne diseases mainly through the removal of pathogens and 2) they have ensured reasonable protection of the environment through the removal of nutrients. However, their efficiency could further be improved by ensuring that: 1) the quality and quantity of the treated effluent and surface water is preserved with the ultimate purpose of water recycle and/or saving (Gaydon et al., 2007:iv) ; 2) they are made naturally sustainable by contributing to the concept of a closed-loop of nutrients being returned to the earth especially in view of the dwindling P-reserves; 3) they are rendered cost effective.

Considerations of WW environmental sustainability demand that the N, P and endocrine disruptors burden on surface water be reduced to conserve surface water quality, especially in view of rapidly increasing water demand for food production and urban use as more and more people become urbanized and connected to the water supply and sanitation networks and increase their quality of life and demand for food (Economist, 2010:6, Ekama, 2010). To sustain this growth in water demand will require greater recycle and re-use of available water which in turn demand better effluent quality of used water. One way this can be achieved is through separation of urine at source. The principles of cleaner production and resource recovery already applied in industrial waste management would point to not diluting the small flow of concentrated urine into the large WW flow and rather treat it separately as a concentrate and recover the nutrients from it (Wilsenach and van Loosdrecht, 2003:103; Wilsenach, 2006:18). Source separation of urine not only offers improved conservation of water quality but also water quantity. Various studies by Larsen and Gujer (1996), Jonsson et al., (1997), Wilsenach and van Loosdrecht (2003), and others show that source separation of urine with separate treatment and nutrient recovery can bring significant surface water benefits (quality improvement and quantity savings) and unlock greater treatment capacity at existing WWTPs, all aspects aligned with greater sustainability of urban water and sanitation systems (Ekama, 2010).

What does the term sustainability or sustainable development mean? This has multiple dimensions or aspects when applied to urban wastewater management (UWWM).

Outline of this section

This section contains an overview of the development of UWWM from post industrial revolution to this day. From the medieval period to the beginning of the 20th century, European cities did not have a proper means of treating their WW. Post 1850, the concept of UWWM grew out of the recurrence of waterborne diseases which were caused by a lack of understanding of the origin and role of pathogens. Engineers and scientists thought that the *"dilution"* of wastes was the solution to the many ailments (Wilsenach, 2006:3; Lofrano and Brown, 2010:5259). In the early 1900s, the discovery of the role of micro-organisms such as pathogens was a breakthrough in science. This pioneered the concept of WW treatment and UWWM changed from simple collection & discharge, to collection, *treatment* & discharge. Over the last century, biological treatment of WW changed from the concept of sedimentation, through organic removal to today's advanced biological nutrient removal activated sludge systems (BNRAS). BNRAS include nitrogen (N) and phosphorus (P) removal from WW which, have the detrimental effect of stimulating eutrophication of receiving waters if not removed properly. Conventional BNRAS plants have the potential of removing organics as well as nutrients to satisfactory low water quality standards that do not endanger human health or the environment. However, their efficiency could be enhanced by ensuring that the effluent discharged is of a quality acceptable for direct water reuse which becomes a consideration when there is rapid population growth and urbanisation as more and more people get connected to the urban water system. One way to achieve better effluent quality is through WW source control such as urine separation, because urine contains 80 % N and 50 % P of total WW but represents a mere 1% of the flow. Urine separation offers additional benefits such as water-saving, nutrients recycle and/or recovery and reduction in biological WW plants space and carbon footprint. This first section also highlights the first valuable contribution of this research, namely the consideration of WW treatment in the South African context while Wilsenach (2006) focused on WW treatment as currently practiced in the Netherlands

2.2 CONCEPT OF SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

In discussingthe concept of sustainability, Wilsenach (2006) mentions the most commonly found definitions of sustainability or sustainable development. The first definition was that presented by the Brundlant commission at the World Commission on Environment and Development (WCED) in 1987 which, states that sustainability is: *"…development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. The second definition is that of the World Conservation Union in 1991 which is stated as :*"Improving the quality of life while living within the carrying capacity of supporting ecosystems"*. Wilsenach argues that both definitions of sustainability or sustainable development are unclear because the phrases *"needs"* and *"quality of life"* are very subjective as they depend on personal and/or cultural experience, and therefore cannot be standardised or quantified. For example in Europe where the average living standard (GDP (PPP)) is high (±$40.5 compared with ± $1.1 for Africa;World Bank, 2010), the improvement in quality of life is achieved through the preservation of the ecosystems while, in the developing world (Africa, South America and Asia), poverty eradication is an appropriate target. In an almost similar way, Mitcham (1995) as reported by Balkema et al. (2002:154) had to say the following on Brundlant's definition : "*sustainainability can and will be interpreted differently by different people, evoking the critique that the term sustainability could mean almost anything".* That is, this definition leaves ample room for interpretation which, the authors value by saying that views on sustainability cannot escape being the subject of intense discussion over time and place, because different generations have issues differing from one another and that cultures and local circumstances will generate different perspectives on these issues. Hence, the elementary three dimensions of sustainability namely economic viability, environmental sustainability and social-cultural acceptability which, Wilsenach (2006:29) refers to as pseudo-quantitative (economical domain), both quantitative and normative (biological and geophysical domains) and normative aspects (social and cultural domains).

There are methodologies for specifically assessing *the sustainability of WW treatment systems* that are presented in a literature review by Balkema et al., (2002). This paper will elaborate on these assessment tools at the end of this chapter. However, following is a brief description of what each of the three dimensions of sustainability entails:

a) Natural sustainability: is generally based on the concept of environmental protection and surface water quality protection through the prevention of eutrophication (biological criteria, see **Section 6.1.3.A**of this chapter) and ingress of micropollutants and, to a larger extent to the concept of closed-loop of nutrients being returned to the earth and to water saving (geophysical environment, see **Section 6.1.3.B**of this chapter). Material such as nutrients should be recycled to the earth and reused as fertilisers. That way humus could be sustained and reserves of nutrients produced when the soil content of these materials is increased (Otterpohl et al., 1997:121). In a similar way water local recycling should be developed which should answer not only the problem of water availability but also of water applicability (Wilsenach, 2006:23)

b) Economic sustainability: is generally based on the concept of cost-saving in WW transport and/or treatment, each of which comprise a capital, operation and maintenance component (see **Section 6.1.2**of this chapter). With nitrification being the BNRAS size governing bioprocess in WW treatment, this may not be necessary if 80 % of the nitrogen (N) is removed through urine separation source control.

c) Socio-cultural sustainability: is based on the concept that any project should not fail due to cultural taboos, social beliefs and habits of the community involved with such projects (see **Section 6.1.1**of this chapter). Social concerns should be addressed and incorporated in any project design and implementation and proper monitoring ensued (Austin and van Vuuren, 1999:19).

WW treatment forms part of UWWM. Any UWWM system in turn is dependent on the fractions or components of the WW that is generated. In the subsequent sections, a description and identification of the fractions of urban WW are given before proceeding to a classification and description of South African UWWM systems.

Outline of this section

In this section, the concept of sustainability or sustainable development is cited as well as some of the arguments around it. Sustainability is a recent concept – born in the mid 1900s – and requires that all new technical developments be assessed in terms of their sustainability. Some authors argue that the most common definitions of sustainability (Brundlant's Commission, 1987; World Conservation Union, 1991) are biased. They contain words such as *needs* and *quality of life* and so have socio-political and economical content and therefore cannot be readily quantified or standardised. Some authors value this subjectivity by stating that it gives ample room for discussion especially given that the needs or concerns of people differ from one generation to the other and that each generation has its own approach to issues of life. However, all authors agree to the three dimensional character of the concept of sustainability namely environmental, economic and socio-cultural. These dimensions are discussed further, in **Section 2.6**.

2.3 SOURCES OF URBAN WASTEWATER (UWW)

The sources of WW identified in most literature are domestic, commercial, industrial and rainwater (Lofrano and Brown, 2010:5255). Municipal WW is a term often used to identify the grouping of domestic and commercial WW. Whereas rainwater and industrial WW are generally identified from the other WW sources, this is seldom the case for domestic and commercial WW. It is necessary to distinguish between domestic and commercial WWs because they differ from one another particularly in the volumes of their sources e.g. depending on the type of business, toilet water can be the main volume contributor to commercial WW. This is particularly the case for office blocks and buildings. More than 50% of all urine in WW is urine from these sources (Wilsenach, 2006:46). It is reasonable to assume that variations in the quantities of domestic or commercial WW are functions of the area serviced by a particular WW system. In addition, it is important to distinguish between solid/liquid wastes as described in medical, dietary or other source and solid/liquid wastes from collection systems. The latter varies as composition is averaged over time and user group; chemical alteration occurs in a non-sterile environment; dilution with water (e.g. flushing water) adds elements such as calcium and magnesium that can further alter the composition (Maurer et al., 2006:3153).

2.3.1 Dosmetic WW

The other word for domestic WW is *household*WW. The term domestic identifies residential areas and may include bars and restaurants, apartment houses, resort accommodations, hotels, motels, boarding houses, trailer courts, schools, theatres and summer camps. However broad the spectrum is, WW from residences (dwellings, habitations) is by far the main contributor to domestic WW.

2.3.1.1 Greywater

Morel et al. (2006:5) define domestic greywater as water produced in a household apart from toilet water. Other terms used are sullage, grey WW or light WW. Greywater is water from baths, showers, hand basins, washing machines, dishwashers, laundries and kitchen sinks. Literature such as those considering management options for greywater exclude kitchen greywater because it contains detergents or dishwashing soap which can be toxic to plants (Otterpohl et al., 1997:124).However, kitchen greywater is the main contributor of nutrients and organics (proteins, oils and fats) to household greywater (Morel et al., 2006:5).In terms of quanitity, He et al. (2006:2) report that greywater can be estimated between 60% and 70% of the total household WW. Armitage et al. (2007:438) were able to calculate greywater generation based on the assumption that 75% of the water consumed in a household ends up as greywater. Greywater composition reflects household activity i.e. it depends on factors such as living standards, cultural habits and type of household chemicals used. (Morel and Diener, 2006:5). Greywater normally contains low levels of both organics and nutrients when compared to toilet WW (Otterpohl et al., 1997:124). N and P are important nutrients given their potential negative impact on aquatic environment. Following is a summary of the characteristics of the components of greywater.

A. *Kitchen greywater*

Kitchen greywater is the main source of N in domestic greywater. Nitrogen in greywater originates from ammonia (NH_3) as well as ammonia-containing cleansing products, proteins in meats and vegetables. Sometimes, the water supply is the main source of ammonium-nitrogen. The main groups of organic substances found in greywater are found in kitchen wastes (Morel et al., 2006:13). The organics are proteins (mainly from food), carbohydrates (sugar and cellulose), fats and oils. Kitchen greywater also contains suspended solids (SS) from food residues and usually include dishwashing detergents. Greywater from dishwasher may be very alkaline, show high-suspended solids and salt concentrations. It occasionally contains drain cleaners and bleach. The amounts and types of substances (detergents, soaps, oils and fats) used in the household depend on socio-economic factors. Where the water supply is relatively low, these substances are high in concentration e.g. typical values of nitrogen in mixed household greywater are found within the range of 5-76 mgN/ℓ (Morel et al., 2006:5, 12 &13; Henze et al., 2008:34).

B. *Laundry greywater*

Laundry greywater is the main source of P in household greywater. This is especially the case in countries where dishwashing and P-containing detergents have not been banned (Morel and Diener, 2006:13; Larsen and Gujer, 1996:88). Concentrations of 4-14 mgP/ℓ have been found in countries where non-P based detergents are used. However, these concentrations can be as high as 45-280 mgP/ℓ in households where P-containing products are used (Morel and Diener, 2006:13). Laundry greywater contains high concentrations of chemicals and organics (from detergents), possibly oils and SS (e.g. non-biodegradable fibers) from clothing. It can contain high amounts of pathogens when nappies are washed as well as synthetic organic molecules such as surfactants that are not easily biodegradable (Morel and Diener, 2006:12; Henze et al., 2008:34).

C. Bathroom greywater

Bathroom greywater is regarded as the least contaminated of household greywater. It may contain very insignificant amount of nutrients – lowest N content in greywater - or pathogenic microorganisms due to traces of urine and faeces. It contains body fats, chemicals from toothpaste and body care products, SS from shaving wastes (skin and hair) (Morel and Diener, 2006:5, 13).

2.3.1.2 Toilet water

In most literature, the term *blackwater* is used to identify toilet water i.e. wastes containing both faeces and urine. It may also include flush water (depending on the sanitation system in place) and toilet paper (Winker et al., 2009:4091). Wilsenach (2006:19) uses the terms brownwater and yellowwater to distinguish between flush-water-mixed faeces and flush-water-mixed urine respectively. The term *wet* sanitation means that flush water is used for conveying wastes. The water can be provided through either a conventional water supply system (piped system) or an on-site container/tank for water storage (Graham, 2003: 33-41). As will be seen later, when classifying WW systems currently existing in urban and peri-urban or suburban South Africa, some sanitation options are called *dry* since they do not involve the use of any water. Because this research aims at evaluating the impact of urine separation on WWTP that treat liquid wastes, the focus will be on conventional WW systems associated with wet sanitation. Toilet water normally contains higher levels of nutrients but less organics compared to greywater (Wilsenach, 2006:21; Larsen and Gujer, 1996:88).

Below is a summary of the characteristics of the main constituents of toilet water:

A. Brownwater (faeces)

Wilsenach (2006:21) states that brownwater is larger contributor of COD and lower contributor of nutrients than urine in toilet water (Larsen and Gujer, 1996:88). The nutrients available in the organically bound form are too low for recycling without treatment (Winker et al., 2009:4092). Depending on the toilet cultural practice of a particular group of people, brownwater can contain considerable amount of suspended solids (SS) such as stones or ash e.g. in some cultures, people are washers as opposed to wipers (Graham, 2003: 22). Anal cleansing is often with water whereas anal wiping may include objects such as toilet paper, stones, sticks, etc. These inert particles have a negative impact on the potential use of faeces as a fertiliser and affect the potential treatment options. In addition, faecal matter is the source of most pathogens in WW making this a major handicap for a long time when used in food-crop production

(Winker et al., 2009:4092; Vinnerås et al., 2003:47). Some literature gives actual concentrations of nutrients in faeces alone (Larsen and Gujer, 1996:88). Most literatures provide data on blackwater i.e. the mixture of urine and faeces (Otterpohl et al., 1997:124; Winker et al., 2009:4091). Nevertheless, given that urine contains 80% N and 50% P in WW and that blackwater contains more nutrients than greywater, one can conclude that the nutrients (N & P) content of faeces is low between 10 – 40% in black water. Winker et al., (2009:4091) argue that this low nutrient content in faecal matter is a result of the high dilution of faeces with flushwater. Larsen and Gujer (1996:87) give a more scientific explanation stating that what remains after the metabolism of organics in the human body is predominantly water-soluble nutrients that are evacuated in the form of urine.

B. Yellowwater (urine)

Maurer et al. (2006:3151) state that a large amount of data on urine composition is available in medical literature. Yet, it is important to distinguish between urine described in medical sources and urine from collection systems. The latter varies as composition is averaged over time and user group; chemical alteration occurs in a non-sterile environment; dilution with flushing water adds elements such as calcium and magnesium that can further alter the composition (*ibid.*).

(a) N and P Concentration in Urine

Of the total domestic WW volume, that of urine is estimated to a mere 1% (Wilsenach, 2006:21; Larsen and Gujer, 1996:90). However, urine contributes the largest share of nutrients N (80%) and P (50%) in toilet water, and in overall domestic WW (Wilsenach, 2006: 21; Beal et al., 2008:46). Larsen and Gujer (1996:90) attribute 88% N and 57% P in WW to urine. Rohrer (1998) and Jenssen (1996) as reported by Burkhard et al. (2000:213) state that urine contains 88% Nitrate & 57% Phosphate and 81% Nitrate (NO_3) & 48% Phosphate (PO_4) respectively. Because Ammonia (NH_3) is the generally available form of N in urine, what the authors suggest by the word "nitrate" is the "potentially nitrifiable ammonia". Urine is a concentrate of various elements which require it to be treated before discharge to the environment. **Table2.1** lists the composition of urine measured in various investigations. Larsen and Gujer (1996:88) show that in fresh urine, 85% of N is fixed as urea, 5% is ammonia and all of the P is in the ortho-phosphate ionic form (PO_4^{3-}). However, with time the chemical composition of urine changes. Urea is hydrolyzed to ammonia and bicarbonate resulting in an increase in pH as follows, where the CO_2 comes from the breakdown of organics,

$$NH_2\,(CO)\,NH_2 + 2\,H_2O = NH_4^+ + HCO_3^- + NH_3 \qquad \textbf{[Eq II.1]}$$

The pH increase leads to higher concentrations of free ammonia (NH_3) which escapes as a (odorous) gas and is harmful to the environment and human life. This also reduces the efficiency of recovering nitrogen from the urine. However, this is not a major problem as nitrogen is abundant in the atmosphere and ammonia can be synthesized through the Haber-Bosch process (Otterpohl et al., 1997:122), as it has been for the past 80 years. During this chemical alteration ammonia volatilization (release of gaseous ammonia) and precipitation of struvite ($MgNH_4\,PO_4.6H_2O$), hydroxyapatite ($Ca\,(PO_4)_6(OH)_2$) and Calcite ($CaCO_3$) also occurs. Hence the composition of fresh urine and stored source separated urine is different.

In contrast to Nitrogen, Phosphorus and Potassium are scarce elements. Wilsenach (2006); Otterpohl et al. (1997); Larsen and Gujer (1996) and others show that the recovery of P and K from source separated urine treatment will be an important source of these elements in the future. However, nutrients and element recovery seem not to be of much interest in numerous countries and the inorganic fertilizer industry because no market for P-precipitate has been developed at present (Larsen and Gujer, 1996:94). Interest in this has mainly been shown in fringe experimental projects in Sweden (Vinnerås and Jönsson, 2002), Holland (Wilsenach, 2006:163) and Nepal (Tilley et al., 2008) This might be due to the fact that source separated urine treatment is a recent development and its emphasis has been on improved WWTP effluent quality, nutrients recycle, action against global warming through self-energy reliant treatment systems and/or use of faecal matter in agriculture (Liernur, 1873 as reported by Otterpohl et al., 1997:125; Otterpohl et al., 1997:125; Austin et al., 1999:18; Gounden et al., 2006:2; Vinnerås and Jönsson, 2002:281; Ekama, 2010).

(b) Micropollutants

These include endocrine disruptors which are also identified as environmental estrogens. The most common group of micropollutants mentioned are hormones. Substances such as medicine residues and pharmaceutical compounds (e.g. antibiotics) are also identified as endocrine disruptors capable of affecting the gender of fish and reptiles at WWTP discharges and believed to be detrimental to human health (Cadbury, 1998; Beal et al., 2008:47). Lienert et al. (2007:4471) state that urine can contain up to 70% of pharmaceuticals.

Table II.1: Composition of urine measured in various investigations.

Parameter	**Unit**	**Concentration**					
Source		**Hh**[1]	**Hh**[2]	**Hh (informal settlement)** [4]	**Workplace (no-mix toilets)** [5]	**Workplace (dry urinal)** [6]	**Fresh Urine**[3],[b]
Dilution[a]	**(-)**	3	1.33	0	3.96	0	1
N$_{tot}$	**(g/m^3)**	1795	3631	3496	1694	6551	8830
P$_{tot}$	**(g/m^3)**	210	313	182	101	—	800-2000
COD	**(g/m^3)**	—	—	6944	1582	7771	—
K	**(g/m^3)**	875	1000	781[c]	489[c]	1848[c]	2737
S	**(g/m^3)**	225	331	704[d]	457[d]	1284[d]	1315
Na	**(g/m^3)**	982	1210	1448[e]	572[e]	2147[e]	3450
Cl	**(g/m^3)**	2500	1768	2433[f]	908[f]	3958[f]	4970
Ca	**(g/m^3)**	16	18	25[g]	22[g]	30[g]	233
Mg	**(g/m^3)**	1.63	11.1	1.0[h]	1.5[h]	3.0[h]	119
Mn	**(g/m^3)**	0	0.037	—	—	—	0.019
pH	**(-)**	9.0	9.1	—	9.0	9.0	6.2
Alk	**(g/m^3)as CaCO$_3$**	—	—	11040	4532	18173	—

[1] Kirchmann and Pettersson (1994), as reported by Maurer et al.(2006); [2] Jonsson et al. (1997), as reported by Maurer et al.(2006) ; [3] Tabelen et al. (1977), as reported by Maurer et al.(2006); [4],[5]&[6] data from CSIR (2009); [a] defined as (V_{urine}+V_{water})/ V_{urine}; [b] value measured in undiluted urine without precipitation; [c] only ions-K (K^+-K); [d] only sulphate-S (SO_4^{2-}S); [e] only ions-Na (Na^+-Na); [f] only ions Cl (Cl^--Cl); [g] only ions Ca (Ca^{2+}-Ca); [h] only ions Mg (Mg^{2+}-Mg).

(c) Other Compounds in urine

Urine also contains magnesium, calcium, and sulphur which will mostly precipitate. Magnesium and Calcium are added when water mixes with urine (Maurer et al., 2006:3153). Organic substances measured as COD are also present in urine (about 6 to 10g/ℓ) and have to be removed. Most of the COD in urine is biodegradable and can easily be removed biologically. Wilsenach and Loosdrecht (2003) conducted an experiment with synthetic urine in which the COD in the *urine* was used for denitrification in a sequencing batch reactor. This way energy was saved as external organics were not required for denitrification.

2.3.2 Commercial WW

Commercial WW is seldom separated from domestic WW (Lofrano and Brown, 2010:5255). A possible explanation is that because today's urban development aims at decentralization; the resulting sewage system is one that serves a combination of domestic and commercial establishments. Decentralization in urban planning is achieved through zoning whereby suburbs within the same geographical region may constitute small cities that are quasi-independent from the CBD (Central Business District). Examples of such development are Sandton in Johannesburg or Claremont in Cape Town (Del Mistro, 2007). Wilsenach defines commercial WW as one from public buildings and office blocks because these sources contain more than 50 % of the total urine in WW. WWs from sources such as kitchens, laundries and bathrooms – which make up greywater - are low contributors to the total volume of commercial WW. Therefore, the organic contamination (proteins, carbohydrates, fats and oils) of commercial WWis small. A possible explanation for the low organic pollution in commercial greywater is the type or character of activities found in offices and public buildings. However, the nutrients contamination of commercial WW is larger than it is in domestic WW. One can simply estimate the number of times people use toilet facilities while at work. For the chemical and physical characteristics of commercial greywater, refer to **Section 2.3.1** on domestic WW bearing in mind that the ratio of greywater/toilet water is inversely proportional in an office environment to what it is in a residential setting.

2.3.3 Other sources of WW

Design of modern UWWM system is such that rain water is collected, transported, treated and disposed off into receiving waters together with other municipal WW streams (domestic and commercial) or separated from it. When stormwater is combined with municipal WW, the sewage system is referred to as combined sewer system (CSS) (Burkhard et al., 2000:199). Otherwise, the sewage system is a separate sewer system (SSS) which drains storm water separately - without treatment – into natural water streams. In Africa and particularly in urban South Africa, SSS is common. Industrial WW is managed and disposed of separately and so are liquid wastes from hospitals. These sources are carriers of heavy metals and hazardous substances such as chemicals (pharmaceutical products, medicine residues, hormones). For further details refer to the South African guidelines on industrial waste management (Oosthuizen and Bell, 2009).

2.3.4 Outline of this section

In this section, the two main components of urban or municipal WW are presented namely domestic and commercial WW. These are described in terms of their composition and quantities to help understand how diverting urine (yellowwater), as opposed to faeces (brownwater) or greywater, has the significant potential advantages of reducing the loads of nutrients N & P as well as micropollutants on the environment and recycling or recovering resource-depleted nutrient such as P. Each of domestic and commercial WW is made up of grey, brown and yellow WWconstituentswhich, are present in different quantities and composition. Characteristics of these sub components of urban WW strongly reflect the socio-cultural aspects of the people being serviced by the particular WW management system i.e. they depend on factors such as living standards, cultural habits, type of household/commercial chemicals used. Wilsenach (2006:46) argues that WW from office blocks and buildings should be given particular attention because more than 50% of urine in municipal WW is collected from these sources. This can be explained by the type of activity taking place in offices. Office workers use toilet facilities several times a day when at work for urinating but much less frequently for activities such as washing, cooking, bathing and defecation.

Consequently, to effectively investigate the impacts of urine separation on BNRAS WWTPs, the attention should be focussed on keeping separate commercial WW.

2.4 URBAN WASTEWATER MANAGEMENT (UWWM)

Given the three main constituents of conventional urban WW namely municipal WW (domestic and commercial), industrial WW and rainwater/stormwater, it is relevant to identify the existing techniques for UWWM in South Africa. Burkhard et al. (2000:199) identify two systems for traditional UWWM i.e. *combined sewer systems (CSS)* and *separate sewer systems (SSS)*. CSS combine both the municipal WW and the stormwater whereas SSS conveys them separately into two parallel piped systems. The type of UWWM studied by Wilsenach (2006) is a CSS as currently exists in the Netherlands. In urban SA, SSS is common. Depending on the state of maintenance of sewer pipes, there may be infiltration of rainwater into the sewer system but this is often not a significant impact on the WWTP because they are usually constrained by organic load (number of people connected). Domestic and commercial WWs are collected and transported into the same sewers whereas industrial WW is sometimes managed separately.

2.4.1 Scope and limitations

This research will focus on separate sewer system (SSS) collecting domestic and commercial urban WWs – as is currently the case in most of urban South Africa - and will therefore exclude rainwater and industrial WW. The term urban will embrace both rapidly globalising and poor and marginalised segments of cities. The former are generally served by conventional sewer systems (with flush toilets) the majority of which were built in the 1960s, 1970s and 1980s (Kirsten, 2006:122). The marginalised segments of cities can also be identified as peri-urban or sub-urban. They consist of non-serviced suburbs, new developments, remote houses or informal settlements and are located where conventional sewerage systems do not exist or the ground is not suitable for sub-surface sewage drainage (e.g. the location of many informal settlements around South African cities) (Gaydon et al., 2007:iii)

2.4.2 UWWM in South Africa

Urban WW management options in South African cities can be classified into three main groups namely 1) large-scale centralised system serving the rapidly globalising or old sectors of cities; 2) large-scale decentrilised system serving the new developments around city centres and 3) small-scale decentrilised systems found in informal settlements. Each group is described subsequently.

Characteristics of South African cities

Although SA is considered the most developed nation on the African continent, it is still viewed as a developing country by western standards. Half of the population (45%) lives under the minimum living level *(MLL)* of *R 1 871* (Landman et al., 2003:5). The country has experienced considerable urbanisation over the past two decades mainly as a result of its change in political and socio-economic system in the early 1990s when it became a new democracy. Although the country is experiencing an ever growing emerging middle class, a significant part of the population (45%) is still considered poor and often do not have access to basic safe water supply and sanitation. The country is experiencing a sanitation backlog (Gounden et al., 2006:1). The 2001 census indicates that South Africa had an urbanisation of 56.25% (Network, 2006:17).An analysis of the 21 key urban centres – which are the biggest contributors to the country's economy – shows that 5.8 million people (or 24.7% of national population) live below MLL (Network, 2006:16). Of the 5.8 million people, 77.31% inhabit regions that are within 60 km of areas that generate at least R1 billion of Geographic Value Added (GVA). While these areas generate 95.59% of the total national GVA, they only represent 31.24% of the national land surface (Network, 2006:11). Major cities abound with slums inhabited mostly by people who have emigrated from rural areas in search for better life but who often end up working in poorly paid jobs because of their lack of skills or qualifications. One of the main problems SA is facing at present is the provision of adequate services such as water supply and sanitation to the millions of people living in informal settlements in and around major cities. Because of the nature of informal settlements such as their high density, random house sitting, and the fact that they are often located on land that is not appropriate for construction or underground sewage drainage (e.g. the low-lying land of the Cape Flats in the Western Cape Province), not all sanitation options are viable solutions for them. Several options have been designed and developed successfully as adequate options in many informal settlements, others have failed. Often, the adequacy is from a construction and land-management point of view that ignores socio-economic aspects such as community buy-in, level of income and education, social acceptance or a combination of these (Austin et al., 1999:18).

Given the poverty and subsequently the malnutrition of people living in informal settlements, it is with no surprise that most decentralised WW management projects originated and continue to exist only in those areas. These projects are initiated as appropriate options because they are life-sustaining, e.g. the urine separation toilets or "dry box" allows the rapid dehydration of faecal matter and its subsequent potential use as a soil fertilizer for domestic food production (*ibid.*).It is mainly in this context that source separation of urine has been applied in SA. Because of a lack of implementation by high-income section of SA it is regarded by some communities as an *"inferior"* form of sanitation. The scarcity of fresh water resources will change this in the long term (Ekama, 2010)

2.4.3 Classification of UWWM

While studying infrastructure services for the upgrading of informal settlements, Eberhard et al. (1992) and Graham (2003:25) categorized SSS in SA into two groups namely on-site and off-site systems. On one end, on-site systems are characterised by permanent or temporary containers (ground or sub-surface storage such as pit, tank, etc.) for the storage of wastes (faeces, urine and/or other household wastes) that allow its degradation before it can be used as a fertilizer or pumped mechanically and transported to a WW treatment works. On the other end, *off-site* systems are distinguished by a *piped system* for the transfer of wastes to amunicipal treatment works. Each off-site and on-site system can further be subdivided into wet or dry (Eberhard et al., 1992), a classification that was adopted by the World Bank (WB) during the sanitation decade of the 1980s (Graham, 2003:24). The distinction between wet and dry is dictated by the sanitation system associated with it i.e. whether or not *water is used for flushing* toilets.

Burkhard et al. (2000:205) use the terms *centralized* and *decentralized* conventional systems to distinguish merely between two piped systems. The difference between centralised and decentralised is that the former allows the transport of wastes to a large-scale municipal treatment works and the later includes transport to a treatment works that is essentially decentralised i.e. serving a small community of 100s of people. Remote houses such as new developments would be serviced by a decentralised system. Decentralised systems are subdivided into three groups namely non-biological treatment (NB), package biological plants (PB) and leachfields. They comprise on-site collection, treatment and disposal and can be hazardous to human health through ground or surface water contamination. In Europe, decentralized conventional systems have been abandoned (Burkhard et al., 2000:206). However, in SA, PB systems exist and are present mainly in peri-urban areas. They include all on-site sewage treatment systems as well as privatively-owned plants that discharge < 2000 m^3/day (Gaydon et al., 2007:iii). The WB classification of *on-site sanitation systems* (Graham, 2003:24) can also be described as *techniques for water and wastes re-use* (Burkhard et al., 2000:211) because these are small-scale systems for the management of blackwater, brownwater or yellowwater that may use human wastes as fertilisers in crop production e.g. the use of degraded faeces or sterilised urine as fertiliser in agriculture (refer to case study of urine separation in eThekwini and Umtata, **Section 4.4.2** of this chapter). The 2001 SA census of people with toilet facility is presented in **Table II.2** below.

Table II.2: 2001 South African census for toilet facility (statistics SA, 2003).

WW System	**Type of sanitation**	**Total population (in millions)**	**% of Total population**
Large-scale centralised or decentralised	Flush toilet (connected to sewerage system)	*5.9*	*50%*
(wet on- or off-site)	Flush toilet (with septic tank)	*0.35*	*3%*
Small-scale decentralised (dry or wet on-site)	Chemical toilet	*0.23*	*2%*
	Pit latrine with ventilation (VIP)	*0.66*	*6%*
	Pit latrine without ventilation	*2.6*	*22%*
	Bucket latrine	*0.46*	*4%*
	None	*1.6*	*13%*
	Total	**12**	**100%**

In 1996 the South African Department of Water Affairs and Forestry (DWAF) defined the *"well-constructed VIP toilet"* to be the BASIC LEVEL of sanitation service in the country (Austin et al., 1999).

2.4.4 Centralised WW systems

Also known as conventional centralized treatment works, they are based on the conventional approach of transporting WW into a drainage system – piped system – and transferring it to a municipal treatment works. They are common in urban areas in most of South Africa. The centralized treatment works consist of several stages namely *primary, secondary* and *tertiary* treatment (PT, ST and TT). PT and ST stages are the bare minimum nowadays; tertiary stage exists where there are known problems of eutrophication i.e. where the effluent from a WW plant needs advanced treatment or because it is discharged into a sensitive environment. They produce significant quantity of sludge and are generally very energy consuming (Gujer, 1996 as reported by Burkhard et al., 200:205) but very low (less than 2 %) on a per capita basis (< 10 Watts/person) compared with domestic power consumption (more than 500 Watts/person)(Svardal and Kroiss, 2009). For most conventional treatment works, the PT is similar in the sense that waste screening is a pre-primary stage and it (PT) consists of a settlement area (Primary Settling Tank, PST) where grit and other settleable solids can settle out and fats, oils and grease (FOG) can be removed by flotation (Burkhard et al., 2000:205).

Secondary treatment (ST) is the centre of attention for alternative methods because it is more diverse. It can be either*chemicalor biological*. However, because chemical treatment involves high costs mainly due to the cost of chemicals, biological treatment is the norm in SA. Basic biological treatments operate on the same principles - such as the simple degradation of organic matter by microorganisms that are ubiquitous in the environment. Biological processes require oxygen input i.e. they are aerobic processes.

The only dissimilarities between the different processes are the physical constraints to which they are subjected (Henze et al., 2008:55). The well known aerobic biological WW treatment are *activated sludge (AS);percolating filters or trickling filters (TF); rotating biological contactors (RBC); Oxidation ponds (OP) (aerobic, anaerobic and facultative ponds); surface aerated basins (SAB)* (Burkhard et al., 2000:205). AS and TF are the most commonly found biological treatments in SA. However, the focus will be on AS because they are found in both large-scale centralised and decentralised WW treatment.

2.4.4.1 Activated sludge (AS)

Most conventional WW treatment plants in SA are activated sludge plants.The physical constraints to the AS system include the flow regime in the reactor, the size and shape, number and configuration of the reactors, recycle flows, influent flow and other features incorporated either intentionally, or present involuntarily or inevitably (Henze et al., 2008:55). AS covers a variety of mechanisms and processes, which are based on the bacterial degradation/removal of organics in the presence of supplied dissolved oxygen (DO) - in aerobic conditions – or removal of nitrate (NO_3) – in anoxic conditions. There is increase flocculation in the process as bacteria grow and particulates get enmeshed in the sludge mass. Under ideal conditions, organics are degraded; Ammonia is converted to nitrite (NO_2) and then nitrate (NO_3) in an aerobic process known as *nitrification*. Eventually NO_3 is converted to Nitrogen gas (N_2) in an anoxic process known as *denitrification*. Both nitrification and denitrification processes constitute what is called Biological Nitrogen Removal (BNR). Besides, when phosphate removal is also a concern, the AS may be subjected to anaerobic condition. The combination of N and P removals give rise to a process called Excess Biological Phosphorus Removal (EBPR) BNR. The response of the organisms and that of the system differ in that the former is dependent on the organisms' nature (biological process behaviour) and the latter is guided by a combination of the organism behaviour and the physical constraints that define the system e.g. the mixing regime inside a reactor and the sludge return. Therefore, they need to be given particular attention. The two extremes of mixing regime are plug flow and completely mixed (Henze et al., 2008:55).

In the plug flow regime, the reactor is in the shape of a long channel type basin with the influent coming at one end. The influent flows along the channel and is mixed by air bubble spargers and/or horizontal shaft surface aerators. The concept of plug flow regime is that each downstream volume of liquid remains unmixed with the volume of liquid upstream from it. Discharge to the clarifier happens at the end of the channel. There is an underflow recycle for returning sludge from the clarifier to the influent end. Depending on the magnitude of the recycle ratio (0.25 to 3 times the average influent flow rate) this creates an intermediate regime between plug flows and completely mixed. *Conventional activated sludge plants* in SA have a regime identified as *intermediate*. However, when the recycle ratio is too high, the mixing regime resembles that of a completely mixed (Henze et al., 2008:56)

In the completely mixed regime, the influent is constantly mixed with the reactor contents, thereby giving effluent compound concentrations equal to that inside of the reactor. There is a settling tank/clarifier just downstream which overflows with treated waste stream but of which the underflow consists of concentrated sludge that is returned back to the reactor. Unlike in the plug flow regime, the sludge rate of return has no effect on the conditions in the biological reactor unless the clarifier is filled with sludge. Reactors have square or circular plan shape and mixing is achieved either by mechanical or diffused air bubble aerators. Examples are extended aeration plants, aerated lagoons, pasveer ditches and single reactor completely mixed activated sludge plants (Henze et al., 2008:56).

2.4.4.2 Other centralised WW treatment systems

The other well known aerobic biological WW treatments are *percolating filters or trickling filters (TF); rotating biological contactors (RBC); Oxidation ponds (OP) (aerobic, anaerobic and facultative ponds)* and *surface aerated basins (SAB)*. Only the TF is common in SA. The impact of urine separation on these systems is not considered in this thesis. Because these systems remove N & P in excess, a reduction in N & P loads due to urine separation will result in a proportional reduction in nutrient load in receiving water. For a detailed description of this and others refer to White (1987); Gray (1989); Metcalf and Eddy (1991); Escritt (1984) and Salvato (1982) as reported by Burkhard et al. (2000:205).

2.4.5 Decentralised WW systems

Decentralised WW management is based on a piped system for transferring WW to a treatment works that is essentially decentralised (on-site). This can be the case for remote houses e.g. new housing developments or areas where the soil conditions are not appropriate for underground drainage or where regional drainage systems do not exist. They also include all privately owned WWTPs that discharge < 2000 m^3/day and are called package plants. There is an estimated 600 of these small scale plants installed in SA (Gaydon et al., 2007:iii). Package plants are often resorted to as adequate solution to water pollution problems or appropriate alternatives to septic tanks. The technology for package plants covers a broad spectrum from the simplest anaerobic treatment systems (e.g. septic tank, soil drains with no energy requirement) to the more complex systems such as engineered ponds and artificial wetland treatment systems, trickling filters, rotating biological contactors and mechanically aerated treatment systems (Gaydon et al., 2007:iii). The three fundamental technologies available in these small scale plants are *activated sludge (AS), submerged bio-contactors (fixed or random packing)* and *rotating bio-contactors.* Package plants are supplied by small businesses that design and manufacture their own plants. 88% of these businesses have operated for more than 5 years and 12% have operated between one and five years (Gaydon et al., 2007:32)

2.4.5.1AS package plants

In addition to the basic concepts of the AS described in **Section 2.4.4.1** on AS for conventional treatment works, the following apply to package plants. They are mainly conventional extended aeration (CEA) or sequencing batch reactor (SBR) systems. A SBR is a unit (60m^3 capacity) in which aeration and sedimentation take place sequentially in the same reactor. Once the aeration cycle is completed, the aeration pump is stopped and the content of the reactor is allowed to settle before the effluent is decanted out into two plastic tanks in series. Disinfection of the effluent is achieved by dosing a solution of sodium hypochlorite prior to the flow into the first plastic tank. That way, the two plastic tanks serve two purposes namely that of allowing sufficient chlorine contact timeand flow balancing and effluent outflow. Some package plants make provision for the sand filtration of the effluent using a pressurised upflow filter even though this is not a common feature in sewage treatment except where very low effluent P concentrations have to be achieved. Changes to aeration cycle, sedimentation time and chlorine dose can be monitored with the aid of a programmable logic controller (PLC) (Gaydon et al., 2007:38).

2.4.5.2 Other decentralised WW treatment systems

The other essential technologies of package plants commonly found in SA are submerged bio-contactors and rotating bio-contactors. For a detailed description of these technologies, refer to Gaydon et al., (2007:36) or White (1987); Gray (1989); Metcalf and Eddy (1991); Escritt (1984) and Salvato (1982) as reported by Burkhard et al. (2000:205).

2.4.5.3 Decentralised systems in rural and informal settlements in South Africa

The systems also can be identified as techniques for water and wastes reuse because they are appropriate to rural, suburban and informal dwellings in South Africa. They are referred to as cost effective options for informal settlements given the socio-economic conditions e.g. urine diversion gives the potential of using separated urine or faeces in agriculture for local food production. The systems include on-site collection, storage and/or treatment plus disposal or reuse of greywater and solid or liquid human wastes. Human excreta can be hazardous to human health through ground, surface water contamination or unsafe handling. Therefore, the community involved with such wastes must properly manage them to maintain public health.

While the focus of this research is on conventional biological nutrient removal (BNR) WW plants, it is nonetheless important to give attention to ways of managing domestic WW in informal settlements. Indeed, it is for these poor and densely populated areas that the first and only urine separation schemes in SA were conceived, designed and developed with the objective of benefiting from the value of urine as a fertiliser (Austin and van Vuuren, 1999; Gounden et al., 2006)

A. Blackwater management

There are several techniques for the management of blackwater, that currently exist in SA informal settlements. These are Sanplat, Ventilated Improved Pit (VIP or ROEC), chemical, composting and pour flush toilet, aqua privy and septic tank (Graham, 2003). However, given the concept of a closed-loop of nutrients being returned to the earth (see natural sustainability in **Section 6.1.3**of this chapter) only the *composting toilet* fulfils this requirement. The technique is described below.

(a) Composting Toilet

Composting toilets are also called ecological toilets because they are based on the concept of a closed-loop of nutrients being returned to the earth. They have existed in countries like China and India for centuries because these countries view human excreta as a valuable resource. In Europe, the use of human excreta in agriculture only goes back to last century when people discarded it into backstreets and then farmers or food-growers collected it on carts for recycling onto fields. Composting toilets resemble pit or VIP toilets where human excreted wastes are stored in a container located below a pedestal or squat hole (**FigureII.1**). The main difference with other pit or VIP toilets is that in the container, the builder creates conditions to allow the anaerobic degradation of wastes so that it can be used as a fertiliser. The container is often one situated above ground – for ease of emptying - and is divided into two watertight compartments. The compartments are used alternatively to allow extended composting time (6 – 12 months). Some of the requirements of the composting process are maintaining the equal amount of wastes in the vault and regularly adding organic matter to increase the carbon nitrogen (C/N) ratio inside the vault (Graham, 2003:29). South Africa has no account of the use of composting toilets even though the basic principle is very similar to that of the Reed’s Odourless Earth Closet (ROEC) toilet, which has existed in SA since 1944 (Graham, 2003:27). However, there are several case studies of the use of *dry urine diversion toilets* in SA post 1997. Dry urine diversion is considered an elaborate version of ROEC or VIP toilet where one can benefit from the potential value of urine as a fertiliser (Austin et al., 1999: 18) and accelerated faeces dehydration. In the late 1990s, the Council for Scientific and Industrial Research (CSIR) made an agreement with the Eastern Cape Appropriate Technology Unit (ECATU) to construct a number of experimental urine diversion units in rural communities (Austin et al., 1999:18). These together constituted the first urine diversion project in SA.

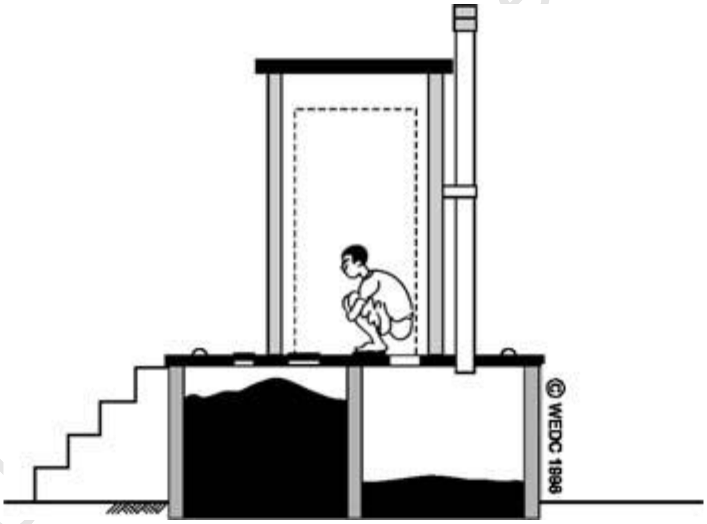


Figure II.1: Composting toilet with an underground container for the collection of human excreta. The toilet has two compartments that can be used alternatively and which allow the extended composting time (6 - 12 months). (Health Library for Disasters, 2011)

B. Yellowwater management: urine diversion

Dry urine diversion toilet – i.e. no flush water used - can be taken as an elaborate version of the composting toilet in the sense that it consists of a special pedestal for the separation of urine and faeces (**Figure II.2**). The separation of urine from faeces improves the composting process because less organic matter needs to be added to the faeces. Ash and wood shavings are added to promote drying and to avoid odour and fly problems (Gounden et al., 2006:2). Feachem (1983) as reported by Graham (2003:29) states that on average 6 months and 6 – 12 months storage are required for urine and faeces respectively before it can be safely used. This depends on the storage conditions such as the high temperatures that allow the faeces to be dessicated inside the "dry box". A good fertiliser can be obtained out of water-diluted urine (Jonsson, 2001 as reported by Graham 2003:29). Two successful SA case studies of dry urine diversion are presented below. It is important to consider them because they constitute the first urine separation technologies, which were conceived, designed and developed in SA to date (Austin and van Vuuren, 1999; Austin, 2006; Gounden et al., 2006)

Figure II.2: Dry urine separation toilet consisting of a pedestal for the separation of urine and faeces. (Livingprinciples, 2011)

(a) SA First Dry Urine Diversion Projects

South Africa has no account of *wet* urine separation to this day because the idea of urine separation or "dry box" toilets originated from upgrading VIP or ROEC toilets such that dry faeces could be collected and used in agriculture. In a country like South Africa, where many people rely on agriculture for subsistence, this was deemed an important development (Austin et al., 1999 and Gounden et al., 2006).

i. First Urine Separation Toilets Installed In Local Villages In Umtata

The project came out of an agreement between the CSIR and ECATU in 1997 to equip three rural communities (Sinyondweni, Gwebinkundla and Manyosini all three near the city of Umtata) each with 15 urine separation units. The CSIR was in charge of technical and social research aspects whose main objectives were:

…to test the basic acceptability of the technology among the communities and to determine the potential for resource reuse … previous research carried out by the CSIR, particularly in water supply and sanitation projects, proved community participation to be a major factor in the sustainability of these services (Austin et al., 1999:18).

A year after the implementation, the conclusion from the project monitoring team was that this first urine separation pilot project worked satisfactorily provided it was implemented properly. The success of such project was as much dependent on experienced social scientists and community workers as it was on technology. In addition, the project was likely to have more takers amongst the local community because people felt some sense of ownership or consideration from project developers. For instance, to respond to hygiene and health concerns such as the washing of hands after the use of the toilets, a small container filled with water was provided just outside each installation. In addition, people were not averse to handle faeces for use as a soil conditioner.

Scientists often avoid discussing political, social and cultural aspects of project sustainability (Balkema et al., 2002:160). But it is important to mention that this first urine separation project was not a failure owing to proper community participation. This did not only include workmanship (e.g. trench digging, pipe laying, etc.) but also a participation in decision taking and control of resources (Austin et al., 1999:18). Nonetheless, a drawback of the project was people's perception of urine handling for agriculture. Urine was considered taboo (Austin et al., 1999:19). For that reason, the separated urine was soaked away into the ground.

ii. Urine Separation Toilets as Free Sustainable Basic Sanitation In Durban

Following the outbreak of cholera in the year 2000, the South African government reviewed its sanitation policy. This led to the promulgation of the National Sanitation Policy (2001) and consequently the development of a national strategy to eliminate the sanitation backlog over the following 10 years (Gounden et al., 2006:1). The eThekwini Municipality (EM) in Durban attempted to address the problem of sanitation among its rural population (60 000 households) by a sustainable approach which integrated water supply, urine separation toilet as well as health and hygienic education as part of the Integrated Development Planning (IDP) process. Like its predecessor, this endeavour was promising because it was based on the principle of adequate community representation and participation. Although in its early stages (having been in existence only since 2003), the eThekwini's rural water and sanitation programme completed the installation of 45000 units in 2006 at a rate of 1000 units per month. While the level of acceptance of the daily water supply was high, that of the urine diversion toilet was not. Later with adequate information on maintenance and upgrading to make it more user-friendly, there was less resistance to adopting it. The main drawback of the project is the discard (or channelling) of urine to a soak away and the burial of degraded faeces instead of using it as fertiliser. In 2006, the University of Kwazulu Natal and the eThekwini Water and Sanitation (EWS) commenced a pilot project to assess the potential re-use of the toilet contents in agriculture (Gounden et al., 2006:3), aspects of which are continuing at present supported by the Gates Foundation "urine to fertilizer" project.

(b) Wet Urine Separation in Villages in Sweden

In wet sanitation, water can be provided either through a conventional water supply system (piped system) or on-site containers for water storage. Examples of sanitation schemes that make use of the latter are aqua-privies, pour-flush toilets and septic tanks (Graham, 2003).

Wilsenach and Loosdrecht (2003) reporta wet urine separation project namely the *Ekoporten*. This was an experiment carried in ecological villages in Sweden (in 1999) where 18 blocks of flats were equipped with double flushed urine-diverting toilets. The aim was to recover and recycle nutrients as well as to prevent the pollution of receiving waters. The objective was to assess how much nutrients could be recovered when using a double-flushed urine diversion toilet combined with Aquatrons for faecal separation (**FigureII.3**). The P recovered here is entirely in a soluble form i.e. an Orthophosphate form.

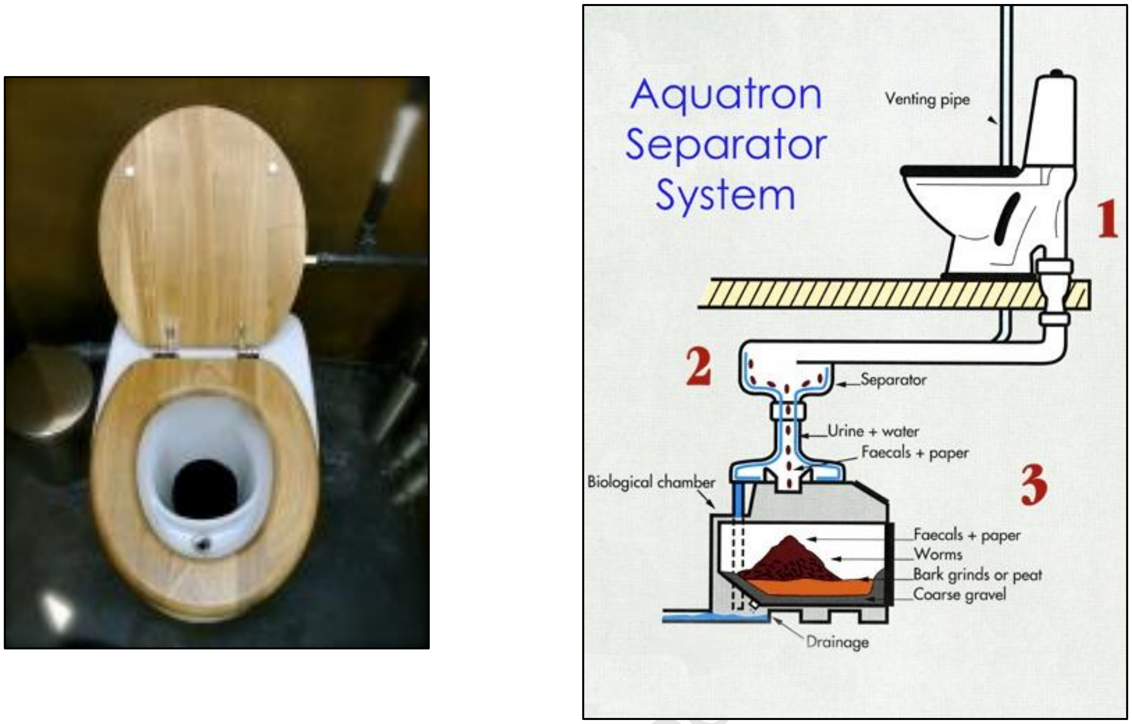


Figure II.3: The Ekoporten no-mix toilet in the ecovillage in Sweden. The facility is a double-flushed urine diversion toilet combined with Aquatrons for faecal separation.(Schmieg, 2011)

Two parallel Aquatrons separated the faeces from the flush water. Each toilet unit was equipped with a sewage system that conveyed greywater, brownwater – including toilet paper and flush water – and yellow water – urine and flush water - separately. Yellow water was conveyed to two tanks, which could be used alternatively; brownwater was conveyed to two Aquatrons to separate the solid matter – faeces – from the water. The solid matter was then discharged to an on-site composting tank where it was composted with source separated household biodegradable solids (Vinneras and Jonsson, 2002:5). The separated water was conveyed with greywater to an on-site treatment facility. The total mass flows and the compositions concerning dry matter, nutrients and heavy metals were measured and analyzed for solid biodegradable waste, greywater, urine and faecal water as described by Vinnerås and Jonsson (2002:5). With the Ekoporten it was possible to collect 60% of N, 46% of P and 43% of K. The authors reasoned that these concentrations could have been higher had it not been for some mechanical problems associated with the operation of the toilets. In addition, poor community participation and education is the reason for the negative environmental effects created by the use of the Ekoporten. Had the community been educated to use less flush water and no domestic cleaning products, the concentrations of heavy metals in the suspended solid (SS) fractions would have been less.

For additional case studies of urine separation, see also Otterpohl et al. (1997); Beal et al. (2009).

C. Greywater management

In higher income areas – most of which are sewered areas - kitchen and washing machine greywaters are highly polluted (see **Section 2.3.1.1**) because of socio-economic characteristics of such group e.g. nutrient-rich human diet or chemical-rich detergents used in laundry. The pollution restricts the use of greywater in specific applications to sources such as baths, showers and basins (Jefferson et al., 2004:157). There is no record on the management of greywater in middle or high income areas of South Africa.

South Africa has records of greywater management projects all of which are limited to low-income areas such as informal settlements. The projects focus on recycling greywater for applications such as garden watering or toilet flushing depending on the type of sanitation available.

In SA low-income areas the delivery service is mostly of the type dry on-site sanitation with communal water stand point. For that reason, Armitage et al. (2007:433) recognize the importance of greywater management and its potential for causing environmental and health problems. They examine the handling of greywater in 39 informal settlements in 6 of the 9 provinces in SA, the purpose being to assess the health risks associated with its usage and to propose controlled recycle and reuse of such water. Proposals for greywater management options are given, so is a guideline for its planning and handling in informal settlements. The authors find that greywater management in informal settlements has been overlooked in the planning process of service delivery. The consequences of this neglect are visible when considering the issues related to the disposal of greywater such as mosquito infestation from smelly, stagnant water and children falling ill after playing in the water. Additional findings from the authors are that: 1) the quality of greywater in non-sewered areas differs from that in middle or higher income areas greatly varying in pollutants and having higher concentrations in the later. Therefore, there are considerable risks associated with the on-site disposal of greywater; 2) even though the correlation between the use of greywater and the amounts of detergents it contains is still to be scientifically established, there is reluctance from people in informal settlements to use greywater for irrigation because it is considered harmful to certain plant species; 3) methods for reducing sodium and phosphorus in greywater need to be researched and the use of phosphate-containing detergents banned; 4) the high density of non-sewered areas and the quality of greywater are fundamental to decision-making on the endorsement of greywater disposal. The disposal of such water is aimed at avoiding negative impacts and encouraging the safe use of greywater in informal settlements; 5) greywater management options can be guided by the determination of greywater generation rates in non-sewered areas.

2.4.6 Outline of this section

In the current section, UWWM - as exists in most urban South Africa – is described. It consists of separate sewer system (SSS) where domestic and commercial WWs are collected together but separately from stormwater. More attention is given to the treatment stage which is the secondary phase in large-scale centralised WW works. Secondary treatment is mostly biological. Biological processes such as the activated sludge (AS) are described because they are common to both large-scale centralised (off-site) and decentralised package systems. On-site systems — do not include conventional treatment such as AS but several techniques for the recycle of human wastes e.g. use of shower greywater for toilet flushing or gardening; use of urine in agriculture for local food production or else underground decomposition of faeces to prevent health risks. These small-scale systems are referred to as cost effective options and are typical to informal settlements in and around SA cities because of the physical and socio-economic conditions prevailing in them. A 2001 census of SA toilet facility shows that an alternative form of sanitation related to a small-scale decentralised system services 47 % of the SA population. It is important to mention that the concept of urine separation is not new to SA. it is for informal settlements that the first *"dry"* urine diversion system was successfully designed and developed in SA. However, the country has no record of wet urine separation (flush water used) like many European countries (e.g. Sweden, Germany). Applying the concept of wet urine diversion to the South African context seems to have good prospects.

2.5 NEW DEVELOPMENTS AND ARGUMENTS AGAINST CONVENTIONAL SANITATION AND ARGUMENTS IN FAVOR OF SOURCE CONTROL SUCH AS URINE DIVERSION

2.5.1 Scope and limitation

Conventional WW management, with combined or separate collection systems (CSS or SSS), comprises two parts namely WWtransport and treatment. This section will focus on the *treatment* of WW in SA with biological nutrient removal (BNR) methods. However, reference is made to the existing WW transport system where necessary.

2.5.2 Improvements and new developments in conventional sanitation

The main development stages presented here are those for AS conventional biological WW treatment as it is applied worldwide today. Conventional WW treatment offers conditions for the removal of both organics and nutrients mainly by subjecting a single sludge to a series of unaerated and aerated conditions. These conventional systems are referred to as biological nutrient removal (BNR) systems and cater for nitrogen (N) and phosphorus (P) removal by biological means. When BNR systems combine both N and P removal, the systems are called nitrification-denitrification excess biological phosphate removal (NDEBPR). Henze et al. (2008: Chapter 7) give information on the development of NDEBPR technology.

As Wilsenach (2006:13) puts it, advanced biological nutrient removal was developed from knowledge based on experimental systems to build a better understanding of biological interactions. When the first NDEBPR was developed, design procedures were empirical and solely based on estimates - from experimental work – for dimensioning denitrification and anaerobic (AN) reactors in terms of hydraulic retention time (HRT). No logical method for calculating N and P removal was available.

- In 1965, Levin and Shapiro conducted the first research into the concept of P uptake. After conducting extensive batch tests experiment, Levin made use of the concept of P release and P uptake in anaerobic and aerobic conditions respectively and copyrighted the first commercial system for P removal, the PhoStrip process (Henze et al., 2008:165), refer **FigureII.4 a)**.

- However, the characteristics of the PhoStrip process were that it offered both chemical and biological P removal; was appropriate for non-nitrifying systems and was a side-stream process. Later modifications to the system were brought to alleviate these problems. These modifications consisted of supplementing the stripper tank with part of the influent flow in order to encourage P release, elutriating the release P from the "stripped" sludge by recycling around the stripper tank and providing an anoxic tank before the aerobic reactor with a recycle of mixed liquor from aerobic to anoxic tanks.

Note: The BCFS process differs from the PhoStrip in that the AN reactor of the activated sludge reactors has a built-in stripper-process (van Loosdrecht et al., 1998 as reported by Henze et al., 2008:166). In the modelling of urine separation, Wilsenach (2006) made use of a pilot plant with BCFS process.

- In mid-1970s, even though the PhoStrip process had then been developed and commercialised as the first EBPR, there was less assurance in its adoption as a potential practical technology. Nonetheless, during the same period a finding was made that improved practical implementation of EBPR: the fact that subjecting a single sludge to a sequence of unaerated and aerated zones stimulated biological P removal.

- In 1975, Barnard developed the first conventional EBPR system. This came about while investigating a ND response of a system he developed for that purpose, the 4-stage Bardenpho which, showed excess P release. Barnard suggested then that the AS should be subjected to anaerobic conditions at some stage before the end of the system. The anaerobic conditions should be followed by aerobic conditions. P release would take place in anaerobic conditions after which there would be P uptake in aerobic conditions.

- In 1976, Barnard postulated that the anaerobic conditions should be such that the demand for oxygen exceeds the supply of both oxygen and nitrate. These anaerobic conditions would be fulfilled inside an AN reactorwhere the AS becomes anaerobic through the reducing potential of the incoming sewage. This principle was termed *Phoredox*.Barnard applied this to the 4-stage Bardenpho by including an AN reactor prior to the anoxic (AX) reactor. The AN reactor would receive two inflows namely the influent flow and the recycle flow from the clarifier (or secondary settling tank, SST). This configuration became known as the 5-stage Bardenpho, see **FigureII.4 b)**. However, this configuration could be simplified to a 3-stage Bardenpho or modified Bardenpho (no secondary anoxic or reaeration reactor) if reduced nitrogen removal is required. Barnard stated that nitrate entering the AN reactor could be countered by increasing the retention time of the reactor. Although Barnard developed a system that appeared to include all the conditions for EBPR, these conditions were not clearly understood. This prompted further research.

- In 1978, Osborn and Nicholls, after noting the weakness of the 5-stage Bardenpho regarding recycled nitrate to the AN reactor, developed the Johannesburg (JHB) configuration. The JHB system arrangement is such that the secondary AX reactor is repositioned in the underflow recycle stream. In this configuration, the mass of nitrate that needs to be removed in the secondary AX reactor to give zero nitrate discharge to the AN reactor is reduced s/(1+s) times that which needs to be removed in the secondaryAX zone of the 5-stage Bardenpho (Henze et al., 2008:170). Wheras the JHB system solves the problem of measuring the anaerobic mass fraction; the denitrification rate is very slow compared with that in the primary AX reactor of the UCT system – as noted below - so that protection of the AN reactor from nitrate can only be achieved at lower influent TKN/COD ratios than the UCT system.

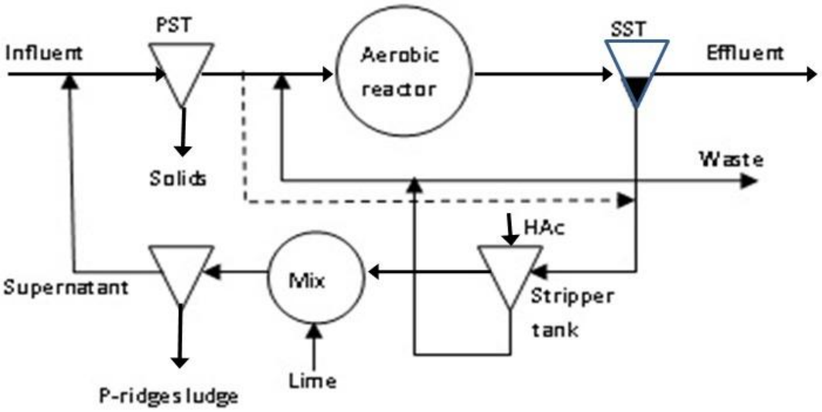
- In 1980, after reviewing their unsuccessful attempts to obtain consistent EBPR with the modified Bardenpho, Rabinowitz and Marais came to the conclusion that any nitrate recycled to the AN reactor had great relevance (also see Hascoet and Florentz, 1985 as reported by Henze et al., 2008:169). The nitrate recycled to the AN reactorhad to be kept to a strict minimum in order to obtain consistent EBPR. A possible solution to this problem was to decrease the recycling rate to avoid loading the AN reactor with nitrate. After extensive research in trying to protect the AN reactor from recycled nitrate, Siebritz et al. (1982) developed the University of Cape Town (UCT) system, see **FigureII.4 c)**. In the UCT system there are three recycles for returning mixed liquor to AN (*r-recycle*) and AX (*a-recycle*) from AX and AE reactor respectively. The s-recycle returns sludge from the clarifier to the AX reactor. By simply controlling the a-recycle, the nitrate in the AX reactor can be set to be zero in order to avoid nitrate being recycled to the AN reactor. As Siebritz et al. (1982) state, as reported by Henze et al. (2008:169), this was the greatest achievement with the UCT system namely that it was possible to eradicate the disrupting effect of nitrate on P removal so that other factors influencing P removal could be studied. However, this great achievement was at the expense of i) the AN reactor volume and ii) the ability to achieve complete denitrification.

- In 1985, the Modified-UCT system was born simply out of inability to control the a-recycle specifically under cyclic flow and load conditions due to the variations in TKN/COD ratio, see **FigureII.4 d)**.

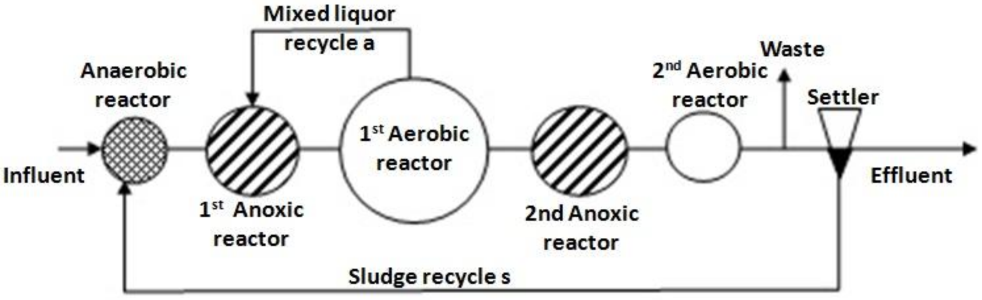
*Note:*In the modelling of urine separation, Wilsenach (2006) made use of a pilot plant with BCFS process. The BCFS process was developed in the late 20th century in the Netherlands with the aim of supporting the biological process. This would be achieved in two ways 1) by phosphate stripping and 2) by potential phosphate recovery in the main line. The benefits of such process would be the stabilisation of the sludge settling properties and the optimisation of the control of nitrogen removal. Stable and low Sludge Volume Index (SVI) (around 120 ml/g) would be stimulated by compartmentalisation and better nitrogen control would be achieved by providing a third recycle from aerobic to anoxic which would maximise denitrification. A section of the AX reactor is aerated at times of peak flows so that consistently low effluent ammonium and nitrate values would be produced (e.g. 0.5 mgNH_3-N/ℓ and 5-8 mgNO_3-N/ℓ), the former to promote good settling sludge. Chemical P removal would take place in the AN reactor as result of the addition of precipitants to it. However, this chemical P removal may be at the expense of EBPR especially when too much precipitants are added such that there is not enough phosphate available for the Polyphosphate Accumulating Organisms (PAOs). Some of the disadvantages of the BCFS are 1) the cost of chemicals (precipitants) necessary for chemical P removal; 2) the delayed response time of the biological phosphorus removal (some days to weeks) to changes in chemical addition (Henze et al., 2008:171).

The NDEBPR process with UCT and JHB configurations are the systems selected for the current research. The UCT system offers the significant following advantages:

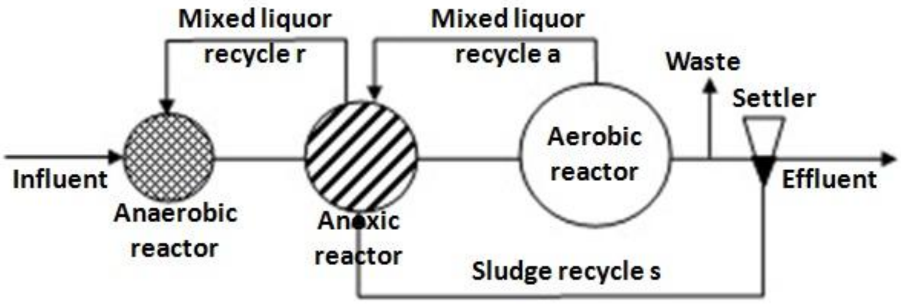
1. Nitrification-denitrification (ND) process happens independently from the EBPR (BEPR) process
2. *a-recycle* can be controlled to avoid nitrate being recycled to the AN reactor
3. Addition of precipitants to the AN reactor in order to enhance P removal is not required. P removal is achieved biologically only
4. Most biological plants in South Africa can operate as a UCT system.



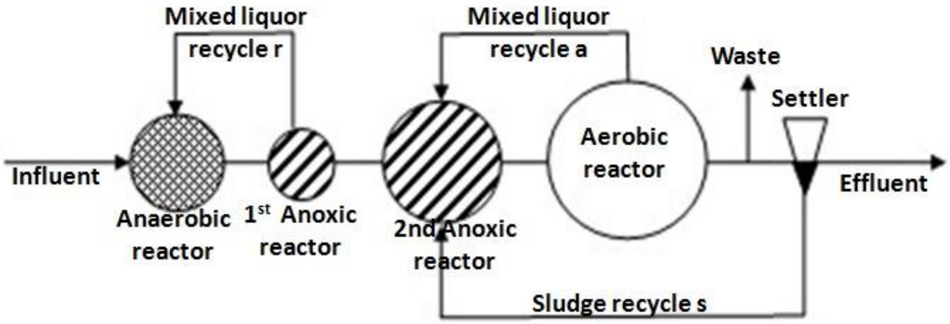
a) PHOSTRIP PROCESS (1965)



b) MODIFIED BARDENPHO (5 STAGE) (PHOREDOX) (1974)



c) **UCT (1980): VIP (1985)**



d) ***MODIFIED-UCT (1981)***

Figure II.4: Development of Biological Nutrient Removal Activated Sludge (BNRAS) processes from 1965 onwards. (Horan et al., 1994:188; Henze et al., 2008:165-171)

2.5.3 Improvements in effluent quality from advanced WW treatment processes

The understanding of biological nutrient removal systems progressed considerably over the past 50 years, going from empirical knowledge merely based on experimental observation to a better understanding of biological interactions (Wilsenach, 2006:13). Once carbonaceous removal was achieved at most treatment plants (thereby ameliorating receiving water deoxygenation), the prevention of eutrophication became the subsequent goal for WW treatment. This required a greater understanding of the effects of WW on the environment and stimulated advanced treatment including the removal of nutrients such as N and P. The development of computer simulation models created a new basis for optimisation. Depending on the receiving water streams, most plants are required to remove N, P or both (Lofrano and Brown, 2010:5262). Today state-of-the-art activated sludge NDEBPR systems such as the UCT system offer good effluent qualities e.g. Chemical Oxygen Demand (COD) < 50 mg/ℓ; N_{tot} or Total Kjeldahl Nitrogen (TKN) < 10 mg/ℓ; NH_3< 1 mg/ℓ and P_{tot} (PO_4) < 1.0 mg/ℓ (Wilsenach, 2006:4).

2.5.4 Minimisation of resources requirements

The concept of sustainability or sustainable urban development and urban water management has brought new concerns amongst which is the call for the minimisation of resources usage (see geophysical criteria of environmental sustainability in **Section 6.1.3** of**Chapter 2**). These include reduced water consumption and reuse, nutrient recovery such as N & P, reduced energy required for WW treatment, reduced space required for WW treatment works and reduced greenhouse gas emissions.

2.5.4.1 Biological nitrogen (N) and phosphorus (P) removal or recovery

Livestock consume the crops produced with inorganic fertilizers and the crops and livestock are consumed by people. The generally high human protein diet results in high concentrations of ammonia in urban WW, mostly from the urine in WW. While WWTPs have been modified over the years to remove N and P (point source control), the largest contributor to eutrophication of receiving surface water systems is the runoff of N and P from agricultural land (diffuse pollution) due to high fertilizer application rates to deliver high crop yields. So, over the years the surface water systems have been a N and P sink of the atmospheric N and mined P, and consequently have shown rapid deterioration due to widespread algal and water plant blooms due to eutrophication[1].

In the production of inorganic fertilizers, large quantities of N and P are extracted from primary sources. Nitrogen is extracted from the atmosphere for the production of ammonia with the Haber-Bosch process ($N_2 + 3H_2 = 2NH_3$) and phosphorus ore is mined. Phosphorus bearing ore is a non-renewable resource and its quality and quantity are declining. Some countries have stopped its import because it was found to be the greatest contributor of cadmium to agricultural land via the application of inorganic fertilizers. While P and N removals have been implemented for many years at WWTPs, dwindling P reserves have started a drive for P recovery from WW for reuse. While the BCFS process offers the possibility to recover P directly, e.g. via Struvite ($MgNH_4\ PO_4.6H_2O$) precipitation, EBPR process such as the UCT process biologically transforms P into a form that is easily available for recovery. The process of EBPR is mediated by PAOs which take up more phosphorus than they need for biological growth – thus the word "*excess*" BPR - and accumulate it into long chains of polyphosphates (polyP). Thus, the overall P of the biomass is increased from the ordinary value of 0.02 mgP/mgVSS to values around 0.06-0.15 mgP/mgVSS. However, this is dependent on plant operating and design parameters that stimulate the growth of necessary micro-organisms e.g. PAOs and OHOs (Ordinary Heterotrophic Organisms) (Henze et al., 2008:156). After P is taken up by PAOs, one of the P recovery techniques can be used to recover P from sludge. Brett et al., (1997), as reported by Wilsenach (2008:16), give an overview of P recovery techniques.

---

[1] The discharge of acid mine drainage (AMD) from operating or abandoned mines has also had its negative impact on surface water quality. The high sulphate and metals concentrations have caused increasing salination, which, if the total dissolved solids increases above 1000 mg/ℓ, renders the water unusable for agriculture and difficult to treat to avoid corrosion and aggression to water storage and distribution systems.

2.5.4.2 Energy generation

Optimisation of BNRAS systems such as the UCT system were possible through a better understanding of the micro-organisms involved in biological WW treatment, notably the role of the PAOs and denitrifying PAOs (DPAOs). The latter require a low COD/N ratio and reduce nitrate while simultaneously taking up phosphate. This way, more COD can be removed in PS. The efficiency of PS can be improved through chemically enhanced primary treatment (CEPT). The more particulates COD removed in primary sedimentation (PS), the more biogas can be produced in anaerobic digestion of PS sludge. This can render WW treatment plants virtually energy self-sufficient (Wilsenach, 2006:14). But Svardal and Kroiss (2009) warn that any energy and resource saving at WWTP that is at the expense of effluent water quality is counter productive because from a sustainability perspective the water has a much greater value than the reduction in energy/greenhouse gas emissions.

2.5.4.3Area requirement

Because the requirement to nitrify governs the sludge age of the BNRAS system and therefore the reactor size, strategies seeking to reduce sludge age have been implemented over the past two decades. For maximum specific growth rates of nitrifiers at 20^{o}C (μ_{nm20}) around 0.45/d, to guarantee nitrification, the sludge age of the single sludge system must be around 20 to 25 days at 14^{o}C, if 40 to 50% of the sludge mass in the system is aerated. Such long sludge ages result in large biological reactors per ML of WW (WW) treated. To reduce the sludge age, and hence the biological reactor volume per ML WW treated, internal fixed media such as Ringlace™ have been placed in the AE reactor (Wanner et al., 1988; Sen et al., 1994; Randall and Sen, 1996). The nitrifiers grow on the fixed media establishing a population permanently resident in the AE reactor. These nitrifiers are not subject to either the aerobic sludge mass fraction or the suspended mixed liquor sludge age, with the result that both can be reduced. Such a reduction in system sludge age is particularly beneficial for low temperature WWs (10-15^{o}C). However, the effectiveness of the internal fixed media has not been as good as expected, and yields a rather high cost/benefit ratio.

An alternative approach for reducing BNRAS system sludge age is external nitrification (Hu et al., 2000). By achieving nitrification in an external fixed media reactor like old trickling filters at WWTPs, nitrifiers no longer need to be sustained in the AS with the result that the sludge age of the BNRAS system can be reduced from the usual 15 to 20days to half, around 5 to 8 days. The reduction in sludge age increases the WW treatment capacity of the system by some 50% or, alternatively, reduces the biological reactor volume requirement per ML WW treated by about a 1/3rd, without negatively affecting either biological

N or P removal. In fact, a reduction in sludge age increases both biological N and P removal per mass organic load (WRC, 1984; Wentzel et al., 1990) and this would be particularly beneficial for low temperature WWs (10-15^{o}C). Because nitrification is no longer required, the aerobic mass fraction is governed by the P uptake process, for which aerobic mass fractions can be smaller than for nitrification. However, unless specific site conditions apply, external nitrification BNRAS is only cost effective at WWTPs where trickling filters in a reusable condition are available.

2.5.5 Correlation between influent TKN/COD and TP/COD ratios and sludge age for N and P removals

The minimum N and P requirements for biological (heterotrophic) growth depend on sludge age, the shorter the sludge age the higher the N and P requirements and decrease when settled WW is treated. For normal (non-BEPR) activated sludge N/VSS (f_n) and P/VSS (f_p) ratios of 0.10 gN/gVSS and 0.025 gP/gVSS respectively, the influent TKN/COD and TP/COD ratios for raw and settled WW at 5, 8, 10 and 20d sludge age are given in **Table II.3**. At these ratios, all of the influent N and P will be used for sludge production so that no nitrification-denitrification (ND) and biological excess P removal (BEPR) will be required. From **TableII.3**, for 1000 mgCOD/ℓ, the influent TKN concentration of mixed grey and brown WW would need to be below 31 to 23 mgN/ℓ for raw WW and 25 to 16 mgN/ℓ for settled WW to eliminate ND from the BNRAS system and the TP concentration below 9.3 to 6.8 mgP/ℓ for raw WW and 7.6 to 4.9 mgP/ℓ for settled WW to eliminate BEPR from the BNRAS system. To unlock capacity at existing BNRAS WWTP, it is much more important for ND to be eliminated from the system because then sludge ages can be halved from 15-20d to 8-10d. BEPR can be achieved at short sludge ages (5-10d).

Table II.3: Influent TKN/COD and TP/COD ratios for complete removal of N and P without requiring ND and EBPR processes.

Sludge age (d)	**Raw WW**		**Settled WW**	
	TKN/COD	**TP/COD**	**TKN/COD**	**TP/COD**
5	*0.031*	*0.0093*	*0.025*	*0.0076*
8	*0.028*	*0.0084*	*0.022*	*0.0066*
10	*0.026*	*0.0079*	*0.020*	*0.0061*
20	*0.023*	*0.0068*	*0.016*	*0.0049*

Note: In the simulation study of the impacts of urine diversion on WWTPs, Wilsenach and Loosdrecht (2003) utilized a BNR system called the biological/chemical P and N removal process (BCFS). The results showed a 70% decrease in total effluent nitrogen content with increasing urine separation up to 60% and nearly 100% P removal without urine separation. At greater urine separation, the model showed no improvement in effluent quality due to the magnitude of the Monod affinity constants in the kinetic equations (do these affinity constants also set the limit of technology – LOT - in real WWTPs?). The predicted effluent N and P concentrations only decreased below the affinity constant limit concentrations once nutrient limitation took place.

2.5.6 Reasonably low per capita investment and costs in conventional WWT systems

Wilsenach (2006:17) states that the overall cost of conventional WW in industrialised European countries is small when one considers the total number of people connected i.e. the *per capita* cost is low. The down payment of civil and mechanical construction often amounts to 60 % and the remaining 40 % is for operation and maintenance. Of the 60 %, the bulk (50 %) goes to mechanical and electrical installations and the remaining to structural works and land value. Such analysis needs to be done for the context of SA as it offers better prospects given that storm water is collected separately from other municipal liquid wastes thereby reducing the hydraulic load on the plant and therefore also its size.

2.5.7 Arguments against conventional WW management

Wilsenach (2006:22) argues that there are two growing but not aligned movements of thoughts that criticise current conventional WW system. The first movement endorses the advancement of current UWWM by stating that it should happen by progressive innovation. The second movement insists on the development of alternative (completely different) management systems. Some of the arguments against conventional system, that are also applicable to the SA context, are:

a) Greater quantities of water are used to flush urine (5 times/d) than faeces (1 time/d)around 35ℓ/(p.d) (Wilsenach and Loosdrecht, 2002:104). This is wasteful and unsustainable. There is a need to recycle greywater from sources such as bathrooms and washing machines. This can be used for flushing toilets because these are relatively less polluted.
b) Conventional treatment systems do not sufficiently remove micropollutants such as natural hormones and pharmaceutical products.
c) Conventional sanitation systems are wasteful and unsustainable while ecological sanitation (ecosan) such as composting toilets are based on the principle of recycling or composting human waste.

d) Sewers usually leak thus polluting the surrounding groundwater. Also, rainwater can infiltrate sewers thereby diluting the WW even further. The capital costs of sewers are high and their repair and maintenance are often disruptive and expensive.
e) Lack of maintenance and operational skills. Most conventional treatment plants do not produce the desired effluents standards, not because the treatment processes are inappropriate but because of a lack of technical expertise of operators to support and maintain them (Gaydon et al., 2007).

For detailed discussions on arguments against conventional WW management system, refer to Wilsenach (2006: 22-26). Attention should be paid to the fact that urban SA is serviced by SSS and not CSS.

2.5.8 Source control is the closest to the concept of natural sustainability

A principle for cleaner production also favours changing the conventional sanitation. Different waste streams (human wastes, faeces and urine) should not be mixed with the other domestic WW components (kitchen sink, washing machine, shower or bathtub WW). Some wastes (like urine) are better treated separately in concentrated forms (source control), see **FigureII.6** below. The domestic WW components are: 1) *Toilet water*. Also identified as black water, it consists of faeces (brownwater) and urine (yellowwater); 2) *Greywater*. It is a mixture of washing, kitchen, bathtubs, showers and basins wastes.

Burkhard et al. (2000:211) follow the same line of thinking stating that the techniques for separate collection and treatment of WW come closest to the concept of natural sustainability i.e. they have the potential for improving the water cycle and reintroducing nutrients from WW to the local environment. Urine contains high amounts of N (80%) and P (50%) in total domestic WW whereas faeces are poor in nutrients but rich in COD. Source control like urine separation, argues Wilsenach (2006:32), will also take care of the problem of treating micropollutants that are not removed well in conventional WW treatment. Micropollutants (pharmaceutical products, estrogens, etc.) are found in large proportion in urine. Lienert et al. (2007:4471) found that 70% of 42 pharmaceuticals (with ecotoxicological hazard) studied were excreted with human urine. It seems wasteful to contaminate a large volume of water with an extremely low volume of urine (< 1 percentage of WW flow).

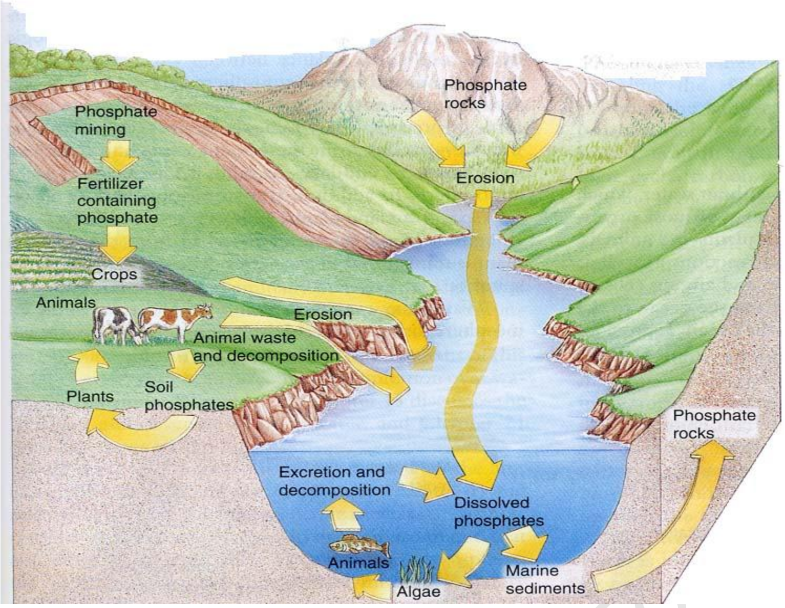
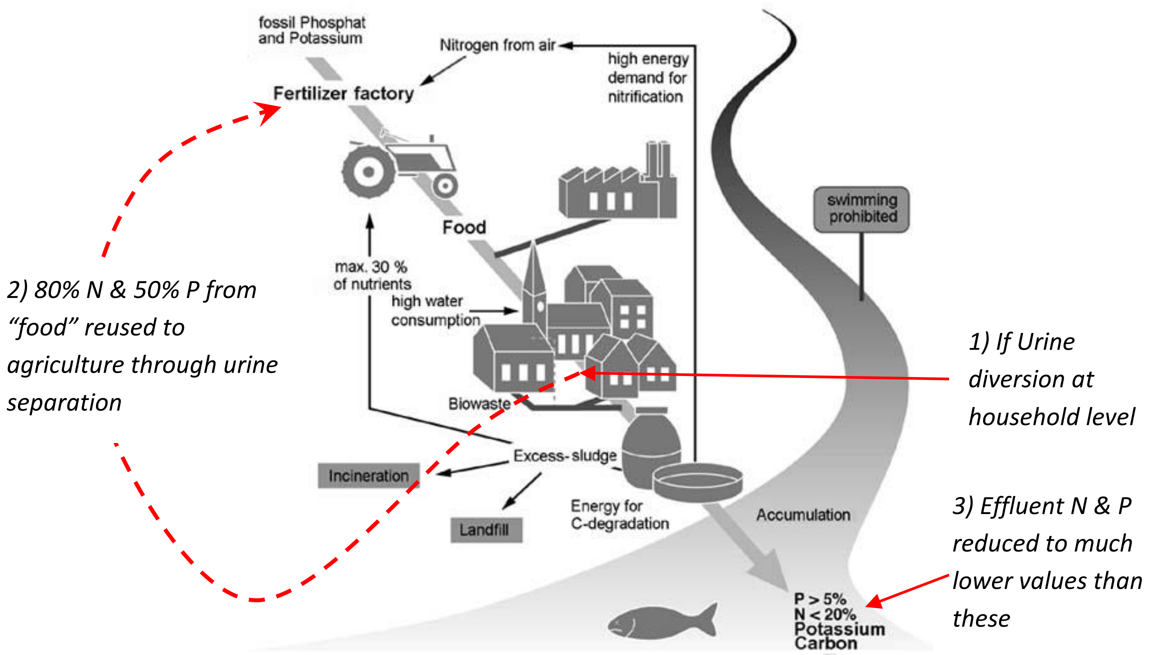


Figure II.5: Description of the P cycle also showing P-ore, which is mined. The sketch also shows that water bodies have become the sink of leached P from agriculture. (Nikkicarman, 2011)



2) 80% N & 50% P from “food” reused to agriculture through urine separation

1) If Urine diversion at household level

3) Effluent N & P reduced to much lower values than these

Figure II.6: Description of nutrients flow in conventional sanitation that is linear. If N & P were separated at household (hh) level and recycled to agriculture, it would create a closed-loop of nutrients from hh to agriculture. It would also reduce nutrients accumulation into water bodies from WW plants outflow. (Srinivas, 2011)

2.5.9 Source separation of urine has the best prospects of improving WWM systems

2.5.9.1 Reduction in water consumption

Separate urine collection reduces the flush water usage resulting in lower per capita WW generation and therefore in a lower water consumption and water saving. There will be additional costs in installing urine separation toilets and collection systems. However, these will be once off costs which can be recovered by continuous savings in water and increased WWTP capacity. With reduction in water, N and P fluxes to the WWTP, savings in energy at WWTP will be made (Vinnerås and Jönsson and, 2002:275), which reduce operating costs.

2.5.9.2Increased WWTP capacity

A. Reduced hydraulic load

By implementing separate urine collection and treatment the capacity of existing WWTPs may be increased. Around 35ℓ/(p.d) is used to flush urine, while separate toilet urinals and no mix toilets may eventually require almost no flushing water (Wilsenach and Loosdrecht, 2002:104; Jonsson et al., 1997:145). This implies that with separate urine collection, the flow of WW to WWTPs will be less by about 35ℓ/(p.d) (ignoring the volume of urine per person) or about 90% hence leading to an increase in brown water that can be treated. Wilsenach and Van Loosdrecht found that a capacity increase of 40% can be achieved.

B. Reduction in sludge age

For details on how urine separation can reduce the sludge age of the WWTP, see **Section 2.5.5** above.

2.5.9.3 Source separation of urine

If influent TKN/COD ratios can be reduced below those in **TableII.3** by urine separation, then this would be another and perhaps better way to reduce BNR system sludge age. So here, the key question is *what degree of urine separation has to be achieved to not require ND at the WWTP?* The answer will depend on the diet of the community that generates the WW (low protein diets will produce low N content urine) amongst other things.

2.5.9.4 Nutrient recovery

Urine contains high concentrations of N and P which cause eutrophication if not removed at the WWTP. Urine separation reduces emissions of these nutrients to receiving surface water. Separate urine treatment also opens the possibility of nutrient recovery (N, P, Mg, K, Ca) to manufacture fertilizers. P can be recovered from urine by precipitating the phosphate as struvite with $Mg(OH)_2$ dosing. However, practical solutions for large cities have not been developed yet, but small pilot projects in Sweden, Tibet and Holland have demonstrated its potential (Tilley et al., 2008). At this time, inorganic fertilizers can be produced much more cheaply and efficiently relative to production from urine treatment. Therefore, at this stage the driver for adopting urine separation is to save water, improve WWTP effluent quality and keep endocrine disruptors and environmental estrogens out of the water cycle. In time, nutrient recovery (N, P, Mg, K) from WWTP sludge liquors and separated urine will become economically viable as P resource quality and quantity decline and/or natural gas for the production of ammonia runs out / get expensive.

2.5.10 Outline of this section

In the current section, a brief history of the NDEBPR AS UCT and JHB systems is given as well as the significant potential advantages they can offer. Amongst these advantages are the good effluent quality in terms of Organics (COD) < 50.0 mg/ℓ; total Nitrogen (TKN) <10.0 mg/ℓ; Ammonia (FSA) < 1.0 mgNH_3-N/ℓ and total Phosphate (TP) < 1.0 mgPO_4-P/ℓ. Of no-less importance is the fact that EBPR offers the possibility to recover P indirectly from WW by transforming it into a form that is easily available for recovery. Then, P can be recovered through processes such as struvite precipitation or other techniques. There is at present a drive for P-recovery from WW for reuse given the decline in the quality of P-bearing ore worldwide. However, biological P treatment will only limit itself to P removal as long as there is no market for P-precipitates i.e. it is still cheaper to produce inorganic fertilizers with mined P than it is to recover P from precipitates. N is not a limited resource because it is widely available in the atmosphere and can be produced through the Haber-Bosch process.

This section reviews the most commonly stated arguments against conventional sanitation and the prospects of source control such as urine diversion. This is to justify the selection of urine diversion as appropriate alternative solution to the problems of conventional sanitation.

2.6 CRITERIA AND TOOLS FOR THE EVALUATION OF SANITATION AND URBAN WATER SYSTEMS

In **Section 2**, the concept of sustainability was identified as being three-dimensional, the three dimensions being economic, environmental and social-cultural. Each of these dimensions or criteria can contain several indicators depending on the objective(s) of the study. By distinguishing between abstract and real criteria, one can understand where these are likely to transform or remain unchanged overtime, or else where they are more subjective and therefore temporary (Wilsenach 2006:29).

In an extensive literature review on sustainability indicators for the assessment of WW treatment systems, Balkema et al., (2002) propose the *system analysis* approach as a more general approach to such study. The system analysis approach is broader in the sense that it comprises three big steps namely 1) the *goal and scope definition*; 2) the *Inventory Analysis* and 3) the *Optimisation*. The goal and scope definition can be interpreted as the identification step where the sustainability indicators are selected for sustainable solutions to a given problem. These indicators would be associated to the main problems of WW treatment e.g. bottlenecks of WW treatment in SA. The sustainability indicators can be grouped into four domains namely economic, environmental, socio-cultural and functional. The functional domain is related to a system efficiency and may include indicators such as adaptability (possibility to expand the size of the system), durability (lifetime), robustness (ability to cope with influent flow changes), maintenance required and reliability (sensitivity of the system to breakdown or part dysfunction) (Balkema et al., 2002:157). The inventory analysis step can be interpreted as quantification and/or qualification step depending on the indicators defined in the goal and scope. Finally, the optimisation step is the evaluation and judgement step. It includes all three dimensions or domains of sustainability and it is dependent on the objectives set by the WW treatment system. Because WW treatment system is often multi-objective, the optimisation step can be a conflicting one because e.g. *"it is not always possible to design a plant that minimises costs, energy use and land area while at the same time maximising performance"* (*Ibid.*). Unless one finds trade-offs between the objectives of WW treatment, one has to evaluate the sum of the normalised sustainability indicators to produce a final optimum judgement. Because the sustainability value of the treated effluent is so very high, the effluent quality will have to be heavily weighted relative to energy consumption and greenhouse gas emissions (Svardal and Kroiss, 2009).

2.6.1 Goal and scope definition

As previously mentioned, the purpose of the goal and scope step is to single out criteria for sustainable solutions to a given problem. A sustainable solution is one that maximises the benefits of the use of resources whilst minimising the costs or damages in time and space. Problems to a given situation must have already been identified. There are generally three main groups of criteria namely social & cultural; economic and environmental (Wilsenach, 2006:29). Each of these criteria has sustainability indicators (Balkema et al., 2002:157).

2.6.1.1 Social environment and cultural criteria

Social aspects are outside the scope of this study because not only are they complex to quantify but primarily because it would be unsustainable to drag on such matters only to realise that source separation (urine diversion) has no beneficial impacts whatsoever (Wilsenach, 2006:37).

Nonetheless, it is important to recognize that the success of any project directly involving the end-users ultimately rest on indicators such as *institutional requirements, awareness, participation, acceptance, expertise or stimulation of sustainable behaviour* (ETC, 1996; Hellström, Jeppsson and Kärrman, 2000; Jacobs, de Knegt, Koedood and Karst, 1996 as reported by Balkema et al., 2002:158). The indicators depend on aspects of institutional organisation of a country or region, people's perceptions, social and cultural values, habits, religious beliefs, education level, training. Given the sanitation backlog in SA, there is immediate concern with sanitation amongst the ordinary people. However, poverty, level of education and lack of information are often the major challenges to prospective sanitation projects. The fundamental assumption when considering alternative sanitation system in SA is that it should adequately answer the questions of convenience, privacy and prestige (Graham, 2003:15).

South Africa has a growing emerging middle class while a significant portion of its population has little education – results of the country's political and socio-economic history. People are more likely to perceive new ways of using toilets or alternative methods for handling domestic WW as inferior, too demanding (many instructions) or taboo, opposed to cultural moves e.g. certain men find it difficult to sit or aim properly when using a urine separation toilet. People living in informal settlements, especially those near cities, are often quoted as saying that they would like to have the same sanitation (flush toilet) as those living in sewered areas of the cities (Gounden et al., 2006:4). This despite that alternative sanitation options such as urine diversion offer the fertiliser value of urine.

2.6.1.2 The economical environment and cost criteria

The cost criterion is often decisive in many projects (Wilsenach, 2006: 31; Balkema et al., 2002:157). Yet, the principle of valuing a project by what it is worth financially does overlook complex issues such as hidden costs and indirectly related costs which are not easy to set in monetary terms (Wilsenach, 2006:31; Balkema et al., 2002:154). However, water authorities are not likely to consider system changes if not supported by substantial cost saving and/or less complexity (Wilsenach, 2006:31). Generally, the cost of WW management comprises two components namely the cost of transport and the cost of treatment. Each of the latter is composed of a capital phase and an operation & maintenance phase which, are the most commonly used indicators for the economical sustainability of a WW system (ETC, 1996; Hellström, Jeppsson and Kärrman, 2000; Mels et al., 1999 as reported by Balkema et al., 2002:158). Wilsenach (2006:31) states that in the Netherlands the capital cost of WW treatment is less than its operational and maintenance costs which is also true for SA (Little et al., 2002).

2.6.1.3 The environmental criterion

The environmental criterion is based on the fundamental principle that sanitation (or pathogen removal) remains the first objective of WW treatment (Lofrano and Brown, 2010:5254). Therefore, alternative sanitation options should guarantee the same levels of cleanliness and wellbeing for the community being serviced (Wilsenach, 2006:34). Conventional sanitation is already capable to remove pathogens and in recent years additional indicators of environmental sustainability have emerged. These are based on the principles of environmental protection & prevention of eutrophication or optimal resource utilisation. The former can be grouped under the biological environment criteria because it is emission oriented; the latter is part of the geophysical environment criteria, whichis related to resource depletion (ETC, 1996; Hellström, Jeppsson and Kärrman, 2000; Lundin et al., 1999; Mels et al., 1999 as reported by Balkema et al., 2002:158; Wilsenach, 2006:29-34).

A. Biological environment and emission criteria

Some of the most commonly found indicators for environmental protection and prevention of eutrophication are emission-related. These are:

(a) Emissions to Water

As stated previously, pathogen removal and environmental protection remain the prime interests of WW treatment. Today, conventional WW treatment is capable of providing adequate level of hygiene and community health. However, as more and more people (due to population growth and urbanisation) are connected to the water supply so is the pressure to discharge cleaner effluent into the environment that has tolerable quality for direct water recycle (Lofrano and Brown, 2010:5264). In recent times, the prevention of eutrophication in receiving waters has been a growing concern worldwide. For that reason, the *quality of effluent* from treatment plants is also the prime indicator for the biological criteria of sustainability. Other indicators include sludge/waste production, use of chemicals, etc. (ETC, 1996; Hellström, Jeppsson and Kärrman, 2000; Lundin et al., 1999; Mels et al., 1999 as reported by Balkema et al., 2002:158).

In assessing 600 package plants in SA, Gaydon et al., (2007:3) adopted the set of criteria contained in the revised General Authorisation pertaining to the evaluation of effluent quality from such plants (Governement notice 399 in Gazette 26187). The criteria are:

- Chemical Oxygen Demand (mg COD/ℓ)
- Ammonia as Nitrogen (mgNH_3-N/ℓ)
- Ortho-phosphate as Phosphorous (mgPO_4-P/ℓ)
- Nitrite/Nitrate as Nitrogen (mgNO_2/NO_3-N/ℓ)
- Suspended Solids (mgSS/ℓ)
- Electrical conductivity (mS/m)
- pH

Over the past decade another serious surface water quality problem emerged. Concentrations of hormones, medicine residues and pharmaceutical compounds excreted by people are increasing in surface water and the environment. In addition, industry produces many new organic compounds and chemicals annually, the effects of which on the environment and people are unknown. Many of these organic compounds are not readily degraded in WWTPs. The release of hormones, medicine residues and pharmaceutical compounds, generically called endocrine disruptors or environmental estrogens, over the past years have caused severe disruption in the environment affecting the gender of fish and reptiles at WWTP discharges and believed to be detrimental to human health (Cadbury, 1998). The removal of these compounds is becoming increasingly important for the environmental sustainability and human health.

This research will consider the same criteria in assessing the effluent quality as Gaydon et al. (2007) above. For simplification purposes, it will exclude indicators such as faecal coli forms, free chlorine and endocrine disruptors.

(b) Emissions to Atmosphere

Secondary treatment of WW is based on the fundamental concept of microbial degradation of organics (carbonaceous material present in WW) to produce cleaner effluent and in the process emits carbon dioxide gases (CO_2). Other atmospheric emissions result from the use of coal or gas as sources of energy for WW plants (ETC, 1996; Hellström, Jeppsson and Kärrman, 2000 as reported by Balkema et al., 2002:158). The former is fixed by the organic load and bioprocesses (around 20 gC/person/day, Ekama, 2010) so only the latter can be controlled through energy savings especially when considering the current concerns with global warming. Alternative systems should also consider ways of preventing gaseous emissions (Wilsenach, 2006:32). Ekama (2010) has quantified CO_2 emissions from different types of WWTP. However, CO_2 is not the main problem. In efforts to promote denitrification to save energy, aeration systems are turned down – while this does improve denitrification, greater H_2O emission has been observed, which with a CO_2 weighting of 300, is worse than the CO_2 emitted by higher aeration energy consumption. A major concern with the handling of separated urine is the ammonia volatilisation e.g. during the storage or spreading of urine (Udert et al., 2005a as reported by Maurer et al., 2006:3156; Wilsenach, 2006:32).

(c) Emissions to Land

Waste activated sludge from treatment plants is harmful to the environment because it is a carrier of heavy metals, pathogens and can have concentrations of nutrients such as PO_4^+, NH_4^+ or NO_3^-.For this reason, it is aerobically digested or else incinerated instead of being used as a fertiliser in agriculture (Wilsenach, 2006:32). South Africa has guidelines pertaining to the utilisation of WAS from treatment plants for agriculture purposes (Snyman and Herselman, 2006).

(d) Area Requirements

Given the growing rate of urbanisation of SA cities, the physical footprint of treatment plants cannot be ignored (Wilsenach, 2006:33). Hellström, Jeppsson & Kärrman, 2000 and Mels et al., 1999 as reported by Balkema et al. (2002:158) also consider space or land area required for conventional treatment plants as an important sustainability criterion. An investigation of the space required per capita of conventional treatment, the density of population and the amount of free space available needs to be conducted for the context of South Africa.

B. The geophysical environment and criteria of resource depletion

The indicators found within the geophysical aspect of environmental sustainability, are related to the depletion of the Earth resources.

(a) Nutrient Recovery

The criterion of nutrient recovery is based on the knowledge that a resource such as phosphate bearing ore ($Ca_3(PO_4)_2$) is a non-renewable resource and its quality and quantity are declining. Other finite nutrients may include potassium salts (KCl) and sulphates (SO_4^{2-}) (Wilsenach, 2006: 33; Butler and Parkinson, 1997; Hellström, Jeppsson and Kärrman, 2000 and Lundin et al., 1999 as reported by Balkema et al., 2002:158). Unlike Nitrogen that can be extracted from the atmosphere - with the Haber-Bosch process ($N_2 + 3H_2 \rightarrow 2NH_3$) - phosphate ore is mined. While P and N removals have been implemented for many years at WWTPs, dwindling P reserves have started a drive for P recovery from WW for reuse. Because urine contains about half the P in WW, recovering P from WW is a good prospect.

(b) Energy and Work

The energy required in WW treatment is mostly for aeration and mechanical operation (e.g. reactor mixers) which, is low relative to other sectors of the South African economy (Ekama et al., 2011). Energy use is cited as a sustainability indicator by Butler and Parkinson (1997); ETC (1996); Hellström, Jeppsson and Kärrman (2000); Lundin et al. (1999) and Mels et al. (1999) as reported by Balkema et al. (2002:158). Most WW treatment plants are powered by coal or gas that are regarded as finite fossil fuels. Although low quantities of these fossil fuels are used to operate treatment plants, they are essential for global sustainability due to the treated water they produce (Wilsenach, 2006:33).

2.6.1.4 The technological environment and functional criteria

A. Maintenance criteria and quality control

The functional criteria are based on the fundamental principles that WWTPs are able to sustain variations in flow rates and concentrations, but also that they require maintenance to be reliable (Butler and

Parkinson, 1997; ETC, 1996; Hellström, Jeppsson and Kärrman, 2000 as reported by Balkema et al., 2002:157, 158). Plants' operators' main concern is associated with the ease of operation and maintenance of alternative systems. However, as Wilsenach (2006:34) also puts it, only experience can tell if some systems are more difficult to operate and maintain than others. However, one thing is certain, whatever alternative/changed system is implemented to achieve greater sustainability, it will be more complex than the present conventional system.

B. Quality control

The state of quality control of final effluent in large-scale centralised systems is often the reverse of what it is in small-scale decentralised systems. In the former, effluent quality monitoring is the main target and it is mostly achieved even though leakages of faulty pipes often remain unknown. In Decentralised systems, the state of quality control of final effluent is poor (these plants are sources of diffuse pollution) because it is often difficult for local authorities to strictly legislate and regularly inspect them (Wilsenach, 2006:34; Gaydon et al., 2007: vii).

2.6.2 Inventory analysis

The inventory analysis step can be interpreted as a quantification and/or qualification step depending on the indicators defined in the goal and scope. Tools such as substances' mass balancing, calculation of energy consumption, cost benefit analysis, risk analysis and factor analysis can be used (Balkema et al., 2002:159)

2.6.3 Optimisation of sustainability dimensions

This is simply described as the evaluation or judgement of the dimensions of sustainability that have been previously quantified in the inventory analysis. Such evaluation or assessment is quasi-dependent on the objectives one has set for a particular WW treatment. Various objectives can be to minimise costs; minimise energy use; minimise loss of nutrients; maximise products e.g. clean water, biogas, biomass, fertilisers, compost; etc. Because it is often difficult to find a compromise between several objectives, one has to find the sum of the normalised sustainalibity indicators (Adjiman, Schweiger & Floudas, 1998; Biegler, Grossmann & Westerberg, 1997; Schweiger & Floudas, 1998 as reported by Balkema et al., 2002:159).

2.6.4 Outline of this section

This section elaborates on the concept of sustainability which was briefly explained in **Section 2.** This is because today, every new development has to be assessed in terms of its sustainability. However, the term sustainability or sustainable development is not easy to define because it has many dimensions. Therefore, a general method for the examination of sustainability of WW is selected namely the *scope analysis* method which includes the socio-cultural, economic and environmental dimensions of sustainability. These dimensions are essentially criteria that are determined by several indicators depending on the objectives of the particular WW treatment being studied. While it is proposed not to include the socio-cultural criterion for reasons of simplification, the economic and environmental criteria are considered. The economic indicators selected are the capital and operation & maintenance costs of WW treatment – the costs of transport are proposed not to be considered for simplification purpose. The environmental indicators fall into two categories namely biological (related to emissions) and geophysical (related to resources depletion). The biological environment indicators are the effluent quality in terms of COD, TKN, FSA, NO_3& NO_2, TP, SS and pH; the CO_2 emissions to the atmosphere and the size of the WW treatment works. The definition of the different indicators constitutes the goal *& scope definition*, which is the first step of the scope analysis method – for sustainability assessment. The second step is called the inventory analysis and it consists in giving quantitative or qualitative measures to the indicators selected in the first step e.g. calculation of costs; measurement of effluent concentrations; comparison with alternative options; comparison to the national effluent standards; energy mass balance. The third and last step of the scope analysis consists in evaluating or weighting the quantified indicators in order to come up with an optimum decision. The decision is based on the objective(s) set up in the research.

2.7 OBJECTIVES, HYPOTHESIS AND KEY QUESTIONS

2.7.1 Objectives

The objectives of this research can be stated as follow:

- Minimisation of environmental pollution
- Maximisation of water-saving
- Minimisation of treatment costs
- Minimisation of nutrients losses

2.7.2 Hypothesis

Modern BNRAS WWTPs remove organics, nitrogen (N) and phosphorus (P) to reduce receiving water de-oxygenation and eutrophication. Where separate storm and WW collection is practiced, these WWTPs receive predominantly under dry weather conditions, a mixture of brown (faeces and toilet paper), yellow (urine) and grey (kitchen and bathroom) waters. From previous WW separation studies, urine contains about 80% of the N, 70% of micropollutants such as pharmaceuticals (Lienert et al., 2007:4471) and 50% of the P in mixed municipal WW, but it represents less than 1% of the total WW volume. Thus, implementing separate urine collection will considerably reduce the nutrient loads on municipal WWTPs.

2.7.3 Key questions

Will urine separation make a significant difference to BNRAS effluent quality and economics? Here the key questions are:

- With nitrification being the BNRAS size governing bioprocess via the sludge age (SRT), will this still be required with WW comprising only brown and grey water?
- With a significantly reduced P load, will the effluent P concentration also decrease and to what value?
- With eutrophication prevention requiring ever-decreasing effluent N and P concentrations, e.g. $0.1\ mgP/\ell$, is achieving such limits related to the N and P loads or by other factors that set the limits of the BNRAS technology, e.g. affinity constants in Monod kinetics?
- What will be the COD:TKN:TP ratio of urine separated (grey and brown) municipal WW?

Chapter III : MATERIALS AND METHODS

INTRODUCTION

This chapter describes the experimental set-up, operation and monitoring of the pilot-scale urine separation system and the laboratory scale NDEBPR UCT and JHB systems. The CSIR Stellenbosch managed the set up and operation and maintenance of the urine diversion toilets. The UCT and JHB laboratory scale AS systems treating the collected grey and brown WW were operated at UCT. The operation and analytical procedures for the UCT and JHB systemswere the same as has been the practice in the UCT WW laboratory, which is temperature, controlled at 20℃.

3.1 PILOT-SCALE URINE SEPARATION SCHEME

3.1.1 Background history: South African context

As mentioned in the previous chapter, South Africa has no record of wet urine separation no-mix toilets but rather dry urine diversion toilets otherwise called dry no-mix toilets. Dry urine separation is considered by water engineers as an appropriate sanitation for low-income areas that are densely populated and where the soil is often not geotechnically adequate for an underground sewerage system. Some European countries like Sweden and Germany have already experimented with wet no-mix toilet systems that were primarily aimed at protecting the environment from effluent pollution but later at recovering nutrients. The term “wet” means that water (low volumes) is used for flushing toilet. The water can be supplied through a conventional water supply system (piped system) or through the provision of on-site containers/tanks for water storage. Examples of sanitation schemes that make use of the latter are Aqua-Privies, Pour-flush toilets and septic tanks. Basically, the pedestal of a urine separation toilet consists of two chambers for draining solid and liquid wastes separately, a front chamber for draining urine with little or no flush water, while the rear chamber is used for draining faeces (with flush water) (Schoenborn, 2001 as reported by Mphafi, 2009:10). Urinals are another way for collecting urine separately that presumably exists in most men’s public toilets in urban SA. Urinals are assumed to be as old as the conventional WW system which provided sanitation facilities for men in public places. They can be communal or private; they come in different designs and shapes and can be made out of different material such as ceramic, aluminium or plastic.

3.1.2 CSIR pilot-scale no-mix toilets and waterless urinals

With funding from the WRC (Water Research Commission), one no-mix toilet was installed in each of the ladies and gents restrooms in D-block of the CSIR offices in Stellenbosch in 2009. These were imported from Gustavberg Sweden (Germanis, 2009:1). The state-of-the-art no-mix toilets are made of low-tech fibre resin (see **Figure III.1** below).

Figure III.1: CSIR no-mix toilet installed in the ladies and gents restrooms in block D of the CSIR building in Stellenbosch. (Germanis, 2009)

In the gents' restrooms of block D at the CSIR, a *waterless* ceramic urinal was also installed (see **Figure III.2**) by modifying the existing urinal. As the name suggests, the urinal works without flush water thus making the collection of undiluted men's urine possible. It also constitutes a way of saving water as modern urine separation toilets use close to 20 times less flush water/p.d than ordinary toilets (Wilsenach and Loosdrecht, 2003:104). The waterless company, USA (Wilsenach, 2006:37), designed the urinal at the CSIR.

Figure III.2: CSIR waterless ceramic urinal. (Germanis, 2009)

The no-mix toilets, urinal and kitchen within block D of the CSIR building were equipped with a piped system to convey brownwater, yellowwater and greywater separately to outside containers situated on ground level (see **Figure III.3**). All containers were covered to prevent the escape of unpleasant odours or volatile substances, e.g. ammonia (NH_3) can escape from a urine storage container if it is not properly sealed (Udert et al., 2005a as reported by Maurer et al., 2006:3156).

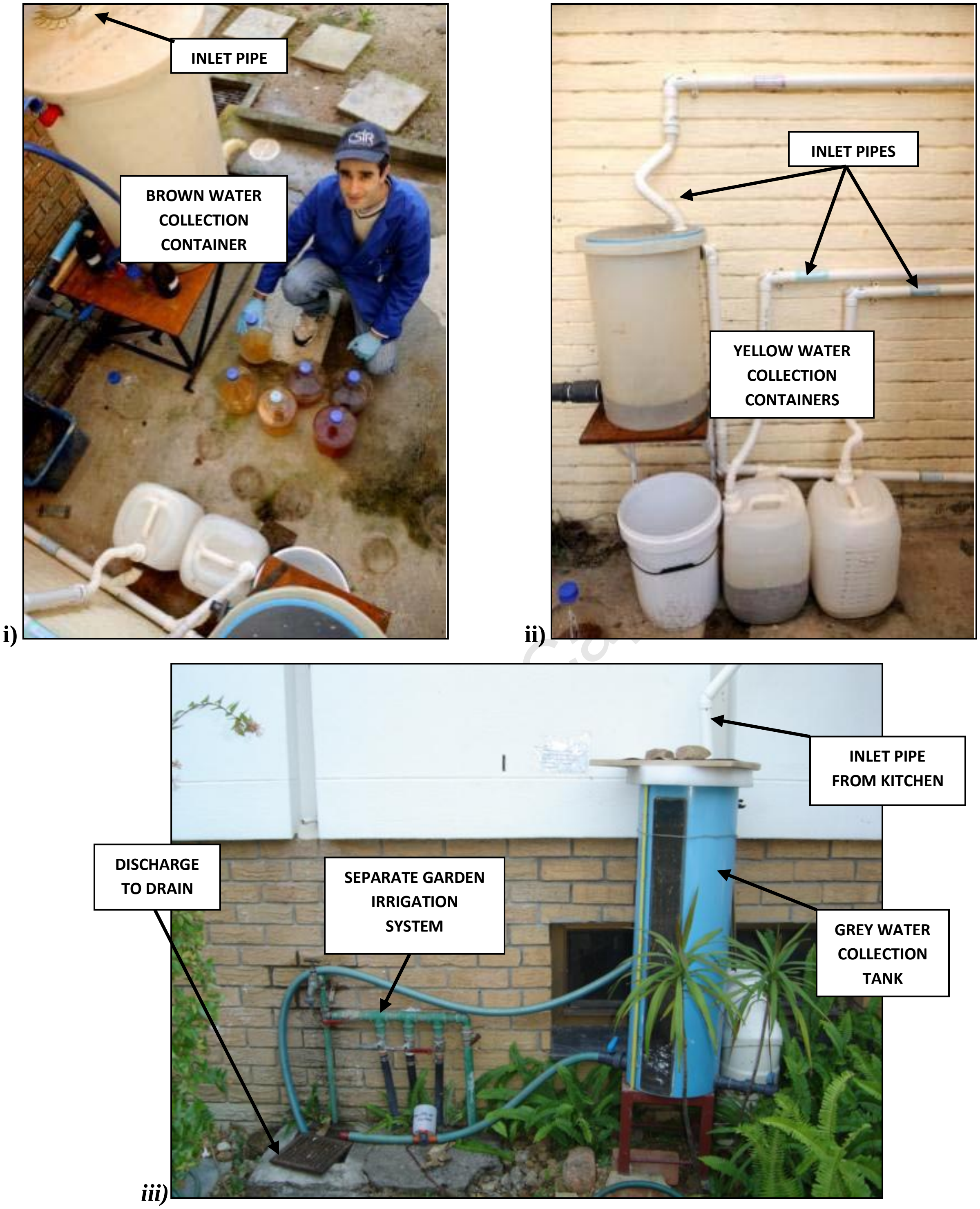


Figure III.3: From i) to iii) collection containers for brownwater, yellowwater and greywater respectively showing the inlet pipes.(Germanis, 2009)

3.1.3 Operation and maintenance of collection system

The regular maintenance and operational procedures were set out in detail by the CSIR. These procedures are presented in **Appendix A**. Also, refer to the 2009 WRC perception survey on the use of urine separation toilets (Germanis, 2009).

The separated streams of greywater and brownwater were supplied to the laboratory of the University of Cape Town (UCT) for testing in two state-of-the-art NDEBPR systems, a UCT configuration and a Johannesburg system (JHB) started later. The supplied grey and brown water were stored separately in 400 ℓ stainless steel tanks in a refrigerated cold room at 4℃. The grey and brown water were tested separately and then mixed in a 1:1 ratio by volume and diluted with tap water to a target COD concentration of *1000 mgCOD/ℓ* before feeding to the two laboratory units. The analysis of the UCT and JHB systems' response as well as their operation and maintenance are described in the subsequent section.

3.2 LAB-SCALE NDEBPR UCT AND JHB SYSTEMS

3.2.1 Experimental set-up

3.2.1.1 Research approach

The UCT system was selected because it offers the advantage that the nitrification-denitrification (ND) processes can occur independently of the biological excess phosphorus removal (BEPR). Once it became apparent that nitrification did not take place in the UCT system at 20d SRT (and 20℃), the JHB system was started up at 5d SRT due to the significantly better N and P performance of this system at the short 5d SRT. The design and operating parameters of the JHB system (given below) represent a significant improvement to the UCT system in terms of both 1) the overall reactor volume which, is a major cost component in WW treatment; 2) the protection and enhancement of P removal provided by an anoxic (AX) reactor placed upstream of the anaerobic (AN) reactor that would prevent any nitrate to be recycled to the AN reactor in the event it does nitrify. The UCT system was set up and operated for a fixed period of 356days prior to the JHB system. Then, both systems were operated simultaneously for a further period of 199 days. The respective data collection periods (SSP = steady state period) amounted to 383days and 154 days for the UCT and JHB system respectively (**Figure III.4**).

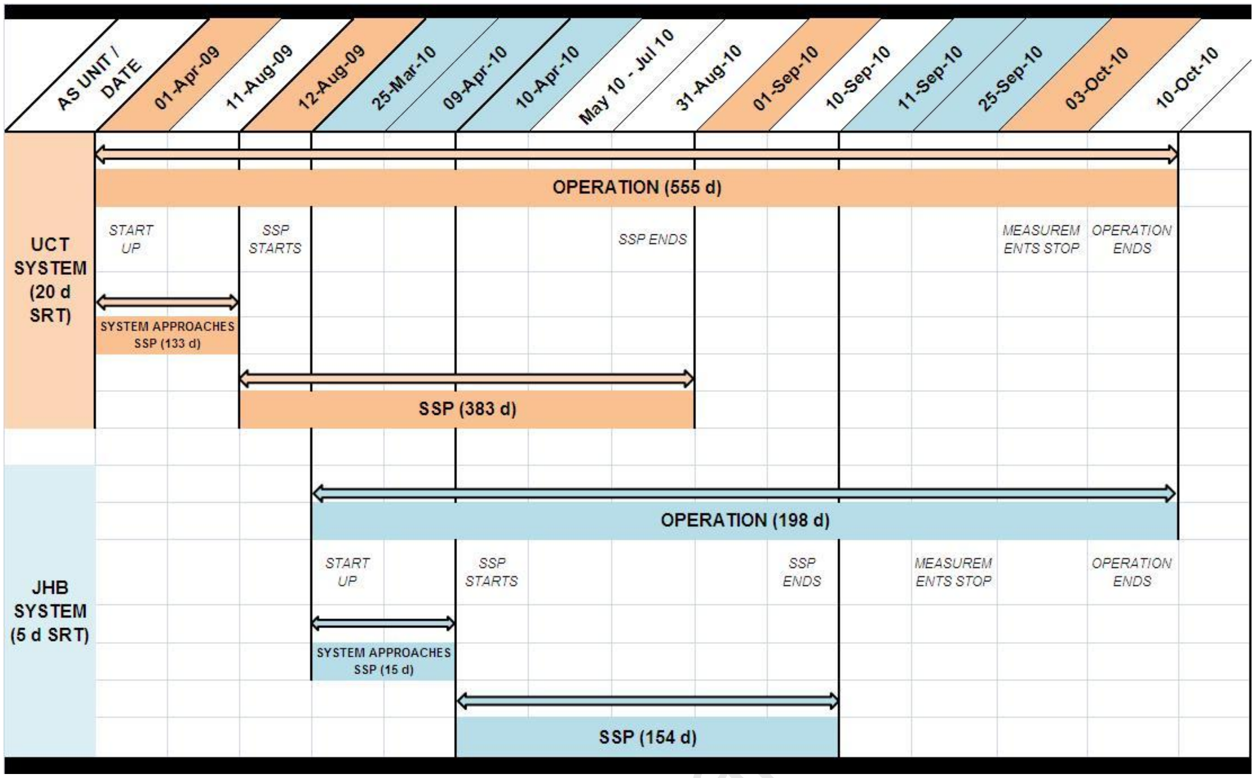


Figure III.4: Time line for the UCT and JHB systems operated at 20d and 5d SRT respectively.

This section describes the experimental set-up, operating, monitoring and analytical measurements of the lab-scale NDEBPR UCT and JHB system at 20 d and 5 d SRT respectively. In both cases, the laboratory operating temperature was 20˚C. The UCT and JHB systems were operated for 133 days (or 6 x SRT) and 15 days (or 3 x SRT) respectively before reaching steady state, during which the operating methods were improved. Once steady state had been reached, each system was operated for a further period of 422 and 183 days respectively. The operation of both the UCT and JHB systems was ended on the same day (see **Figure III.4**).

3.2.1.2 Experimental set-up of the NDEBPR UCT system

The UCT system had the following components (see **Figure III.5**):

1. *Main aeration reactor (AE) or aerobic mixed-liquor (AEML) reactor*. This is a 15ℓ open plastic container. At the bottom of the reactor there is an outlet where the liquid exit the reactor to the outlet, via an inverted Y tube, situated on the side of the reactor. The outlet allows reactor volume adjustment as it can be slid up or down the reactor side. The AE reactor is for nitrification by ANOs

(Autotrophic Nitrifying Organisms), organic degradation by OHOs and P uptake and growth by PAOs. The contents of the AE reactor is stirred by a paddle that is set at the end of a shaft driven by an electric motor, at about 100 rpm. The motor is fixed to a reactor lid, which is set on the top of the reactor. The objective of the stirrer is to keep the contents well mixed independent of the aeration effect for oxygen utilization rate measurement (see 7 below).The *a-recycle* from AE to AX reactor provides nitrate return for denitrification in the AX reactor (see 2 below).

2. Anoxic (AX) reactor. This is a 10ℓ container. Its operation is similar to the main AE reactor. It allows denitrification by OHOs (Ordinary Heterotrophic Organisms) and by PAOs (Phosphorus Accumulating Organisms) if anoxic P uptake BEPR takes place. The AX reactor is not aerated and should not contain nitrate. The a-recycle is set at the appropriate ratio to ensure this is so. It should receive as little dissolved oxygen (DO) as possible to maximize denitrification. The *r-recycle* from AX to AN reactor therefore has zero nitrate to protect BEPR by PAOs.

3. *Anaerobic (AN) reactor.* This is a 7ℓ container. Its operation is similar to the two previous reactors. The AN reactor is upstream of both AE and AX reactors in order to give PAOs preferential access to the influent RBO compounds (Readily Biodegradable Organics) in the WW fed to the system. The AN reactor is also unaerated and must receive no nitrate and no DO from the AX reactor.

4. *Feed drum (FD).* This is a 15ℓ refrigerated open container with a feed take-off of 15 mm in diameter situated at its base. A motor-driven paddle – turning at 20 rpm – constantly stirs the content of the container to prevent suspended solids from settling. The motor driving the paddle is fixed to a platform that fits on top of the container. The FD is placed inside a refrigerator so that the temperature of the feed (kept at 8^{o}C) is unfavourable to bacterial growth prior to feeding to the system.

5. *Settling tank (SST) or clarifier.* This is a 2ℓ inclined (60°C) tube with a central driven shaft to which is attached a windscreen wiper to keep the inside clean, rotating at 1 rpm for 1 min in 10 min. Mixed-liquor is introduced vertically and withdrawn horizontally via parts diagonally opposite each other at the base. The overflow discharges at the top. The s-recycle from SST to AX reactor provides recycled sludge to the AX reactor, which if it contains nitrate will be denitrified to ensure a nitrate free recycle to the AN reactor.

6. *Peristaltic feed and recycle Pump.* All four flows (influent, r-, a- and s-recycles) were pumped by the same 16 channel peristaltic pump (see **Figure III.6)**. Multiple channels were used for recycles that

were multiples of the influent. Its tubing can be tensioned to fine tune flow rates. It is controlled electronically with *on* and *off* timer to set specific required influent flows. The on-off operation also prevents settlement of solids in the reactor interconnecting tubing.

7. *Dissolved Oxygen (DO)/OUR meter*. This has a DO probe which monitors the oxygen concentration in the AE reactor. The DO concentration was controlled between 2.0 and 5.0 mgO/ℓ and the OUR was measured during the aeration off period. **Figure III.6** shows a photograph of the OUR meter box.

8. *Connecting tubes*. These are soft and transparent plastic pipes 10 to 15 mm diameter. The diameter of the tubing is important as too small a diameter may result in inadequate flow whereas too large diameter may result in settlement in the tube.Wall growth is removed by daily actively squeezing the tubes and monthly cleaning with hot water and chlorine.

9. A 20ℓ container for collecting effluent from which effluent grab samples were collected.

The system design parameters and their magnitude are listed in **Table III.1** below.

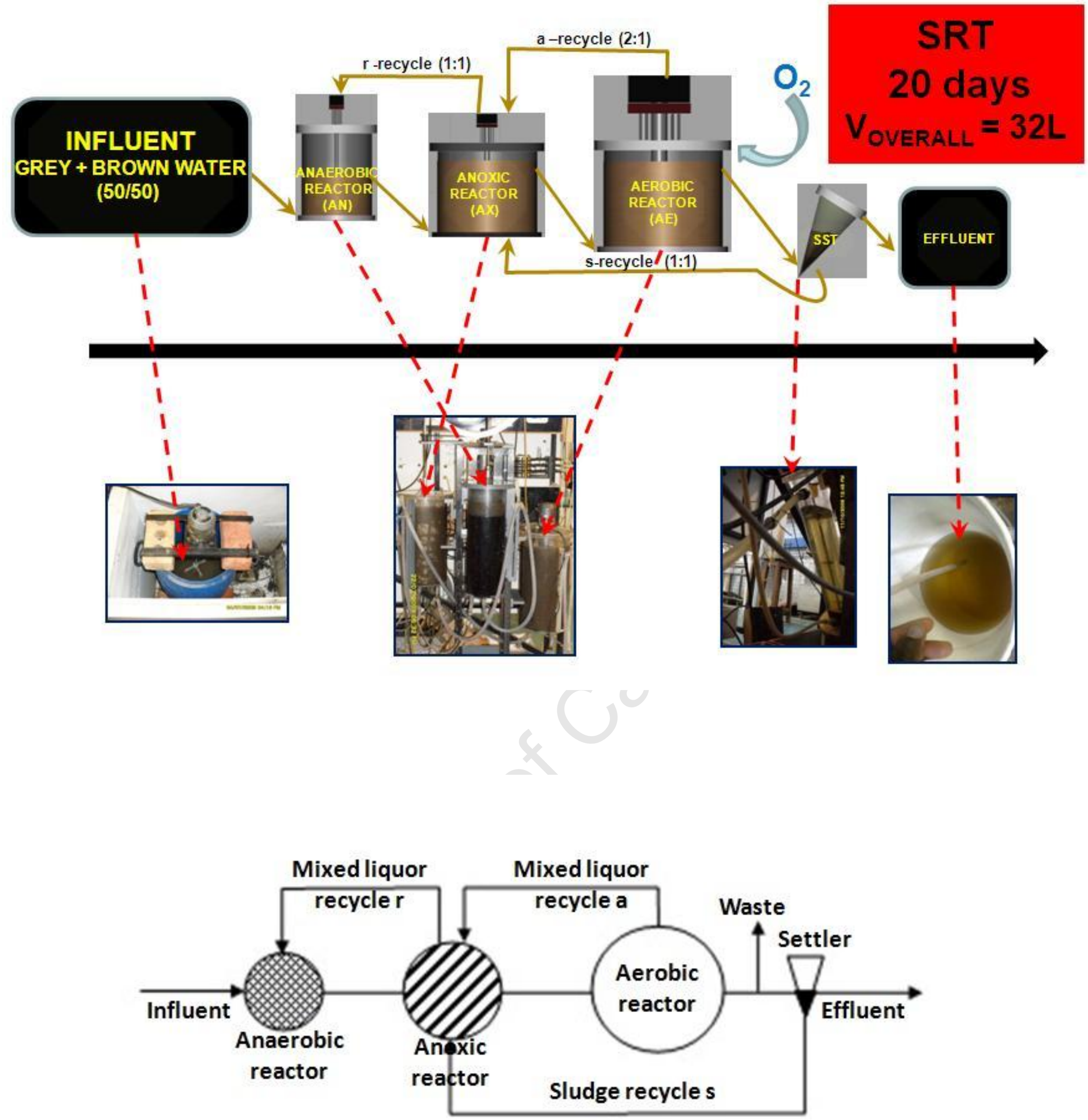


Figure III.5: The NDEBPR UCT system. See **Table III.1** for the design and operating details.

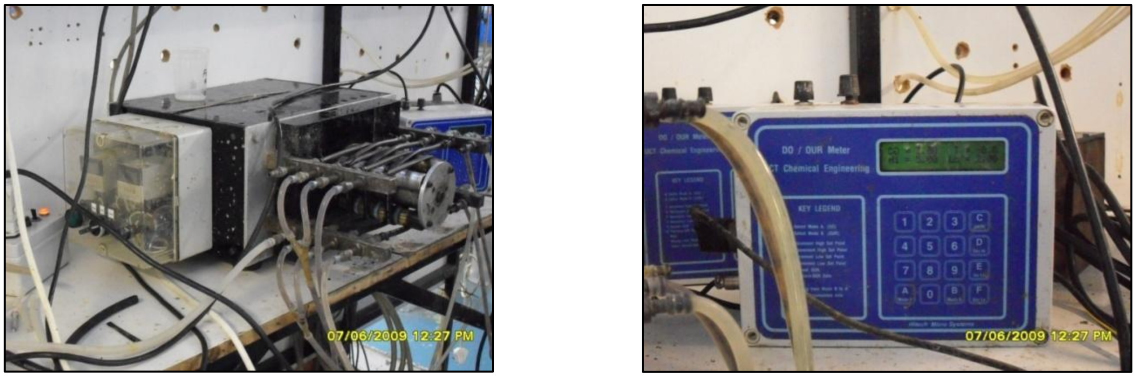


Figure III.6: Peristaltic feed (and recycle) pump and dissolved oxygen (DO)/OUR meter box. Both UCT and JHB systems were equipped with a feed pump and DO/OUR meter box.

3.2.1.3 Experimental set-up of JHB system

The laboratory scale JHB system which was similar in set up to the UCT system, consisted of a 15ℓ refrigerated (8^{o}C) feed drum, a 4.4ℓ anaerobic (AN) reactor and a 1.1ℓ Anoxic (AX) reactor in the underflow recycle; a 8ℓ aerobic (AE) reactor, a 2ℓ clarifier and a 20ℓ bucket for collecting effluent (see **Figure III.7** below), refer to the experimental set up of the UCT system for further details. The system had only a single recycle flow namely the *s*-recycle. This returned the clarifier underflow (sludge mainly) to the AX reactor which was set upstream of the AN reactor to protect this latter from recycled nitrate in the event the system nitrified. Although the primary reason for setting up the JHB system was that the UCT system was not nitrifying, it was nonetheless necessary to protect the AN reactor of the JHB system from nitrate which would jeopardize the P removal within the system. The s-recycle flow was pumped by the same influent flow multi-channel peristaltic pump. **Table III.1** lists the system design parameters.

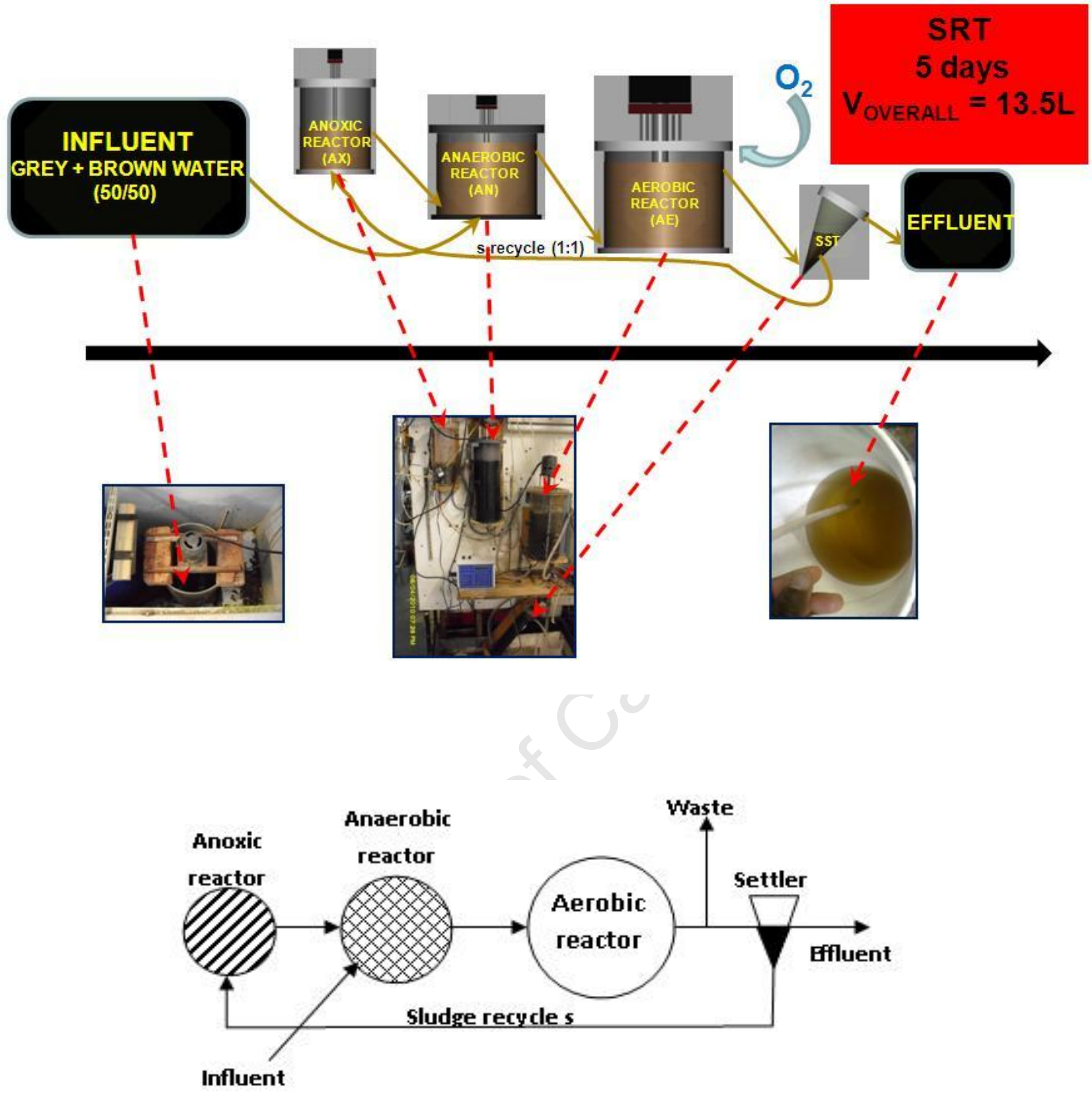


Figure III.7: The laboratory-scale JHB system. See **Table III.1** for the design and operating details.

Table III.1: Design and operating parameters for the UCT and JHB systems

System parameters	UCT	JHB
Sludge age (days)	20	5
Anaerobic mass fraction (%), Volume (ℓ)	24.3 [1]/ 7	26.1[1]/ 4.4
Anoxic mass fraction (%), Volume (ℓ)	37.1 [1]/ 10	44.9[1]/ 1.1
Aerobic mass fraction (%), Volume (ℓ)	38.7 [1]/ 15	29.0[1]/ 8
a-recycle (AE to AX)	1:4	n/a
r-recycle (AX to AN)	1:2	n/a
s-sludge Return Recycle (SST to AX)	1:2	1:1.4
System Hydraulic retention time (day)	2.13	0.90
$f_{S'us}$	0.05	
$f_{S'up}$	0.13	
$f_{S'bs}$	0.27	
MLVSS (AE) concentration (mg/ℓ)	3550[1]/ 2600 [2]	2400[1]/ 2100[2]
MLTSS (AE) concentration (mg/ℓ)	4200[1]/ 3250 [2]	2700[1]/ 2650 2]
Influent flow (ℓ/d)	15	15
Feed COD concentration (mg/ℓ)	1000	1000

[1]For the given a-, r- or s-recycle ratios; [2] predicted using processes and modeling of NDBEPR BNR (Wentzel et al., 1990, 1992).

3.2.2 Sewage collection and influent feed preparation

3.2.2.1 Sewage collection and storage

Grey and brown WW for feeding the biological treatment systems were trucked to the WRL at UCT from the CSIR in Stellenbosch, Cape Town, South Africa (± 60 km). It was carried separately in 22-, 50-, 100- and 200-liter containers. The buckets/containers were sealed and fastened to prevent spillage while driving. Large volumes – more than 200 litres - were brought in and transferred by gravity through a transfer pipe with an in-line macerator into the 400-litre stainless steel storage tanks, two for each of greywater and brownwater. Smaller volumes were directly poured into the respective storage tanks. The storage tanks were located in the laboratory cold room maintained at 4℃ year round. Once transferred, the contents of the storage tanks were recycled through the macerator pump for an hour to prevent blockages in the experimental systems. Depending on the quantity brought in and the COD concentration, a batch of sewage would last a week to 10 days. However, after 14 days it was disposed of - and a new batch was collected – storage of sewage even at 4℃ for longer than three weeks usually caused it to become septic (hydrogen sulphide accumulation) and develop significant sewage characteristic changes. Even though the storage tank contents were thoroughly paddled and mixed manually before collecting a WW batch from it, a batch was not used to within the last 2 to 3 litres as it contained significant amount of particulate solids that could considerably alter the characteristics of the last batch and hence experimental systems. Upon delivery to the UCT laboratory, each of greywater and brownwater was tested separately for COD, TKN (Total Kjeldahl Nitrogen), FSA (Free and Saline Ammonia) and TP (Total Phosphorus or P_{tot}). The results of the COD test were used to determine the quantities of grey and brown water (mixed 50/50 by volume) that would be required for subsequent dilution with tap water to the target influent COD of *1000 mg/ℓ*. This procedure was applied to both AS systems.

3.2.2.2 Feed preparation

In order to estimate the grey and brown water mix, the changes in TKN/COD and TP/COD ratios were calculated at different mixing proportions. The grey and brown WW had COD (mgCOD/ℓ), TKN (mgN/ℓ) and TP (mgP/ℓ) concentrations around 1800, 45 and 5 and 7000, 260 and 90 respectively. From the ratios, the brown water contained about 50% more N and P per COD. Because the per capita generation of grey and brown water varies quite widely, it was decided, for consistency, to mix equal volumes of grey and brown water. So the grey and brown water were mixed 50/50 by volume and diluted with tap water to the target COD of 1000 mgCOD/ℓ. Daily, after thoroughly mixing the stainless steel tank contents, the required volume of grey and brown water was collected through a fine (1mm) mesh (to prevent blockages of the UCT or JHB system interconnecting tubes), and tap water added. In this way 15.2ℓ was prepared, a 200mℓ sample taken and 15.0ℓ transferred to the influent feed drum. The feed volume was doubled when the JHB system operation was commenced. The feed drum was gently mixed (20 rpm) to minimize settlement of particulates. 15ℓ were pumped into each system over 23.5 to 24 hours at the end of which, the particulates not pumped into the system were collected in a small volume of effluent (200mℓ) and added to the AN reactor.

3.2.2.3 System maintenance and operation

The usual maintenance (monthly cleaning) and operational procedures developed in the Water Research Laboratory were applied. These are set out in detail by Clayton et al. (1991) and many other former students.

3.2.3 Sampling of biological systems

Samples were collected from the influent, AN, AX and AE reactors and effluent and tested to evaluate the systems' performance. The parameters tested are listed in **Table III.2**. The sample volumes collected from the reactors were part of the daily mass of sludge wasted from each system to establish the 20d or 5d sludge age, i.e.*1425mℓ* or *2920mℓ* in total when no samples were taken from the UCT and the JHB system respectively (see **Appendix F**, **Equation F.6**). Sampling and sludge wasting were done 2-3 hours after feeding thereby ensuring that the system had adjusted to the new day's feed. All samples taken (except for solids) were immediately filtered through 0.45 µm filter membranes and 2 drops 8.6 g/ℓ HgCl added to prevent further biological activity. Then the samples were stored at 4^{o}C until analysis the next day. The inner walls of the feed drums were brushed off daily and particulates collected with the remaining feed (~ 0.2 ℓ) were added directly to the AN reactor.

3.2.3.1 Sampling of the UCT system

Figure III.8 below shows the different sample volumes taken and their positions in the UCT system.The test analyses mentioned in this section are presented, in more detail, in **Section 3.2.5** on experimental testing methods.

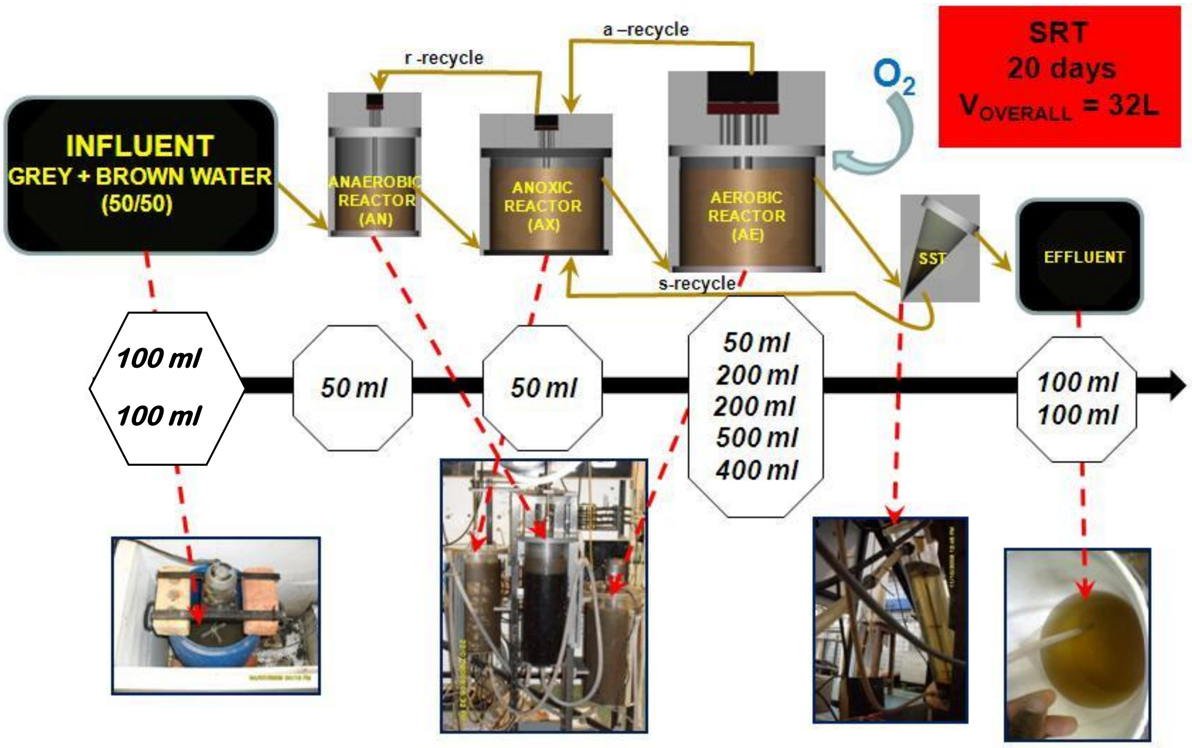


Figure III.8: The NDEBPR UCT system showing the sample volumes and positions.

A. *Influent Feed Sample*

Subsequent to the mixing and dilution of grey and brown water feed two 100 ml samples were taken before feeding for filtered and unfiltered influent concentrations. The pH of the unfiltered sample was measured by means of a pH probe connected to a pH meter. One drop of mercuric chloride solution (8.6 g/ℓ $HgCl2$) added to both samples to prevent any further biological activity (during storage in the cold room). The filtered sample was obtained by filtering through a 0.45 μm membrane. Subsequently, both samples were stored for later analysis in the laboratory cold room maintained at 4˚C.

B. *Reactor mixed liquors*

On every second day, approximately 2 to 3 hours after feeding the following samples were taken:

1. Three 50 ml samples, one from each of the AN, AX and AE reactor mixed liquors, into 50 ml centrifuge tubes to be tested for Settleable Solids (SS) – i.e. Total Settleable Solids (TSS) and Volatile Settleable Solids (VSS). The supernatant was membrane filtered and retained for Nitrite (NO_2) and Nitrate (NO_3), Total Phosphorus (TP or P_{tot}) and OrthoP (OP) analysis, see **Table III.2**. Sampling was done using a calibrated glass pipette the tip of which was ground off to

allow large particles to be included in the sample. The pipette's tip was immersed to within a third of the mixed liquor level whilst bearing in mind the automated stirrer inside the reactor. Immediately after collection, one drop of mercuric chloride solution (8.6 g/ℓ H_gCl_2) was added to each sample to prevent any potential denitrification thereby avoiding inaccuracies in the nitrate measurements of the system. The samples were centrifuged at 3500 rpm for 10 min after which the supernatants were filtered through 0.45 μm membrane filters. To make filtration easier, two drops of polyelectrolyte flocculent (1g/ℓ) were added. The mixed liquor filtered samples were subsequently tested for NO_2, NO_3 and P_{tot} (and OrthoP when necessary). The centrifuged solids at the bottom of the centrifuge tubes were flushed out using distilled water and transferred into glazed clay crucibles that had previously been weighed. Masses were recorded to the nearest 10^{-4} *g*.

2. Two 200 ml samples were taken from the AE reactor into 400 ml plastic containers in order to be tested for unfiltered Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (P_{tot}). These samples were harvested from the bottom of the reactor through a port in the inverted Y outlet on the side of the reactor. Sampling this way was deemed to yield better representative samples for more accurate concentrations of the AEML sludge namely its f_n (mgN/mgVSS), f_{CV} (mgCOD/mgVSS) and f_p (mgP/mgVSS) ratios. After collection one drop of mercuric chloride solution (8.6 g/ℓ $HgCl_2$) was immediately added to each sample to prevent further bacterial activity. Both samples were then stored in the cold room maintained at 4˚C for later analysis.

3. 500 ml of AEML were poured out into a 1-litre glass cylinder in order to measure the DSVI (Diluted Sludge Volume Index).

4. 400 ml were taken from the AEML that represented the remainder of the daily volume of sludge wasted after all the samples had been taken into account.

5. When necessary, one 50 ml sample was immediately taken from the influent (before feeding) and the AE reactor for the *5-point-titration* and accounted for in the daily influent feed volume and sludge waste respectively. The five point-titration is procedure for determining the $H_2CO_3^*$ Alkalinity of the influent and AE reactor mixed liquor (and the effluent) as well as the concentration of volatile fatty acids (VFAs).

6. Occasionally, 2.5ℓ of mixed liquor were harvested from the aerobic reactor for the *nitrification batch test* (see **Section 3.2.5**). Because this volume was more than the daily sludge wasted i.e. 1425 ml (all samples included), no additional mixed liquor waste would be done for 2 days subsequent to the start of the batch test.

C. Effluent Samples

Two 100 ml effluent samples were collected from the 20 ℓ effluent bucket after thorough mixing. One sample was filtered through 0.45 μm membrane filter. The pH of the unfiltered sample was immediately measured and one drop of mercuric chloride solution (8.6 g/ℓ $HgCl_2$) added to both samples. These filtered and unfiltered samples were tested for COD, TKN, FSA, NO_2, NO_3 and P_{tot} (or OrthoP when necessary) as presented in **Table III.2**.

D. In-situ Measurements

The oxygen utilization rates (OUR) of the UCT NDBEPR system was measured continually and automatically online using the DO controller/OUR meter as detailed by Randall *et al.*(1991). A Dissolved oxygen (DO) probe – YSL Model 5739 - was set in the aerobic activated sludge mixed liquor and connected to the automated DO meter/OUR data logger (HiTech Microsystems), which controlled the reactor aeration between high (greater or equal *5 mgO/ℓ*) and low (less or equal *2 mgO/ℓ*) DO set points. The control of DO was made possible via a solenoid valve in the air supply line. When the DO within the activated sludge reactor reached the low set point of 2 mgO/ℓ, the solenoid valve opened and the reactor contents were aerated until the DO reached the high set point of 5 mgO/ℓ, at which point the air was switched off automatically. This cycle was automatically repeated every time the DO reached the low set point. During each air-off period, the slope of the DO versus time relationship was automatically calculated by linear regression to give the OUR at that time, which together with the correlation coefficients, temperature and time, were stored by the OUR meter. The OUR results for each day were downloaded from the OUR meter to a computer at the end of the feeding cycle prior to the new feed. The data were imported into a spreadsheet program where it was plotted and the average OUR for the particular day calculated. The OUR meter was reset immediately after download. The DO probe membrane was regularly replaced and the probe recalibrated to ensure accurate results.

3.2.3.2 Sampling of the JHB system

The sample volumes and positions in the JHB system are represented in **Figure III.9** below. The experimental testing methods were the same as those for the UCT system as described in **Section 3.2.3.1** above.

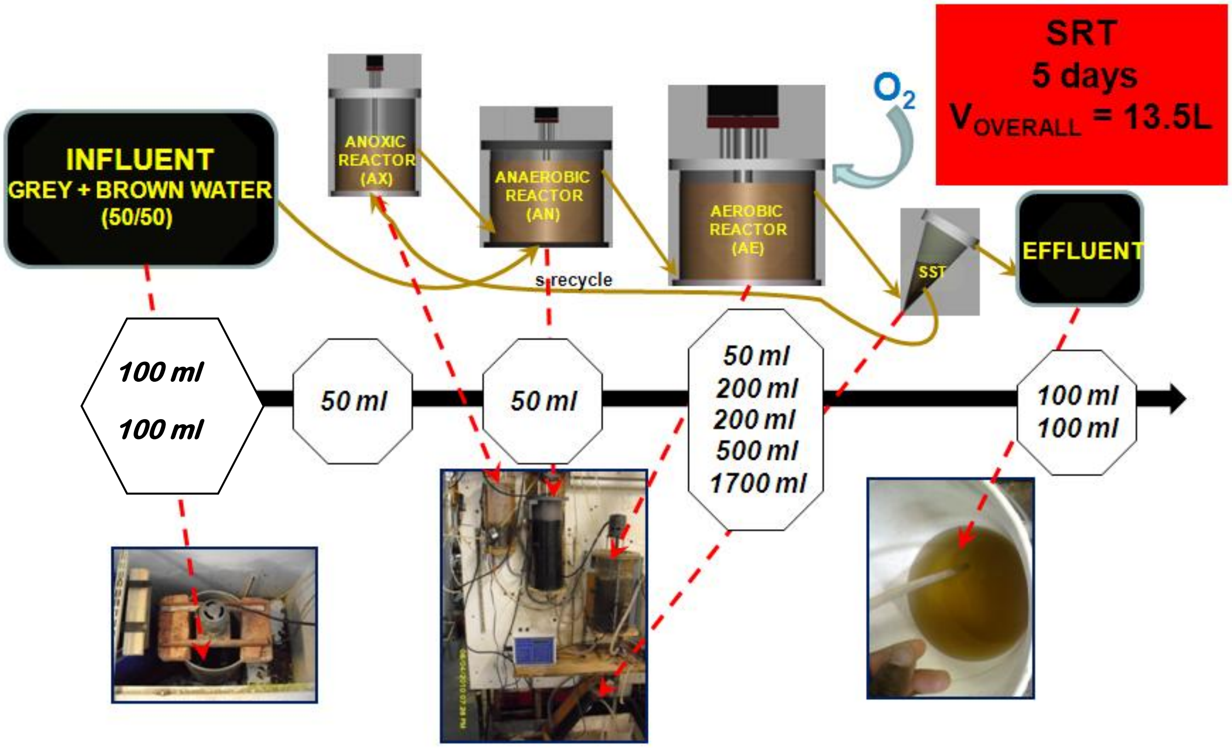


Figure III.9: Sample volumes and positions in the JHB system.

A. *Influent Feed Sample*

Because the influent for the JHB system was made up with that for the UCT system, the influent concentrations were the same for both systems.

B. *Reactor mixed liquors*

The following samples were harvested:

1. Three 50 ml samples were drawn out, one from each of the AN, AX and AE reactor mixed liquors, into 50 ml centrifuge tubes. These samples were processed the same way as those from the UCT system (see **B.1** of **Section 3.2.3.1**).

2. Two 200 ml samples were taken from the AEML reactor into 400 ml plastic containers (see **B.2** of **Section 3.2.3.1**).

3. 500 ml of AEML were poured out into a 1 litre glass measuring cylinder in order to measure the DSVI (Diluted Sludge Volume Index) (see **B.3** of **Section 3.2.3.1**).

4. 1700 ml was taken from the AE reactor which represented the remaining daily volume of sludge wasted after all the samples had been taken into account. Wasting this 1700 ml was done into two batches daily i.e. 1350 ml were wasted in the morning and the balance of 350 ml was wasted in the afternoon when sampling. This was done to avoid causing disturbances to the biological system.

5. When necessary, one 50 ml sample was immediately taken from the influent and the AEML for the 5 point-titration and accounted for in the daily influent feed volume and sludge waste respectively. The 5 point-titration is the procedure for determining the $H_2CO_3^*$ Alkalinity of the aerobic mixed liquor (and effluent) as well as the concentration of volatile fatty acids (VFAs).

C. Effluent Samples

Two 100 ml effluent samples were collected from the effluent bucket after thorough mixing. These samples were processed the same way as those of the NDBEPR UCT system.

D. In-situ Measurements

The oxygen utilization rates (OUR) of the JHB system weremeasured continually and automatically online with an identical DO controller/OUR meter as the NDBEPR UCT system.

3.2.4 Testing of NDBEPR UCT and JHB systems

Each system was fully tested every second day. When one system was fully tested, the other system was tested only for suspended solids concentrations (TSS, VSS and ISS), DSVI and all effluent concentrations. When fully tested, each system component was analysed for Chemical Oxygen Demand *(COD)*; Total Kejdhal Nitrogen *(TKN or N_{total})*; Free and Saline Ammonia *(FSA NH_3)*; Nitrite *(NO_2)* and Nitrate *(NO_3)*; Total Phosphorus *(TP or P_{total})*; Total Settleable Solids *(TSS)*; Volatile Settleable Solids *(VSS)*; pH and Diluted Sludge Volume Index *(DSVI).* Ortho Phosphate (OrthoP) was measured in both filtered samples of AE reactor and influent for Alkalinity purpose.Although following the identical principle of the analytical procedures outlined in “Standard methods”, some laboratory procedures have been modified in minor ways to suit the requirements of the WRL where many samples were tested daily. All results were checked with standards and mass balances over the experimental systems. Most information on these methods is set out in the “Standard Methods for the examination of Water and WW”, American Public Health Association, 13th Edition, 1989. Refer to **Section 3.2.5** for a brief description of the standard methods.

Table III.2summarizes the analyses that were performed on the samples from each biological system.

Table III.2: Sampling position and parameter measurement

	COD [1]	**TKN** [2]	**FSA** [3]	**NO_2** [4]	**NO_3** [5]	**P_{tot}** [6]	**TSS** [7]	**VSS** [8]	**OUR** [9]	**DSVI** [10]	**pH** [11]
Influent	*U;F*	*U;F*	*F*	*F*	*F*	*U*					*U*
AN[a]				*F*	*F*	*F*	*U*	*U*			
AX[b]				*F*	*F*	*F*	*U*	*U*			
AE[c]	*U*	*U*		*F*	*F*	*U;F*	*U*	*U*	*	*U*	*U*
Effluent	*U;F*	*U;F*	*F*	*F*	*F*	*F*					*U*

[a], [b], [c] Anaerobic, Anoxic & Aerobic reactor respectively; U = *Unfiltered* sample; F = sample *Filtered* through Schleicher & Schull ME 25/21 0.45 µm membrane filter; * = Direct measurement taken; [1] to [11]. OrthoP was measured on filtered AE and filtered influent for Alkalinity purpose. Refer to “*Standard Method for the examination of Water and Wastewater”*, American Public Health Association, 13th Edition, 1989. Also see **Section 3.2.5** of this report.

3.2.5 Experimental testing methods

The analytical measurements performed on the samples collected from the greywater, brownwater and the AS systems include the following:

1. Chemical oxygen demand (COD) test
2. Free and saline ammonia (FSA) test

3. Total Kjeldahl nitrogen (TKN) test
4. Nitrate (NO_3) and nitrite (NO_2) analysis
5. Total phosphate (TP or P_{tot}) test
6. Ortho phosphate (OrthoP) test
7. Volatile fatty acids (VFAs) , H_2CO_3Alkalinity and pH measurements
8. Mixed Liquor total and volatile settleable solids (TSS and VSS) tests
9. Oxygen utilization rate (OUR)
10. Diluted sludge volume index (DSVI)
11. Nitrification batch test
12. Aerobic batch test
13. Flow rate measurement

These measurements were sufficient to allow the characterization of the influent WW and to perform COD, N and P mass balances over each system. All the above analyses were performed in the laboratory of the Water Research Group (WRG) in the Department of Civil Engineering, at UCT with the exceptions of the *brucine* and *cadmium reduction* methodsfor the determination of nitrite and nitrate. These different test methods for NO_2 and NO_3were carried out by A.L. Abbott and Associates (Pty) Ltd and CSIR laboratories and were done to validate the WRL NO_2 and NO_3 analyses.

3.2.5.1 Chemical Oxygen Demand (COD)

The method used to determine the COD was the *dichromate and sulphuric acid open reflux* method, followed by a titration with ferrous ammonium sulphate (FAS) (American Public Health Association APHA, 1989). The COD test involves the reflux of a 10 ml sample in strongly acidic solution (15 ml sulphuric acid) with a known excess (~ 5 ml at 0.25 N) of potassium dichromate ($K_2Cr_2O_7$). In principle, the organic matter (electron donor) is oxidized by the boiling dichromate (electron acceptor). After boiling, the quantity of potassium dichromate remaining is determined by FAS (electron donor) titration which gives by difference the electron donating capacity of the oxidized organic matter in terms of oxygen equivalent (Sawyer et al., 2003).

$$COD\ (mgCOD/\ell) = [(a-b)*N*8000*Dilution]/A$$

Where: a = ml of 0.05 N FAS titrated in blank solution *b* = ml of 0.05 N FAS titrated in sample solution

N = normality of FAS (± 0.05 standardized for each batch of FAS made up)

A = ml of sample

3.2.5.2 Free and Saline Ammonia (FSA)

The *titrimetric* method (APHA, 1985:383) was used to determine the Free and Saline Ammonia (FSA) concentration ($mgNH_3$-N/ℓ). The choice of this method depends on the high ammonia concentrations expected (> 1 $mgNH_3$-N/ℓ). It involves steam distillation of the sample into a solution of boric acid (H_3BO_3) and a subsequent titration with standard sulfuric acid solution (*0.001 N* H_2SO_4) (APHA, 1985:377). The distillation apparatus consisted of a 100 ml glass flask containing 10 ml of the sample and attached to a vertical condenser, the tip of which was submerged just below the surface of the receiving boric acid. After pipetting 7 ml of a solution of *sodium hydroxide-sodium thiosulfate* (NaOH), the sample was distilled at a rate of 6 to 10 mℓ/min into a 100 ml Erlenmeyer flask containing 50 ml of a solution of boric acid. The ammonia originally present in the sample is gasified, condensed and dissolved in the boric acid solution turning it from purple to green depending on the FSA concentration in the sample. The ammonia in the distillate was then titrated with standard 0.001 N H_2SO_4 titrant until the indicator again turns purple. The titration reading a (as denoted below), was thenrecorded for subsequent calculation. The FSA concentration was calculated as follows:

$$FSA\ (mgNH_3\text{-}N/\ell) = (a*N*14000)/A$$

Where: *a* = ml of 0.001 N H_2SO_4 titrated (standardized for each 0.001 N H_2SO_4 acid made up)

N = normality of 0.001 N H_2SO_4

A = ml of sample

3.2.5.3 Total Kjeldahl Nitrogen (TKN)

The Total Kjeldahl Nitrogen (TKN) concentration was measured using the *semi-micro Kjeldahl method*, (APHA, 1985:411). Because the method does not remove ammonium initially, the term Kjeldhal is applied to the final result. Since FSA and TKN concentrations were determined individually, the organic nitrogen is obtained by difference. The TKN method involves digesting the sample with a solution of sulfuric acid (H_2SO_4), potassium sulphate (K_2SO_4) and mercuric sulphate ($HgSO_4$), followed by the FSA method. The digestion apparatus was a heating device capable of temperatures up to 370˚C for effective digestion. During digestion, the amino nitrogen of organic materials such as proteins and peptides are converted into ammonium. The subsequent distillation and titration steps and apparatus were similar to the titrimatic method for FSA. TKN was calculated as follows:

$$TKN\ (mgN/\ell) = (a*N*14000)/A$$

Where: a = ml of 0.001 N H_2SO_4 titrated

N = normality of 0.001 N H_2SO_4

A = ml of sample

3.2.5.4 Nitrite (NO_2) and Nitrate (NO_3)

The Hydrazine nitrate to nitrite reduction method was applied using the Technicon Auto-Analyser to measure the nitrite and nitrate and separately the nitrite concentration without reduction. The difference is the nitrate concentration. The procedure is as described in the *Technicon Auto-Analyser methodology* of the Industrial methods (33, 68 and 35.67W) by Technicon corporation (1969: 1-2).The underlying concept to this method is nitrate reduction to nitrite by hydrazine sulphate containing a copper catalyst and then measurement of nitrite concentrations. Four reagents are used for nitrate reduction namely: Hydrazine sulphate ($N_2H_4.H_2SO_4$), Sodium Hydroxide (NaOH), Cupric Sulphate ($CuSO_4$) and colour reagent ($C_6H_8N_2O_2$). The colour reagent with nitrite makes a pink colour, the intensity of which is proportional to the nitrite originally present and that formed from the nitrate. Samples have to be diluted to below 2mgN/ℓ, because this method is limited to this maximum concentration. The nitrate concentration is obtained from the difference between the nitrite concentration from nitrate reduction (nitrate + nitrite) and the nitrite only (with no reduction).

3.2.5.5 Total Phosphorus (TP or P_{tot})

Total phosphorus includes all orthophosphates, condensed and organic phosphates, both dissolved and particulate, organic and inorganic (APHA, 1985: 444). Consequently, the method used to determine the total phosphorus concentration in solution involved two steps namely *persulphate digestion* and *Vanadomolybdophosphoric acid colorimetry* (APHA, 1985: 444-446). The principle is the same as the TKN and FSA. The persulphate digestion method oxidizes organic matter to release phosphorus as dissolved orthophosphate through boiling the sample with sulfuric acid (H_2CO_4) and potassium persulfate ($K_2S_2O_8$). The vanadomolybdophosphoric acid colorimetric method measures all dissolved orthophosphate (APHA, 1985: 438). The basic principle of the colorimetric method is that orthophosphates react with ammonium molybdate ($(NH_4)_6 Mo_7 O_{24}.4H_2O$), in the presence of ammonium metavanadate ($NH_4 VO_3$), to form yellow phosphovandomolybdate solution. The intensity of the yellow colour is proportional to the concentration of orthophosphate present and is measured by absorbance using a spectrophotometer. A *Unicam 8625 UV/VIS* spectrophotometer set at a wavelength of 470µm was used for the colour intensity measurement and is valid up to a concentration of 300mgP/ℓ. The sample concentrations are determined from a TP (and OP) calibration line obtained from regression of standard P concentrations from 0 to 50 mgP/ℓ which were processed in the identical manner as the samples.

3.2.5.6 Ortho Phosphate (OrthoP)

Orthophosphates include all dissolved phosphates species (APHA, 1985). Unlike the method used to determine the total phosphorus concentration, the measurement of OrthoP involved the *Vanadomolybdophosphoric acid colorimetry* step only (APHA, 1985). Refer to section above for further details on this method. The condensed and organically bound P is the difference between the TP and the OrthoP.

3.2.5.7 pH, H_2CO_3, (Alkalinity) and Short Chain Fatty Acids (SCFAs or VFAs)

The 5 pH point titration method was used to determine H_2CO_3**Alkalinity* (*mg* $CaCO_3$*/ℓ*) and the Short Chain Fatty Acids (SCFA in *mgAc/ℓ*) of the influent and the aerobic mixed liquor. The method is as described by Moosbrugger *et al* (1992). A volume of 50 ml was pipetted from the influent or aerobic reactor and immediately centrifuged to separate the solid from the liquid phase. Then 10 ml of the filtered sample were diluted into 40 ml of distilled water to make up a dilution ratio of 1:4. The choice of the undiluted sample size, the dilution factor and therefore the volume of the titration vessel (*Erlenmeyer* *flask*) were primarily to minimize Carbon Dioxide (CO_2) loss during titration. A 100 ml Erlenmeyer was suitable as the titration vessel given its small surface (exposed to the atmosphere) to volume ratio. The titration procedure involved: stirring the sample – using a 25 mm magnetic stirrer – for half a minute after the addition of standard hydrochloric acid (HCl) to reach the predetermined pH points, and recording the respective volume of HCl added to reach the target pH points (equidistant around the $pK_1 \approx 6.3$ and $pK_{HAc} \approx 4.8$ values). The data and the FSA (NH_4), OP (P_t) and H_2S ($S_t$set to zero) were then entered into a computer program (Titra 5), which calculates the $H_2CO_3^*$ Alkalinity (mg $CaCO_3/\ell$) and SCFA (as mgAc/ℓ) concentrations. A Metrohm Dosimat (715) and Metrohm pH meter (744) combo were used in the 5 pH point titration method.

3.2.5.8 Mixed Liquor Settleable Solids (MLSS)

The *MLSS* and *MLVSS* concentrations (*mgTSS/ℓ* and *mgVSS/ℓ* respectively) in the aerobic reactor were determined from the solids accumulated in the bottom of the centrifuge tubes after centrifugation, see APHA (1985). Once the centrifuged solids had been transferred into their respective crucibles (glazed clay dish 50 mm diameter, 35 mm deep) of known masses (*Mass A* in g to 0.1 mg), it was dried in an oven at 105˚C for about 24 hours. The crucibles were then removed from the drying oven, cooled in a desiccator and weighed (*Mass B* in g to 0.1 mg). The crucibles were then placed in an incinerator at 550˚C for 20 minutes after which it was removed, allowed to cool in a desiccator and reweighed (*Mass C* in g).Consequently, *MLSS* concentration $in\ mg/\ell = (Mass\ B - Mass\ A)*10^6 / 50$,$MLVSS\ in\ mg/\ell = (Mass\ B - Mass\ C)*10^6 / 50$ and $MLISS\ in\ mg/\ell = (Mass\ C - Mass\ A)*10^6 / 50$.

3.2.5.9 Oxygen Utilization Rate (OUR)

The DO automated system has already been described in **Section 3.2.3.1**. The DO probe – YSL Model 5739 - was regularly calibrated in a *zero DO solution*, which was made out of 50 g of sodium thiosulphate dissolved into 200 ml of distilled water. The probe was set up as per the instructions on the user's guidelines before connecting it to an automated DO meter/OUR data logger (HiTech Microsystems). Then, it was immersed into the zero DO solution and the *zero button* on the data logger adjusted to $DO = 0.00 \pm 0.01$. After that, the probe was rinsed with distilled water and immersed in DO saturated water (by constant aeration) which for sea level (760 mmHg) and ambient temperature of *20˚C* is 9.07 mgDO/ℓ. The *gain button* could be adjusted when this was not the case. Then, the DO probe was immersed into the AEML to just above the paddle stirrer. This prevented air bubbles being trapped in the DO probe protective casing that would produce spurious readings. The cable was tied onto the reactor's cover to prevent further immersion. In addition, both the high and low DO set points were checked to be *5.0 and 2.0 mgO/ℓ* respectively. Because the air supply was regulated by the solenoid valve on the airline, the power switch on the OUR meter was set to *automate*.

3.2.5.10 Diluted Sludge Volume Index (DSVI)

The diluted sludge volume index (DSVI) is an indication of the sludge settleability. The test procedure consists of diluting 500 ml and 250 ml of AEML each in its own 1 ℓ measuring cylinder and filling them to the 1 ℓ mark with effluent; mixing it thoroughly and allowing the sludge to settle for ½ hour. The volume of sludge is recorded to the nearest 5 ml is the SV_{30} reading for the day but had to be less than 250 ml for the DSVI to be valid. If the SV_{30} is more than 250 ml for the 2 X dilution, then SV_{30} of the 4 X dilution (250 ml sludge into 750 ml effluent) has to be taken. The DSVI (mℓ/gTSS) is obtained as the ratio of the SV_{30} and the measured TSS concentration in the AE reactor on that particular day times the dilution factor. For further details on the DSVI test and its significance see Catunda and Haandel (1992); Ekama and Marais (1984) and others.

3.2.5.11 Nitrification Batch Test on the AEML from the UCT system

The nitrificationbatch tests mentioned in this report were done to confirm whether nitrification was taking place in the UCT system. Therefore, they were conducted on sludge harvested from the AE reactor. To start the batch test, a batch reactor (**FigureIII.10**) was filled with 3ℓ mixed liquor. Since endogenous conditions needed to be established, the mixed liquor was aerated for a long period (at least 12 hours), during which the OUR was measured with an OUR meter, before a small volume (50 mℓ) of concentrated ammonium chloride solution (1 $gNH_4Cℓ/ℓ$) was added. The OUR continued to be measured until endogenous conditions were again re-established. During the test, grab samples were taken, immediately filtered (0.45 µm) and stabilized with 2 drops of 8.6 g/ℓ HgCl. The samples were stored overnight at 4℃ and analyzed for NO_3-N, NO_2-N, and NH_4-N. The difference between the total OUR and the OUR related to endogenous respiration was considered the oxygen utilized (OU) due to NH_4-N oxidation, which is related to the ammonia nitrified via OU/4.57. This could then be compared with the measured ammonia nitrified from the ammonia and nitrate measurements. Later in the investigation, when it became clear that not all the biodegradable particulate (BPO) and soluble (BSO) organics were utilized in the system, these batch test results were used to calculate the concentration of unutilized biodegradable organics (BO = BPO + BSO). The initial OUR before the addition of ammonia in separate batch tests was used to measure the residual BO in the system. The batch tests are described below.

Figure III.10: Batch reactors set up for aerobic batch tests.

3.2.5.12 Aerobic Batch Test on the effluent from the UCT and JHB systems

The aerobic batch tests were done to measure the residual biodegradable soluble concentrations (COD, TKN and TP) not utilized inside the systemand which exited with the effluent from the UCT (and JHB) system. These batch tests were conducted on the effluent collected separately from the BNR systems and to which a known volume of AEML from a different NDEBPR system fed real WW was added. Thissystem was a fully nitrifying BNRmembrane AS system to which normal (real) WW from Mitchell’s Plain WWTP was fed. To start the batch test, a batch reactor (**Figure III.10**) was filled with 2ℓ of fresh effluent. Then, 400 ml of AEML from the membrane system was harvested into eight 50 ml centrifuge tubes and centrifuged at 3600 rpm for 20 min, after which the supernatant was discarded so that only sludgenecessary for the batch test was retained. Bydiscarding the supernatant, mixing soluble concentrations from the membrane system with the effluent concentrations from the UCT (or JHB) system inside the batch test reactor was prevented which would have yielded incorrect results. The centrifuged sludge was then immediately added to the batch test reactor containing the effluent from the UCT (or JHB) system, continuously aerated (even though the OUR was not measured) and constantly mixed by a motor-driven paddle turning at 20 rpm. Grab samples were taken every 3 - 4 hours from the start of the test, immediately filtered (0.45 µm membrane filter) and stabilized with 2 drops of 8.6 g/ℓ HgCl. The samples were stored overnight at 4℃ and analyzed for COD, TKN, FSA, TP and OrthoP the following day. The batch test lasted nearly 10 hours. Two such batch tests were conducted on the effluent from each of the UCT and JHBsystems

3.2.5.13 Flow Rates Measurement

The influent and recycle flows were regularly measured manually. This was done by using a stop watch and volumetric flask. The watch was used for measuring the time to fill the volumetric flask to its defined volume. The flow (mℓ/s) is then given as the ratio of the volume of sludge collected divided by the recorded time. Flows were measured frequently andwhenever the voltage of the main power supply fluctuated. Fluctuations frequently happened at the beginning of a new climate season and more frequently over weekends with a low voltage starting on Friday midday and ending on Saturday evening. The flows used in the mass balance calculations for a WW batch are the average measured flows for that particular WW batch.

Chapter IV : RESULTS AND DISCUSSION

INTRODUCTION

The UCT and JHB laboratory systems were operated for a total of 555 and 198 days respectively (**Figure IV.1**). Due to the many start up problems only the results are presented here from the 383 day- and 154 day-operation of the systems during which times the systems were operated under steady state conditions. During this time, 15 WW batches were fed to the UCT system at 20d SRT and 8 batches to the JHB system at 5d SRT. For each WW batch (which was accepted to represent a steady-state period), the daily results were averaged (after analysis for outliers). These steady-state averages were used to assess the performance of each system directly or by comparison with another system operated in the past. The following process characteristics were calculated: system COD, N and P flux (mass/d) balances; influent unbiodegradable soluble and particulate COD fractions ($f_{S'us}$ and $f_{S'up}$ respectively; Ekama and Wentzel, 1999); influent readily biodegradable concentration (RBCOD); mixed liquor VSS/TSS, COD/VSS, TKN/VSS and TP/VSS ratios; nitrate (NO_3) and P flux (mass/d) changes across each reactor. When necessary, the UCT system's performance was evaluated by comparison with a previously run UCT system such as the conventional activated sludge UCT system (identified here as CAS UCT) operated by Ramphao et al. (2004). This CAS UCT had identical system parameters as the UCT system but was fed normal raw WW from Mitchell's Plain WWTP (Ramphao et al., 2004:5.42). Additional comparison will be made with the predictions of the models for BNR activated sludge systems.

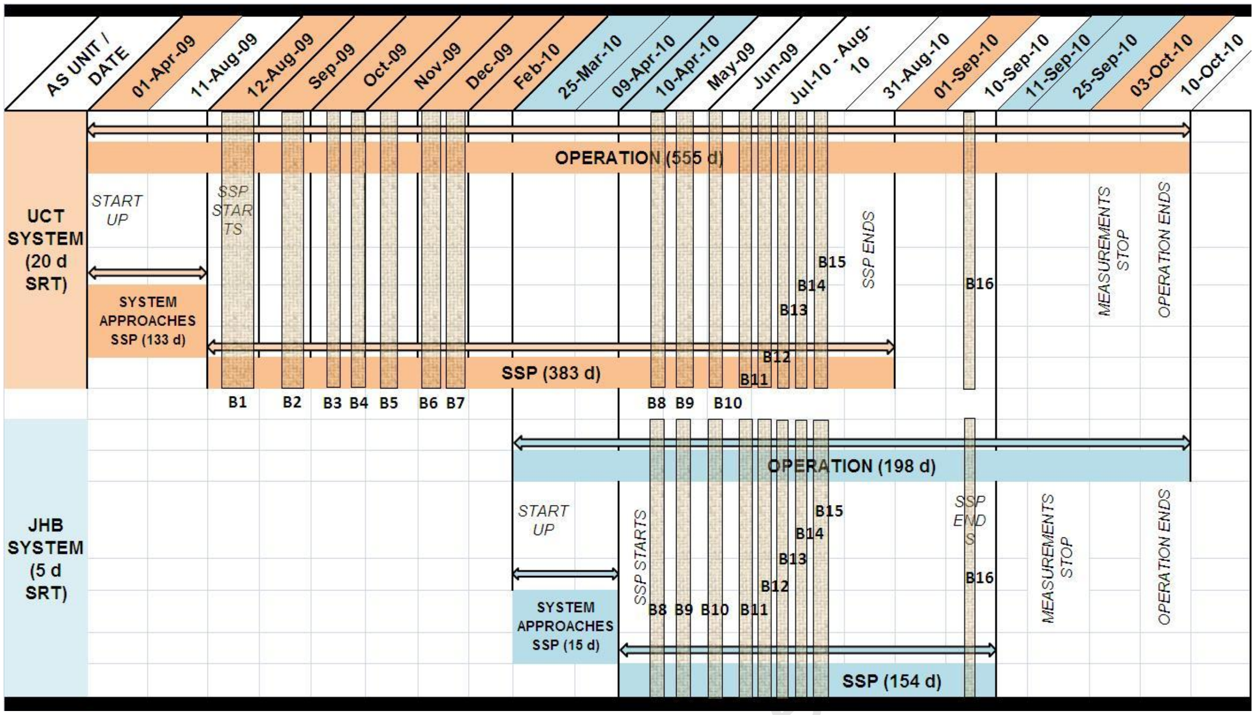


Figure IV.1: Time line for the UCT and JHB systems operated at 20d and 5d SRT respectively showing the WW batches. Also, see **Figure III.4.**

4.1 RESULTS OF BIOLOGICAL TREATMENT OF GREY-BROWN WATER MIX

4.1.1 Steady state periods

Results for both the UCT and JHB systems are presented in **Appendices B** and **C**.The performance of both systems were quantified and analyzed from the daily sampling and testing in the following manner. All periods during which a WW batch was fed were considered a SSP except batch 16 and batch 9 for the UCT and JHB system respectively which were rejected. This means that all rates and concentrations in the systems should remain fairly constant with time. Data from each system were analysed for day-to-day consistency by assessing them within the WW batch 95 % confidence interval. A value outside the confidence interval spanning *sample mean* ± *2*SSD* (sample standard deviation) was considered non-representative of steady-state period of a batch and was therefore discarded. All other values were considered valid and averaged to represent the average response of the system for that WW batch. The influent unbiodegradable soluble and particulate COD fractions ($f_{S'us}$ and $f_{S'up}$); influent readily biodegradable concentration (RBCOD); mixed liquor VSS/TSS, COD/VSS, TKN/VSS and TP/VSS ratios for each WW batch were calculated as a ratio of the average of the valid daily measurements for that particular batch. The overall average (average of WW batch averages) of each of the above parameters, their SSD and the number of data points (number of batches) used to assess the general performance of each system are tabulated in **Appendices B** and **C**.

4.1.2 NDBEPR UCT system

4.1.2.1 Nitrogen (N) mass balance

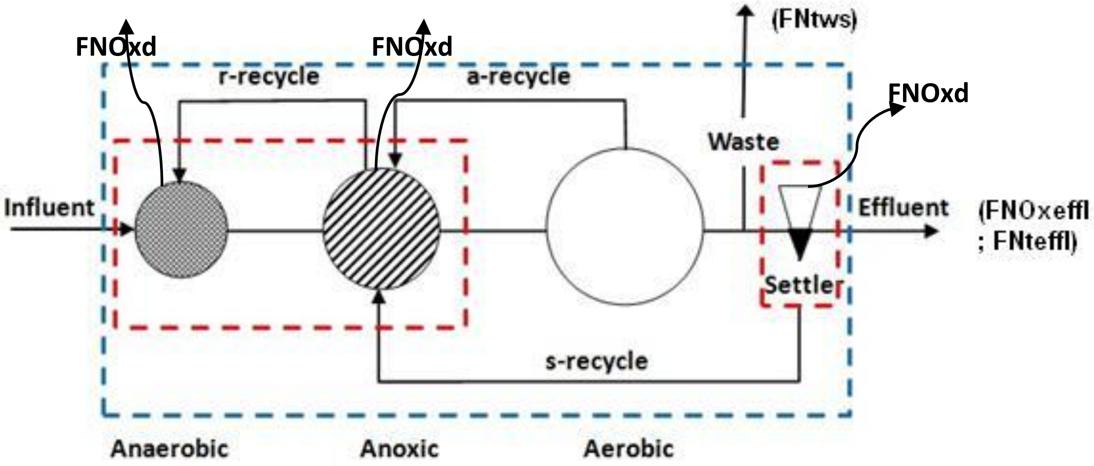


Figure IV.2: Schematic layout of the UCT system. Dotted lines (inside out) indicate the mass balance boundaries around the unaerated zones & clarifier and overall system respectively.

The N mass balance compares the exiting N flux (mass/d) via the effluent, waste sludge stream and nitrate denitrified (from a nitrate balance over the AX and AN reactors) with the N flux entering the system via the influent TKN. The mass balances are calculated to determine the consistency, accuracy and reliability of the system response data. An N balance in the range 100 ± 10% was considered acceptable and indicated reliable data.

The daily flux of nitrogen that enters the system in the form of influent TKN (FN_{ti}) exits it as:

1. Flux of N denitrified (FNO_{xd}, mgN/d)
2. Flux of N in the waste sludge (FN_{tws}, mgN/d)
3. Flux of N in the effluent, i.e. TKN (FN_{teffl}, mgN/d) plus nitrite and nitrate (FNO_{xeffl}, mgN/d)

$$\%NITROGEN\_Balance = \frac{100*(FNO_{xd} + FN_{tWS} + FNO_{xeffl} + FN_{teffl})}{FN_{ti}} \qquad \textbf{[Eq IV.1]}$$

The different components (i, ii, iii) of the N balance for the WW batches are shown in **Figure IV.3**. The N unaccounted for (“Uncc”) is the N deficit to balance the N at 100%. FNO_{xd} is obtained from a nitrate and nitrite mass balance over the anaerobic, anoxic and clarifier sections of the system (see dotted lines in **Figure IV.2**). Because insignificant nitrite was generated (average for all batches was < 0.50 mgNO_2-N/ℓ), NO_3 was accepted equal to NO_x (NO_2+NO_3). The AE reactor and effluent nitrate concentration was found to be very low (< 1mgNO_3-N/ℓ). Because the effluent exits from the AE reactor, such low nitrate concentrations are only possible if negligible nitrification takes place in the AE reactor. Without nitrification, there cannot be any denitrification in the AX (and AN) reactor. The nitrate mass balances over the AX and AN reactors confirmed this. Around 6 % of N exits the system via denitrification (average FNO_{xd} for all batches) and this is most likely due to low spurious background nitrate concentrations which are probably really zero.

Because no (or negligible) nitrification takes place in the system, the nitrogen balance should close at 100% with nearly all the N exiting the system as N bound in waste activated sludge (WAS). While it is true that nearly all the measured N exiting the system exits as N in WAS, the average FN_{tws} exiting the system for all batches is only 56 %, far from 100%. The N balance over the WW batches ranged between 53% and 89%. Provided it can be confirmed that nitrification in the system is negligible, this means that the measured N/VSS ratio of the sludge in the AE reactor is too low. Reasons for this are investigated in the section on discussion.

.

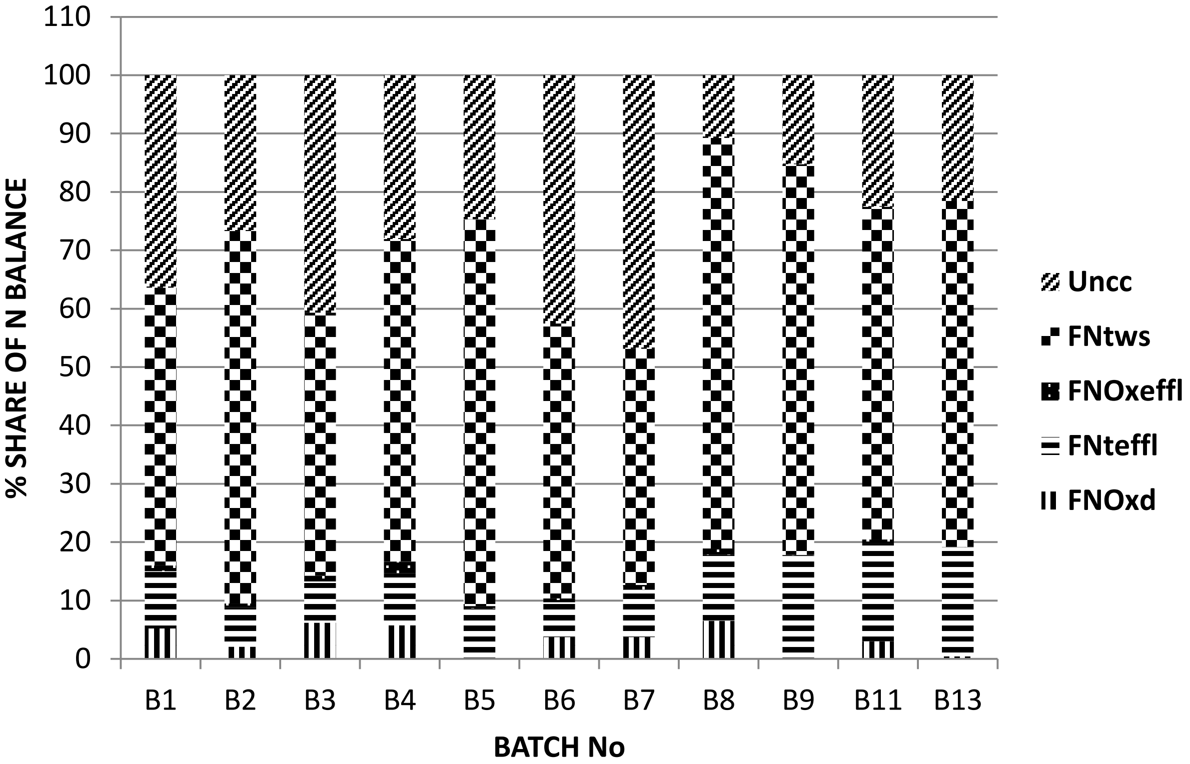


Figure IV.3: Graphical representation of the percentage Nitrogen (N) mass balance for the steady state WW batches for the UCT system. Batches 10, 12, 14 and 15which do not appear, are WW batches for which only the effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured. Batch 16 was rejected as non-representative of SSP performance.

4.1.2.2 COD mass balance

The COD mass balance was calculated by comparing the exiting COD flux via the effluent, waste sludge stream and oxygen utilized in the AE reactor (corrected for nitrification) with the COD entering the system via the influent COD. The mass balances are calculated to determine the accuracy and reliability of the response data. Mass balances in the range 100 ± 10% are considered acceptable and indicate reliable data.

For 100% COD balance, the flux of COD entering the system should be accounted for by the:

i. Flux of oxygen demand required per day for degradation of carbonaceous material in the aerobic reactor (FO_c, mgO/d)
ii. Flux of oxygen recovered by denitrification of nitrate and nitrite (FO_d, mgO/d)
iii. Flux of COD in the waste sludge (FS_{tws}, mgCOD/d)

iv. Flux of COD in the effluent (FS_{teffl}, mgCOD/d)

$FO_c$is obtained by subtracting the nitrification oxygen demand (FO_n, gO/d) from the measured oxygen demand, i.e. $FO_m = OUR_m * V_{aerobic} * 24$ and adding the oxygen recovered by denitrification (FO_d). FO_n is 4.57 mgO/mgN nitrified times the flux of nitrate generated by nitrification, $FO_n = 4.57*(FNO_{xd} + FNO_{effl})$ where 4.57 represents the oxygen requirement for the nitrification of ammonia to nitrate. FO_d is 2.86 times the flux of nitrate denitrified, i.e. $FO_d = 2.86*FNO_{xd}$ where 2.86 is oxygen equivalent of nitrate when denitrifying one mgN of nitrate to nitrogen gas. The measured FO_c is then added to the flux of COD exiting the system via the effluent and waste flows to obtain the total COD exiting the system (**Equation IV.2**). The COD results are shown in **Figure IV.5**.

$$\%COD\_Balance = \frac{100*(FO_C + FO_d + FS_{tWS} + FS_{teffl})}{FS_{ti}} \qquad \textbf{[Eq IV.2]}$$

Figure IV.4 gives the percentage share of the oxygen utilized. As it can be observed the denitrification (FO_d) and nitrification oxygen (FO_n) demands are very small at averages of 1% and 2 % respectively of total oxygen demand compared to the carbonaceous oxygen demand (FO_c) that represents an average of 97 %. This showed that no nitrification took place in the UCT system and that the measured oxygen demand (FO_m) could be used directly in the COD balance ($FO_c = FO_m$). Doing this yielded 98 % to 110 % COD mass balance over the system (**Figure IV.5**).

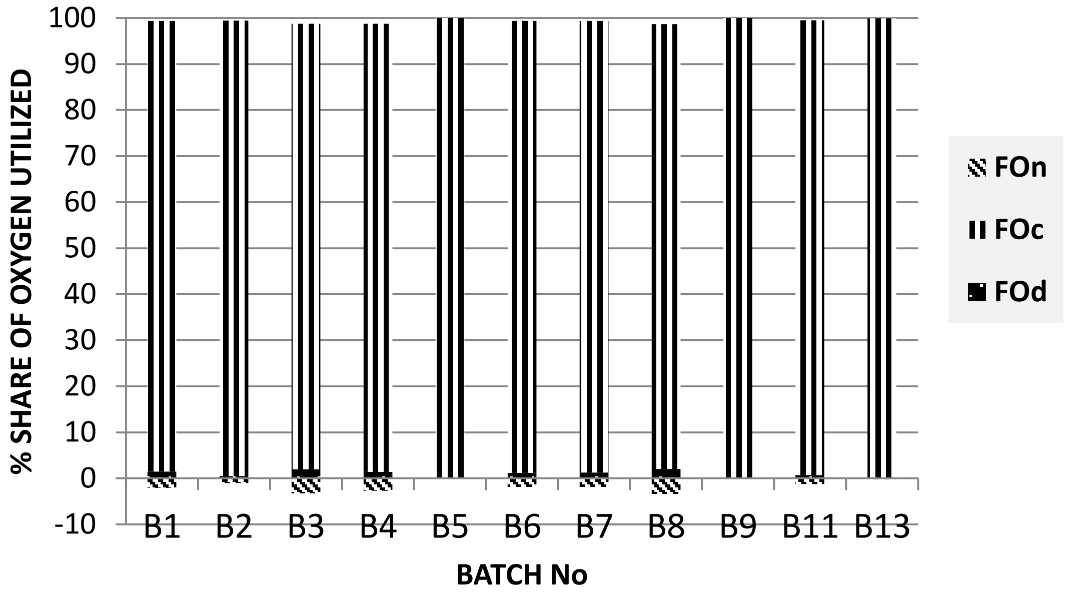


Figure IV.4: Graphical representation of the percentage oxygen utilized for the steady state WW batches for the UCT system.

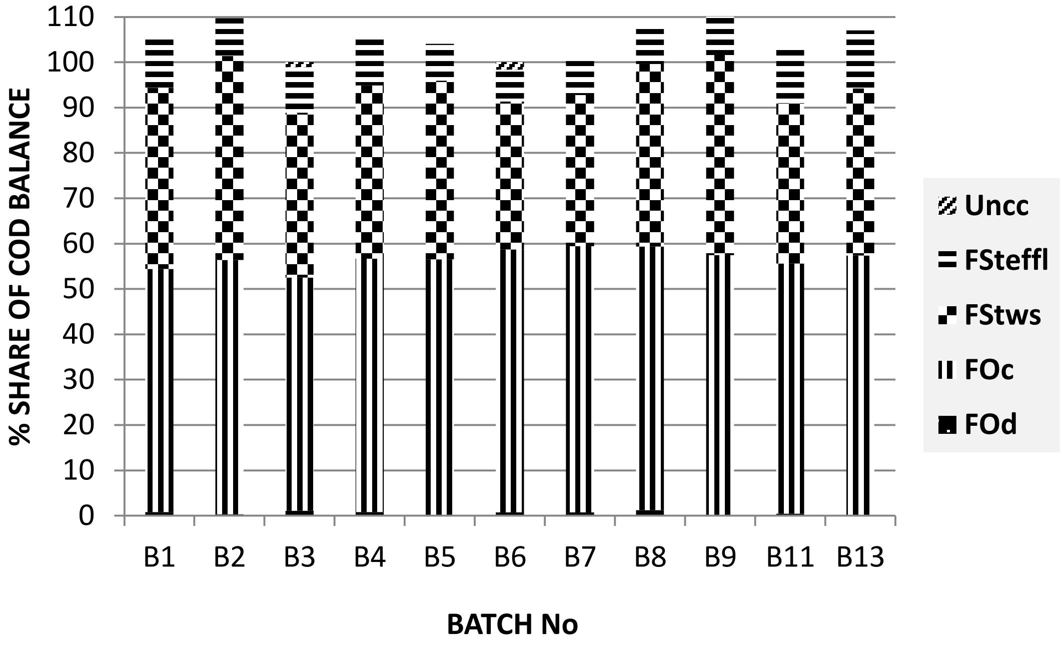


Figure IV.5: Graphical representation of the percentage COD mass balance for the steady state WW batches for the UCT system. Batches 10, 12, 14 and 15 which are not shown, are WW batches for which only the effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured. Batch 16 was rejected as non-representative of SSP performance.

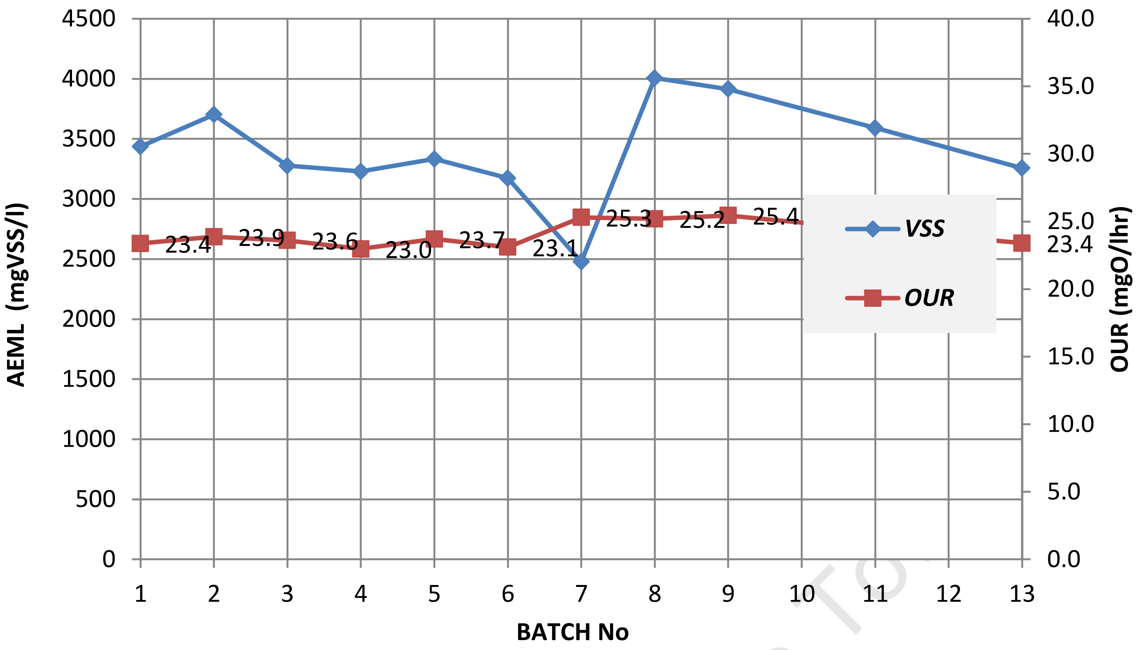


Figure IV.6: Trend in Aerobic VSS and OUR for the WW batches of the UCT system.

4.1.2.3UCT system COD, N and P removal performance

The overall average influent and effluent COD, TKN, FSA and TP concentrations as well as the respective total removal efficiencies are listed in **Table IV.1.** The COD, TKN and TP removals were good at 90 %, 88 % and 84 % respectively compared with 94 %, 97 % and 54 % for the comparative CAS UCT system of Ramphao et al. (2004) (see **Appendix D**). The only reason for the higher P removal of the UCT system is that the CAS UCT had a much higher influent TP due to dosing Ortho P to the influent, which was not done in this investigation. The average effluent NO_2; NO_3 and Ortho P concentrations are lower than those obtained for CAS UCT system at 0.1 mgNO_2-N/ℓ; 0.3 mgNO_3-N/ℓ and 2 mgPO_4-P/ℓ respectively. These effluent concentrations are very good when compared with the general limits specified by the National Water Act (Act 36 of 1998) for plants discharging up to 2Mℓ/d of effluent in any water resource (see **Appendix E**). They are less than the specified limits by 99 %; 98 % and 80 % respectively. The effluent FSA and unbiodegradable soluble COD concentrations of 3.5 mgNH_3-N/ℓ and 85.4 mgCOD/ℓ were 25 % and 35 % respectively higher than that obtained for CAS UCT system. Also, both effluent concentrations were around 15 % higher than the authorized limits. As explained in the discussion section below (**Section 4.2.3**), the filtered effluent concentrations presented in **Table IV.1** consisted of approximately 60 % soluble biodegradable COD (S_{bse}) and 25 % organic N biodegradable soluble (N_{obse}) (but no P_{obse})all of which exited in the effluent. This was not expected and is extremely unusual – it has never been observed in laboratory AS systems fed real WW at UCT.This unusual behaviour was attributed to the specificity of the WW type due to the very small population sample from which it was collected. This made it difficult for microorganisms to adapt to the variations in influent WW quality (grey and brown water mix) from WW batch to WW batch. It is demonstrated below with batch tests that much of the filtered effluent COD was biodegradable by AS harvested from a UCT system fed real WW. The total solids (TSS) in the effluent averaged at 23.3 mgTSS/ℓ, which was 30 % higher than the value obtained for the comparative CAS UCT. This high TSS (and unfiltered COD) is also due to poor AS development and flocculation.The general authorized limit for total solids is 25 mg/ℓ. However good some of the above effluent concentrations might be when compared to the CAS UCT system or to the specified limits, they are much higher than what had been expected from a scenario of 100 % urine diversion.

Table IV.1: Overall average influent and effluent COD, TKN, FSA and TP concentrations and total COD, N and P removal efficiencies for the UCT system at 20d sludge age.

PARAMETER		**Influent**	**Effluent**	**Efficiency**
COD	**mgCOD/ℓ**	*1020.9*	*108.2*[1] *(85.4*[2]*)*	*90%*
TKN	**mgN/ℓ**	*55.4*	*6.4*[1] *(4.4*[2]*)*	*88%*
FSA	**$mgNH_3$-N /ℓ**	*24.7*	*3.5*	*85%*
TP	**$mgPO_4$-P/ℓ**	*19.0*	*2.7*[1] *(2.1*[2]*)*	*84%*
Ortho P	**$mgPO_4$-P/ℓ**	–	*2.0*	–
NO_2/NO_3	**$mgNO_2$-(NO_3-) N/ℓ**	*0.0*	*0.1 / 0.3*	*n/a*
TSS	**mgTSS/ℓ**	–	*23.3*	*n/a*
pH	**n/a**	*5.5 - 6.5*	*5.5 - 7.5*	*n/a*

[1]Unfiltered sample; [2] 0.45 µm membrane filtered sample; Average values include B1-B9, B11 & B13 which represented SSP.

4.1.2.4 Aerobic mixed liquor solids (AETSS and AEVSS) and AEVSS/AETSS ratio (f_i)

TheUCT system was operated for 133 days (6 sludge ages) before detailed sampling and measurements were commenced, to allow it to reach steady state (**Figure IV.1**).

Figure IV.7 shows the variations in VSS (TSS) of the AE reactor of the UCT system. Although there were intermittent small variations and clear periods of disturbance due to varying composition of the WW batches, the VSS and TSS concentrations over a long term period were inconsistent between 3000 – 5000 mgSS/ℓ for a system fed an approximately constant COD daily. The VSS and TSS averaged at 3550 mgVSS/ℓ and 4200 mgTSS/ℓ respectively. These measured concentrations are higher than the predicted values of 2600 mgVSS/ℓ and 3250 mgTSS/ℓ calculated for the average measured influent concentrations (**Table III.1**) by using the NDEBPR BNR system design and simulation models (Wentzel et al., 1990, 1992).

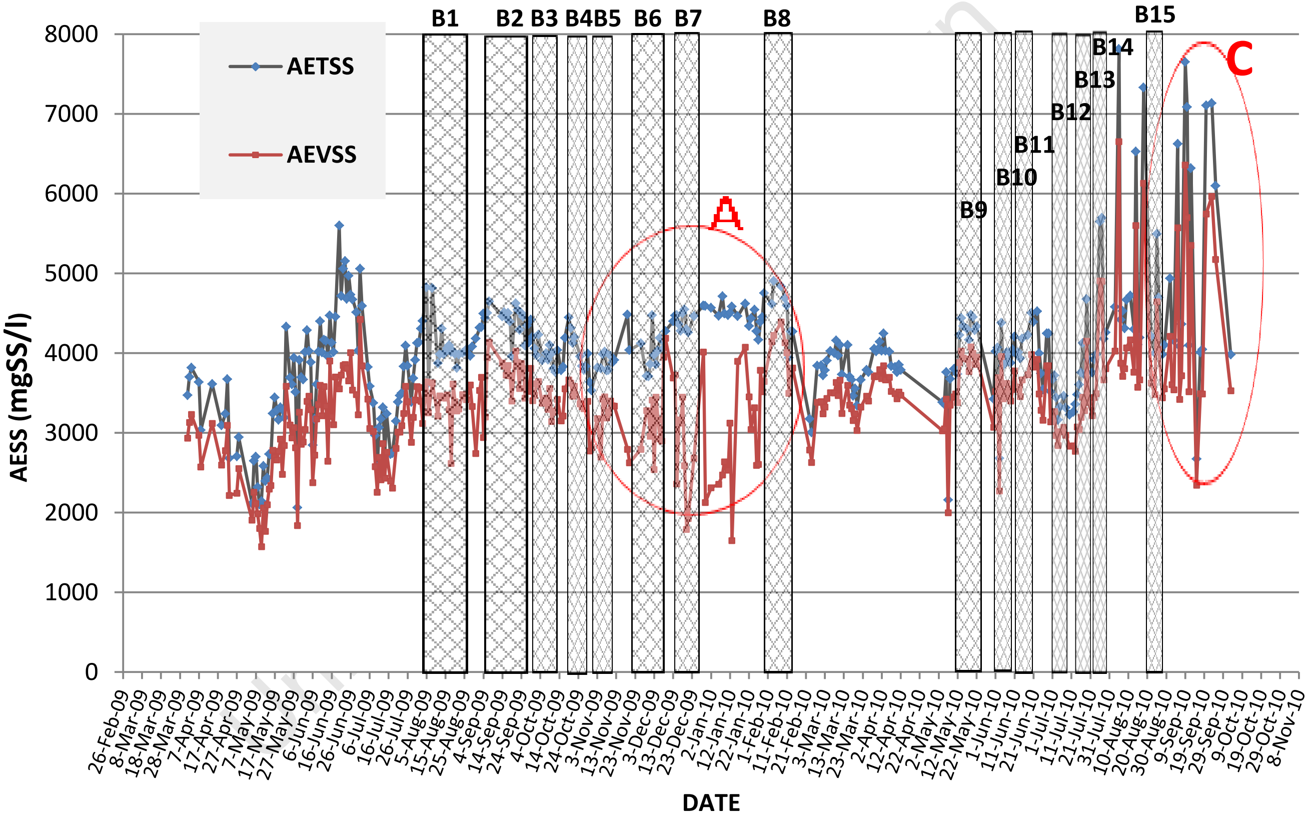


Figure IV.7: Aerobic reactor solids (AETSS and AEVSS) variations for the UCT system, over the entire period of measurement (Apr 2009 – Oct 2010). The circled area *C*indicates the period of major disturbance, see discussion in **Section 4.2.1.4**.

The trend in VSS variation tracks closely that of the TSS, with the difference (ISS) being roughly constant for the entire period of measurement, notwithstanding the periods of significant variations. The daily VSS/TSS ratio was calculated and the average obtained was 0.832 mgVSS/mgTSS with SSD of 0.078. The comparative CAS UCT system yielded 0.817 VSS/TSS ratio (SSD of 0.029). Considering that both UCT systems are BNR systems which build up considerable ISS through the storage of polyP and associated counter-ions, the value of 0.82 ± 0.01 is higher than expected (Ekama et al., 2006) and is indicative of low P removal.

4.1.2.5 Diluted sludge volume index (DSVI)

The Diluted Sludge Volume Index (DSVI), which is an indication of sludge settleability, averaged at 93.5 mℓ/gTSS. However, as the graph in **Figure IV.8** below indicates, there were considerable fluctuations. Initially, the DSVI was around 125 mℓ/gTSS (up to 6 Sept 2009). Then, the DSVI decreased to reach an average of 80 mℓ/gTSS (30 Sept – 22 Oct 2009), increased thereafter to 125 mℓ/gTSS (28 Oct 2009 – 12 Jan 2010). From there, the DSVI decreased to nearly 53 mℓ/gTSS (late Mar 2010) before increasing again to 93 mℓ/gTSS (on 10 Apr 2010). From early April to the end of the experiment (3 Oct 2010) it averaged around 93 mℓ/gTSS despite the major fluctuations from early September onwards. This late period was identified as one of major system fluctuation (period D) which was induced by external factors which had direct impact on system solids concentrations (TSS, VSS and ISS) (see **Section 4.2.1.4**). For full-scale WWTPs, such significant variations in DSVI can cause operational problems such as SST (clarifier) failure and filamentous organism sludge bulking must be avoided in a BNR system when long-term stability is required. Microscopic examination of the UCT system sludge was not undertaken, but from experience with BNR systems, with no nitrification and denitrification, filamentous bulking by AA (low F/M) filamentous organisms (0092, 0041, *Microthrix Parvicella*, 0675) is unlikely from anoxic aerobic alternation (Casey et al., 1992, 1999; Musvoto et al., 1994). However, the high effluent FSA (± 3 mgNH_3-N/ℓ) can stimulate *Microthrix Parvicella* proliferation (Tsai et al., 2003). With DSVI never exceeding 150 ml/g and long term high values of around 120 ml/g, the sludge in the sytem did not manifest filamentous bulking despite its 20 day SRT (DSVI not greater than 150 ml/g, Blackbeard et al., 1986, 1988). Most of the variation in DSVI was caused by variation in TSS concentration. **Figure IV.8** shows the variation in SV_{30}, which is the settled volume (ml) recorded after 30 min settling of AEML and used in calculating the DSVI from $DSVI\ (ml/gTSS) = SV_{30}\ (ml) / TSS\ (gTSS/\ell)$. From the graph of SV_{30}, the effect of TSS on the DSVI can be seen for the period extending from Apr to Aug 2009 and for period D that were both identified as non-steady state periods. Unlike period D, the first period of fluctuation was due to the UCT system approaching steady state.

Comparison with the CAS UCT system showed similar variations in the DSVI. Microscopic examination of the CAS UCT system mixed liquor identified the AA filaments (*M parvicella* and Type 0092) as the dominant ones, and their relative abundance appeared to be linked to the DSVI (Ramphao, 2004:6.8).

Similar microscopic examination should have been done on the aerobic sludge from the UCT system especially because of the particularity of the feed WW (grey and brown water mix), but this capacity had been lost in the UCT WW laboratory and the regional laboratories.

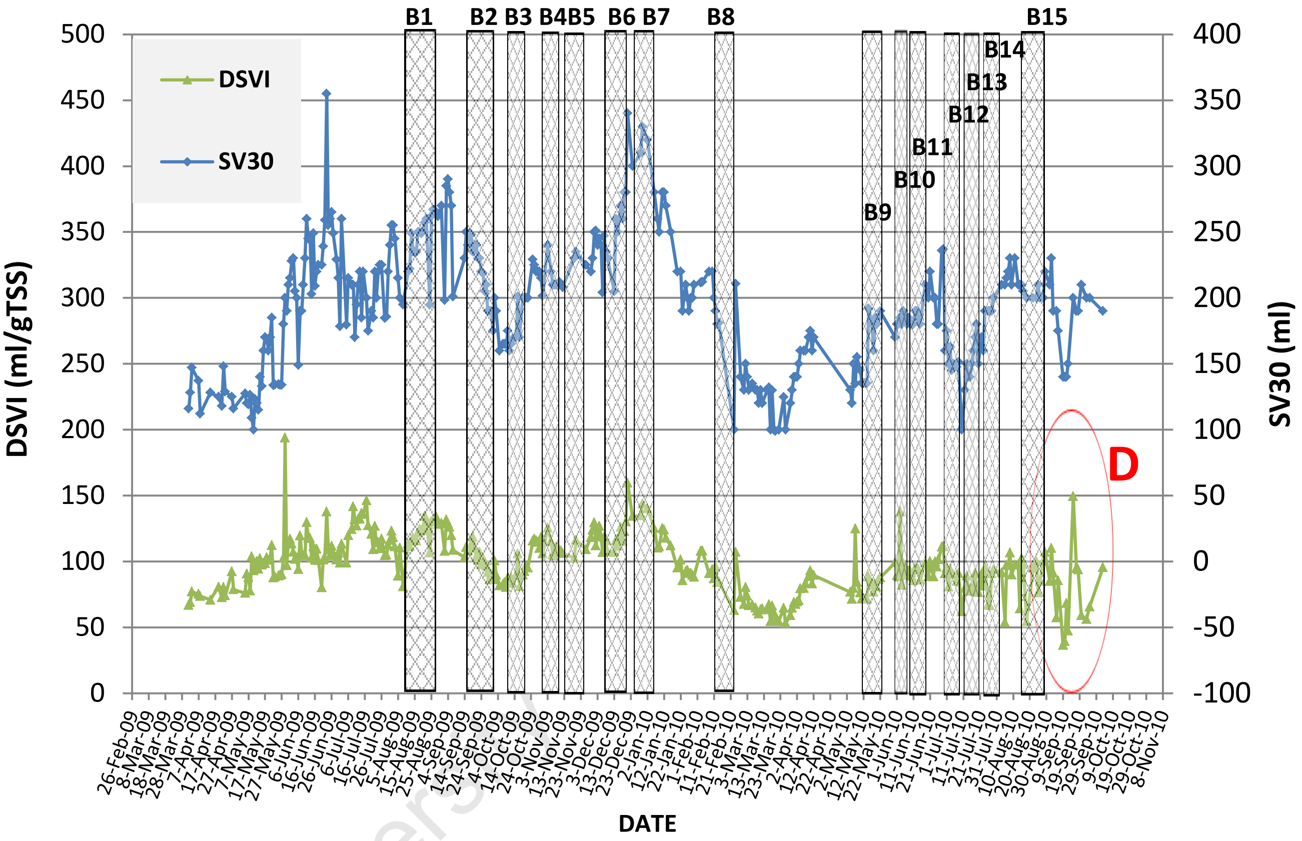


Figure IV.8: DSVI and SV_{30} variations of sludge harvested from the AE reactor of the UCT system, over the entire period of measurement (Apr 2009 – Oct 2010). The circled area *D* indicates the period of major fluctuation caused by TSS concentration fluctuation, see discussion in **Section 4.2.1.4**.

4.1.2.6 Calculating the influent wastewater (WW) and aerobic reactor mixed liquor (AEML) characteristics

Table IV.2 lists the influent and AEML characteristics calculated from the measured results for every WW batch as well as the overall average for the experimental investigation.

A. Unbiodegradable soluble $f_{S'us}$ and particulate $f_{S'up}$

Fixing the unbiodegradable soluble COD fraction ($f_{S'us}$) for the UCT system at the measured value (i.e. $f_{S'us}$ = filtered effluent COD/total influent COD), the $f_{S'up}$ fraction was determined such that the calculated (predicted) VSS mass in the system matched the measured average mass of VSS in the system (Ekama and Wentzel, 1999) (see also**Appendix F**). This calculation requires the influent RBCOD concentration (S_{bsi}), which was measured as the difference between the membrane filtered influent and effluent COD concentrations, i.e. $S_{bsi} = (S_{si} - S_{use})$. Because no nitrate was recycled to the AN reactor, it was accepted that all the influent RBCOD was converted to volatile fatty acids (VFA) and taken up by the phosphorus accumulating organisms (PAOs) in the anaerobic (AN) reactor. The values presented in **Table IV.2** include the dissolved biodegradable COD exiting in the effluent which was estimated at 60 % the fraction of filtered effluent COD, see **Section 4.1.2.3** and **4.2.3**. **Table IV.2** lists the influent WW and AEML characteristics. In estimating the theoretical aerobic VSS (MLVSS), the typical real WW unbiodegradable soluble ($f_{S'us}$) and particulate ($f_{S'up}$) COD fractions of 0.05 and 0.13 were used (WRC, 1984). However, that the average experimental aerobic MLVSS of 3550 mg VSS/ℓ was higher than the predicted value of 2600 mg VSS/ℓ, indicated a significant difference in the soluble and particulate unbiodegradable COD fractions of the grey and brown WW mix. These two fractions averaged at 0.08 (SSD=0.013) and 0.21 (SSD=0.041) or 45 % and 31 % respectively higher than 0.05 and 0.13 (**Table IV.2**). While the $f_{S'us}$ falls within the range (0.04 to 0.10) of typical values expected for domestic WW in SA (WRC, 1984 as reported by Ramphao, 2004:5.45, 6.15), the $f_{S'up}$ is above the upper limit of the range (0.07 to 0.20). A value of 0.084 (SSD=0.026) was obtained for the CAS UCT system treating Mitchell's Plain raw WW. The UCT system yielded 60 % more unbiodegradable particulate COD than the CAS UCT system. This was attributed to significant concentration of biodegradable particulate organics (BPO) not being utilized in the UCT system (which was also true for the biodegradable soluble organics (BSO) already mentioned above).

B. COD/VSS ratio f_{cv} (mgCOD/mgVSS)

The average COD/VSS ratio was calculated from the measured COD and VSS concentrations of the solids for each WW batch. These WW batch averages were averaged to obtain the overall average as described in **Section 4.1.1**. The overall average COD/VSS ratio obtained was 1.18 with a SSD of 0.11. This is approximately 14 % and 17 % respectively lower than the value obtained for the comparative CAS UCT system (1.365 with SSD 0.049) and the theoretical value of 1.42 derived from the widely used formula $C_5H_7NO_2$ (WRC, 1984). The value of 1.18 is far below the lower limit of the range 1.3 – 1.5 mgCOD/mgVSS obtained from extensive experimental research over the years in the UCT Water

Research Laboratory with an average of 1.48 commonly accepted. It is possible that the COD/VSS ratio of the influent solids is very low so that with the undegraded influent biodegradable particulate organics (BPO) and the influent unbiodegradable particulate organics (UPO) in the aerated sludge mixed liquor, the overall COD/VSS ratio also is low.The COD/VSS ratio of the influent solids was not measured to check this. Such a low COD/VSS ratio was not expected. Nevertheless, even with such a low COD/VSS ratio good COD balances (95 – 105 %) were obtained over the UCT system. Therefore, if there is an error then this must be in the VSS data, which also is unlikely because *solids* is not a difficult parameter to measure. The only plausible explanation for the low f_{CV} is that the VSS includes a significant concentration of unutilized influent BPO (116.3 mgCOD/ℓ or 29 % of the total influent BPO, see **Section 4.1.2.8**), which with a low COD/VSS, yields a lower than usual composite mixed liquor f_{CV}. This applies also to the mixed liquor TKN/VSS ratio (f_n), but to a lower extent.

C. TKN/VSS ratio f_n (mgN/mgVSS)

From many years of experimental work, the N content of AS including OHOs and PAOs (f_n) has been accepted at 0.10 mgN/mgVSS in steady state models (Marais and Ekama, 1976; WRC, 1984; Wentzel et al., 1990) and kinetic simulation models (ASM1, Henze et al., 1987; UCTPHO, Wentzel et al., 1992; ASM2, Henze et al., 1995). In this investigation, a somewhat lower value was measured 0.093 with SSD of 0.013, **Table IV.2.** A value of 0.113 mgN/mgVSS (SSD=0.019) was obtained for the comparative CAS UCT system. This close correspondence between the f_n of this investigation and previous investigations validates the measured TKN and VSS measurements on the sludge. However, why this measured f_n ratio yielded an N balance of only 53 – 89 % with the absence of nitrification and denitrification is not clear.

Table IV.2: Influent and AEML Characteristics for the batches of WW over the SSP for the UCT system at 20d SRT.

BATCH No	**Influent Characteristics**					**AEML Characteristics**			
	TKN/COD	**TP/COD**	**$f_{S'us}$[1]**	**$f_{S'up}$[1]**	**RBCOD[1]**	**VSS/TSS(f_i)**	**COD/VSS (f_{cv})**	**TKN/VSS (f_n)**	**TP/VSS (f_p)**
B1	*0.053*	*0.015*	*0.08*	*0.18*	*0.35*	*0.82*	*1.22*	*0.078*	*0.023*
B2	*0.049*	*0.019*	*0.07*	*0.27*	*0.30*	*0.85*	*1.27*	*0.090*	*0.035*
B3	*0.060*	*0.022*	*0.09*	*0.20*	*0.18*	*0.84*	*1.24*	*0.094*	*0.047*
B4	*0.049*	*0.014*	*0.10*	*0.20*	*0.30*	*0.84*	*1.22*	*0.088*	*0.031*
B5	*0.044*	*0.014*	*0.07*	*0.20*	*0.30*	*0.86*	*1.25*	*0.093*	*0.032*
B6	*0.067*	*0.021*	*0.08*	*0.16*	*0.25*	*0.78*	*1.04*	*0.101*	*0.030*
B7	*0.070*	*0.018*	*0.07*	*0.14*	*0.31*	*0.62*	*1.34*	*0.114*	*0.040*
B8	*0.065*	*0.024*	*0.08*	*0.25*	*0.26*	*0.89*	*1.00*	*0.115*	*0.033*
B9	*0.045*	*0.011*	*0.09*	*0.26*	*0.33*	*0.90*	*1.18*	*0.081*	*0.023*
B10	*0.049*	*0.017*	*0.06*	*n/a*	*0.35*	*0.89*	*n/a*	*n/a*	*n/a*
B11	*0.047*	*0.017*	*0.08*	*0.19*	*0.27*	*0.89*	*1.03*	*0.079*	*0.026*
B12	*0.056*	*0.021*	*0.11*	*n/a*	*0.17*	*0.86*	*n/a*	*n/a*	*n/a*
B13	*0.049*	*0.021*	*0.12*	*0.24*	*0.14*	*0.86*	*1.16*	*0.092*	*0.033*
B14	*0.059*	*0.024*	*0.12*	*n/a*	*0.18*	*0.84*	*n/a*	*n/a*	*n/a*
B15	*0.073*	*0.023*	*0.11*	*n/a*	*0.11*	*0.86*	*n/a*	*n/a*	*n/a*
B16	*0.067*	*0.028*	*0.15*	*0.32*	*0.05*	*0.86*	*0.94*	*0.066*	*0.027*
Avg=	***0.054***	***0.018***	***0.08***	***0.21***	***0.27***	***0.83***	***1.18***	***0.093***	***0.032***

---

[1] fraction of the total influent COD, *Sti;* n/a designates WW batches for which only effluent concentrations, OUR and solids (TSS, VSS & ISS) were measured while the JHB system was fully tested; Averages include B1-B9, B11 & B13 which represented SSP.

4.1.2.7Excess biological phosphorus removal behaviour (EBPR) across the UCT system

The theory of EBPR is well documented and can be found in Wentzel et al. (1990); Wentzel et al. (1991) and Maurer et al. (1997) as reported by Ramphao (2004:5.56) or in Henze et al. (2008). Essentially by subjecting the Polyphosphate Accumulating Organisms (PAOs) to a sequence of alternating unaerated (anaerobic) and aerated (aerobic) zones, they are capable of taking up the Volatile Fatty Acids (VFAs) – coming in with the influent or anaerobically fermented from RBCOD by the OHOs – storing it as long chains of poly-β-hydroxybutyrate (PHB) while releasing polyP (P release) in solution. In the aerobic (and sometimes anoxic) zone, the stored VFAs are used by the PAOs as a source of energy for growth and uptake of P (P uptake) from solution to remake the polyP and in the process oxygen is utilized as electron acceptor (nitrate is denitrified if anoxic). If P uptake takes place under anoxic conditions, the PAOs are often called denitrifying PAOs (DPAOs) and this only happens if the nitrate recycled to the anoxic reactor is greater than its denitrification capacity. In the absence of nitrate, the anoxic reactor perpetuates the role of the AN reactor where the RBCOD continues to be hydrolysed, taken up and stored up as PHB by the PAOs as a source of energy with associated P release. In the AE reactor, the PAOs are capable of using the stored PHB as a source of energy in order to take up the polyP in solution (P uptake) and in the process transfer the electrons to oxygen. Here, the PAOs are often called aerobic PAOs (OPAOs). The PAOs have the particular advantage that they can take up the VFAs (fermented RBCOD) with energy generated from the breakdown of polyP chains, a capability which the other microorganisms (OHOs) do not have. However, the PAO mass in the system is limited by the quantity of available VFAs so that the RBCOD hydrolysed to VFA determines the magnitude of P removal within the EBPR system.

When anoxic P uptake takes place, the P removal across the EBPR system decreases compared with aerobic P uptake EBPR. Observations of anoxic P uptake have been reported by Kern-Jaspersen and Henze (1993); Baker and Dold (1996); Kuba et al. (1993); Ekama and Wentzel (1999) as reported by Ramphao (2004:5.63).

.

Table IV.3: P mass changes – i.e. Puptake & Prelease - across each reactor for the batches of WW over the SSP for the UCT system at 20d sludge age.

BATCH No	**ANAEROBIC (AN)**		**ANOXIC (AX)**		**AEROBIC (AE)**	
	P_{uptake}	**$P_{release}$**	**P_{uptake}**	**$P_{release}$**	**P_{uptake}**	**$P_{release}$**
	mgP/ℓ influent	**mgP/ℓ influent**	**mgP/ℓ influent**	**mgP/ℓ influent**	**mgP/ℓ influent**	**mgP/ℓ influent**
B1	*0.0*	*18.5*	*0.0*	*163.9*	*198.3*	*0.0*
B2	*0.0*	*27.1*	*0.0*	*8.4*	*54.2*	*0.0*
B3	*0.0*	*14.2*	*0.0*	*4.1*	*35.1*	*0.0*
B4	*0.0*	*20.0*	*0.0*	*0.6*	*33.6*	*0.0*
B5	*0.0*	*59.9*	*0.0*	*25.1*	*97.7*	*0.0*
B6	*0.0*	*44.7*	*0.0*	*57.4*	*119.9*	*0.0*
B7	*0.0*	*54.9*	*0.0*	*34.7*	*104.7*	*0.0*
B8	*0.0*	*24.7*	*0.0*	*45.6*	*74.2*	*0.0*
B9	*0.0*	*19.5*	*0.0*	*10.0*	*23.0*	*0.0*
B10	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B11	*0.0*	*27.8*	*0.0*	*11.9*	*49.6*	*0.0*
B12	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B13	*0.0*	*21.5*	*0.0*	*23.7*	*66.4*	*0.0*
B14	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B15	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B16	*0.0*	*27.8*	*0.0*	*0.3*	*50.2*	*0.0*
Avg=	***0.0***	***29.8***	***0.0***	***35.0***	***77.9***	***0.0***

n/a designates WW batches for which only effluent concentrations, OUR and solids (TSS, VSS & ISS) were measured while the JHB system was fully tested; Average values include B1-B9, B11 & B13 which represented SSP.

In order to evaluate the EBPR behavior of the system, the change in P concentration in each reactor was calculated by doing a P mass balance over each reactor. The mass change across a reactor was divided by the influent flow to yield the mass change per liter influent. Therefore, the measured P removal across the EBPR system is the sum of the mass balance changes across the reactors and is equal to the difference between the influent and effluent concentrations. **Table IV.3** presents these mass balance calculations for the UCT system. Also calculated for the UCT system was the P mass balance that compares the exiting P flux via the effluent and waste flow with the system influent P flux (**Figure IV.9**). The P unaccounted for ("Uncc") is the P deficit to close the P balance at 100%.

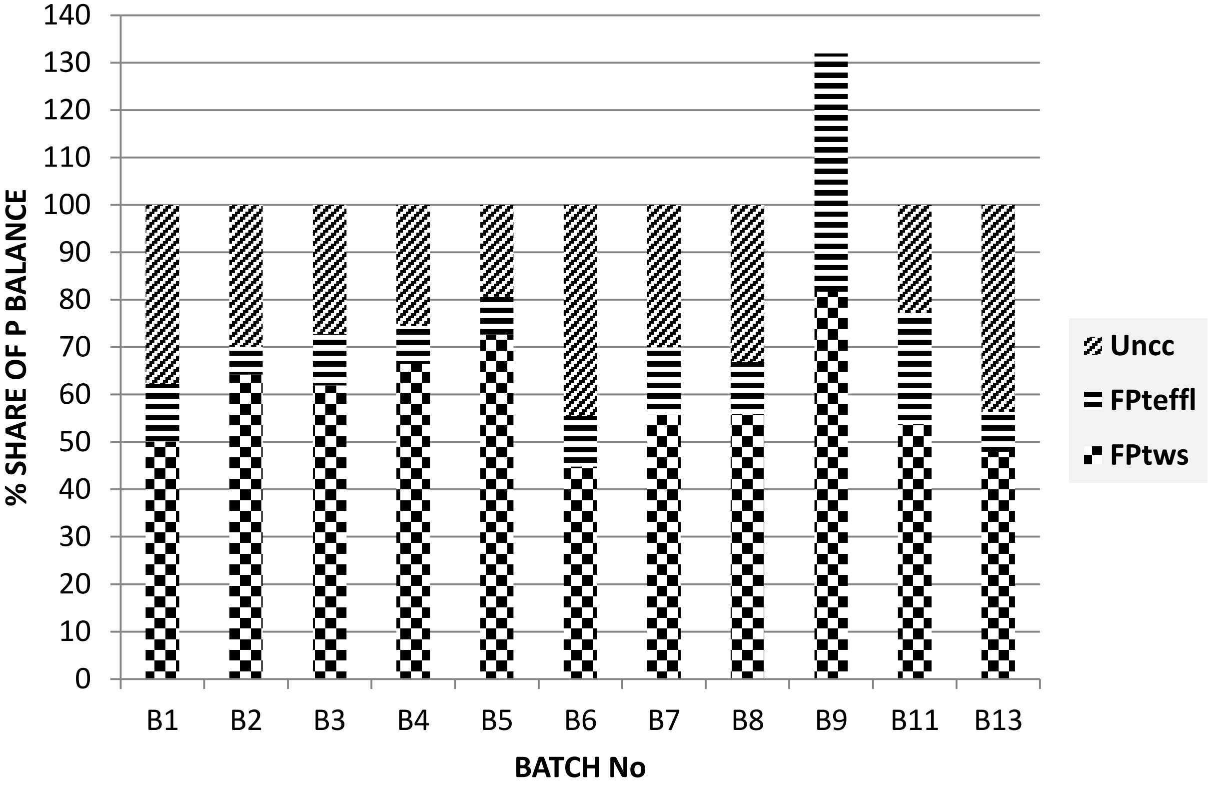


Figure IV.9: Graphical representation of the percentage P mass balance for the steady state WW batches for the UCT system. Batches 10, 12, 14 and 15 which are not shown, are WW batches for which only the effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured. Batch 16 was rejected as non-representative of SSP performance.

- The overall P balance, P removal *[(Influent TP – effluent TP)/influent TP]* and P removal/mg RBCOD were 74 %, 84 % and 0.063 (RBCOD = 0.27 of total influent COD) was obtained, compared with 54 % P removal for the comparative CAS UCT system; as mentioned earlier, the low P removal in the comparative CAS UCT system was because additional P was dosed to the influent;

- The sum of P release in the anaerobic and anoxic (2^{nd} anaerobic actually) reactors was 64.8 mgP/ℓ of which 35.0 (54 %) was P release in the AX reactor. This situation did not fluctuate much for the entire period of measurement where P release was consistently observed in both “AX” and AN reactors and P uptake exclusively in the AE reactor (**Table IV.3**). This consistent P release in the AX reactor can be explained by the very low amount of nitrate recycled into it, which never exceeded 0.3 $mgNO_3$-N/ℓ. The P removal at 15.6 mgP/ℓ for 1000 mgCOD/ℓ influent or 0.063 mgP/mgRBCOD is low (only 2/3 rds) of that usually observed (~ 20 mgP/ℓ per 1000 mgCOD/ℓ or ~ 0.10 mgP/mgRBCOD) with real wastewater.

- The highest anoxic P release and aerobic P uptake occurred for batch B1 where they were nearly 170 and 200 $mgPO_4$-P/ℓ respectively, which seems uncharacteristically high.

- The lowest P removal for 1000 mgCOD/ℓ influent occurred for WW batch B9 where it was only 5.1 mgP/ℓ or ¼ the value usually observed with real wastewater. This low P removal was despite the high measured influent RBCOD of 340.0 mgCOD/ℓ in this period. The low P removal during this WWbatch B9 was attributed to aeration failures that were caused by intermittent power outage during this period.

4.1.2.8 Nitrification batch tests

To confirm whether nitrification was taking place in the UCT system, batch tests on sludge harvested from the AE reactor were conducted. The aerobic batch test reactors are shown in **Figure IV.10.** To start the batch test, the reactor was filled with 3ℓ mixed liquor. Since endogenous conditions needed to be established, the mixed liquor was aerated for a long period (at least 12 hours), during which the OUR was measured, before a small volume (50 mℓ) of concentrated ammonium chloride solution (1 $gNH_4C\ell/\ell$) was added. The OUR continued to be measured (at least 24 hours) until endogenous conditions were again re-established.During the test, grab samples were taken, immediately filtered (0.45 µm) and stabilized with 2 drops of 8.6 g/ℓ HgCl. The samples were stored overnight at 4°C and analyzed for NO_3-N, NO_2-N, and NH_4-N. The difference between the area under the total OUR curve and that under the OUR curve related to endogenous respiration was considered to be the oxygen utilized (OU) due to NH_4-N oxidation, which is related to the ammonia nitrified via OU/4.57.

Figure IV.10: Batch reactors set up for nitrification and aerobic batch tests. Also shown are the OUR boxes for oxygen measurement as well as the pH meters.

The OUR, FSA and NO_3 results of two of six batch tests (batch tests 5 & 6) conducted approximately a month apart (4 Oct and 2 Nov 2009; 18 Jan, 2 Feb, 24 Feb and 26 Mar 2010) are given in **Figures IV.11& IV.12**. For additional batch test results, see **Appendix G**. Unlike batch tests 1 and 2, batch tests 3, 4, 5 and 6 were run over a much longer period i.e. 24 hours after the addition of ammonium chloride to the batch test reactor. The objective was to give the nitrifiers ample time to produce nitrate from the oxidation of the ammonia added. Batch test 5 was carried on the sludge from the UCT membrane NDEBPR system which is a fully nitrifying system to which normal (real) WW from Mitchell's Plain WWTP was fed. The membrane UCT system had the same UCT configuration and had VSS between 6000 – 6500 mgVSS/ℓ. The objective of batch test 5 was to provide results purely as a basis for comparison with the results obtained from the batch tests done on the UCT system.

In batch test 6 (**Figure IV.11**), note that although the concentration of ammonia (NH_3) decreases from 18 to 15 mgN/ℓ over 24 hrs, the nitrate production is negligible, i.e. only 1/6th of the ammonia decrease. In addition, the OU is < 30% that expected from the ammonia decrease. The discrepancy between the decrease in ammonia and the expected OU is similar in batch tests 1, 2, 3 and 4. Nitrification is therefore not taking place. The decrease in ammonia and small increase in OUR is probably a response of the ordinary heterotrophic organisms (OHOs), accustomed to ammonia deficient growth in the UCT system, to a sudden ammonia surplus.

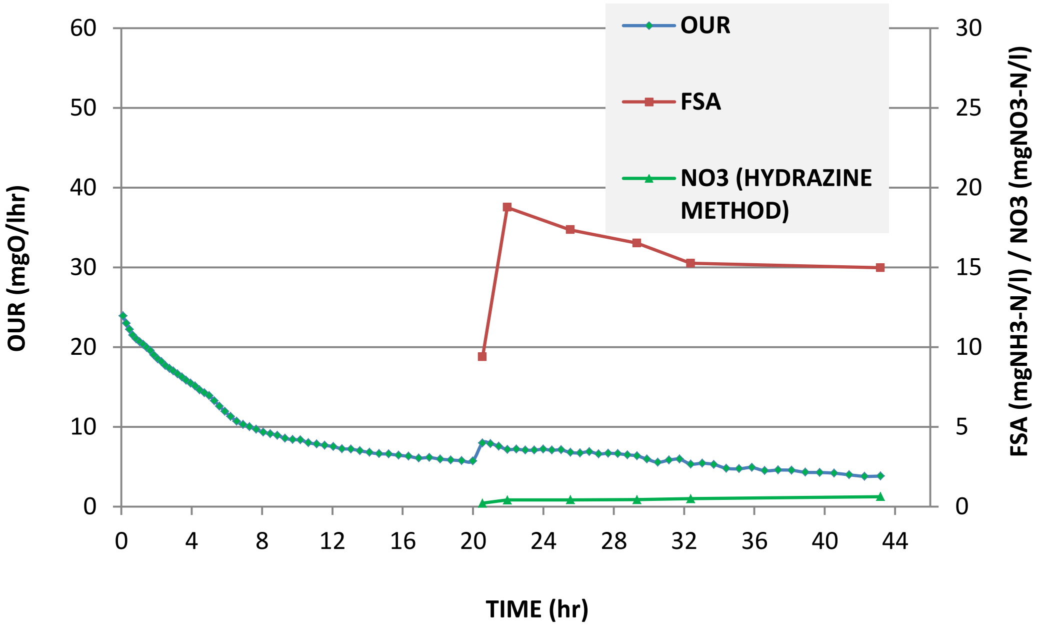


Figure IV.11: OUR, FSA and NO_3results from batch test 6 (Mar 26, 2010). Note the discrepancy between the OU and the ammonia decrease. The OU represents less than 30 % that expected from the ammonia decrease.

In batch test 5 (**Figure IV.12**) done on sludge harvested from the AE reactor of the membrane system, the ammonia decreases sharply from 27 to 5 $mgNH_3$-N/ℓ over 24 hours and there is a high concentration of nitrate produced (19 $mgNO_3$-N/ℓ). In addition, the OU is more than 85 % of that expected from the ammonia decrease.

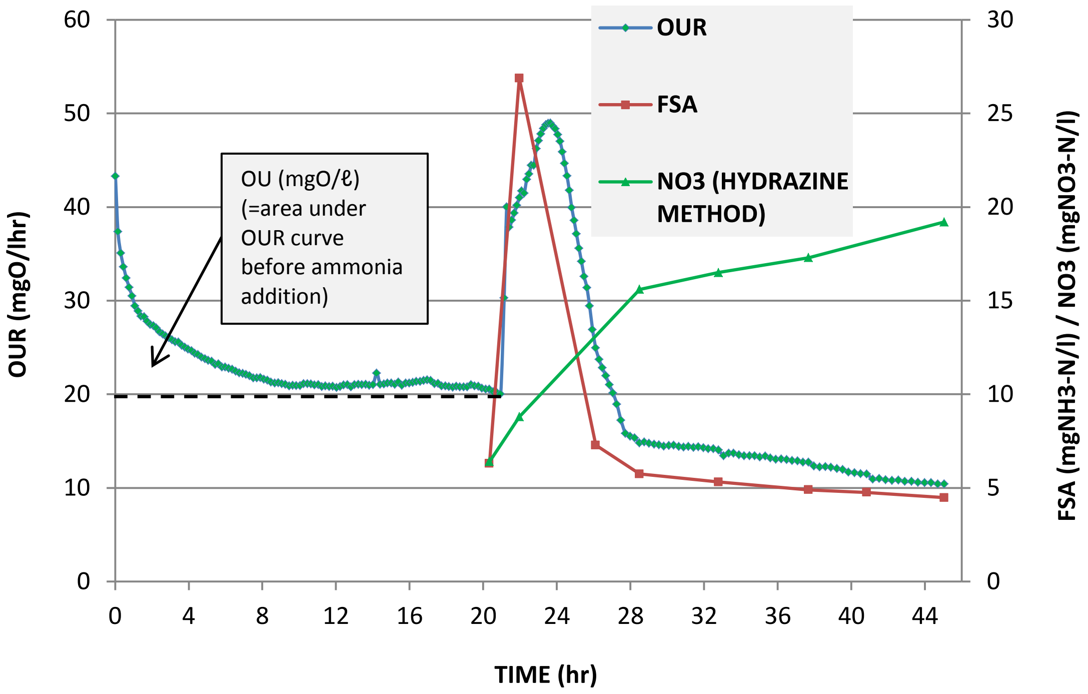


Figure IV.12: OUR, FSA and NO_3 results from batch test 5 (Feb 24, 2010) done on sludge harvested from the membrane unit which, is a fully nitrifying system with the UCT configuration but twice the VSS (TSS) concentration of the UCT system and receiving normal (real) WW.

These batch tests confirm that there were no autotrophic nitrifying organisms (ANOs) in the UCT system, confirming that nitrification could not have taken place in it. All five batch tests on the UCT system yielded this result. Why the OHOs would experience an effluent FSA concentration of ~ 3.5 mgN/ℓ with no nitrification as an ammonia deficient condition is unclear. Perhaps the OHOs have a much higher half saturation coefficient (K_S) for ammonia than ANOs, which would explain why nitrifying AS systems have much lower effluent FSA concentration than FSA limited non nitrifying systems.

Calculating the unutilized biodegradable particulate organics (BPO)

As **Figures IV.11 and IV.12** indicate, the decrease in OUR over approximately 20 hours priorto the addition of ammonia to the batch test reactor wasrequired to establish endogenous conditions within the mixed liquor. From this decrease in OUR, it is possible to estimate the unutilized influent biodegradable COD ($COD_{unutilized}$ = BPO + BSO) from which the effluent BSO (calculatedfrom **Table IV.1** and **Table IV.6** the latter of whichgivesthe results of the aerobic batch tests done on the effluent) can be subtracted to yield the influent unutilized BPO in the AEML of the UCT system. The equation for calculating the influent COD unutilized is as follows:

$$COD_{unutilized} = OU/(1-f_{CV}*Y_H) \qquad \textbf{[Eq. IV.3]}$$

Where *OU* is the *oxygen utilized* (mgO/ℓ) which is equal to the area under the OUR graph before the addition of ammonium chloride (= period of endogenous conditions) minus the OU for endogenous respiration (= the area under the horizontal line at the average low OU before the ammonia addition); f_{CV} is the*COD/VSS* ratio of the AEML at the timeof the batch test and Y_H is the *biomass yield* which is equal to *0.45 mg VSS/mgCOD.***Table IV.4** gives values of the influent unutilized COD for each nitrification batch test done on the AEML of the UCT system and the membrane system (batch test 5).

Table IV.4: Results of influent COD unutilized from the nitrification batch tests done on the AEML of the UCT system and the membrane system (batch test 5).

PARAMETER	**Date**	**Influent $COD_{unutilized}$**
		BSO + BPO (mg COD/ℓ)
BT[1] 1	*4-Oct-2009*	*38.2*
BT 2	*2-Nov-2009*	*32.8*
BT 3	*18-Jan-2010*	*82.7*
BT 4	*2-Feb-2010*	*250.3*
BT 5	*24-Feb-2010*	*142.6*
BT 6	*26-Mar-2010*	*167.6*

[1] Nitrification *Batch Test*

Taking the average influent $COD_{unutilized}$(avg of batch tests 3, 4 & 6) and subtracting the effluent BSOyield an average influent $BPO_{unutilized}$ of 116.4 mg COD/ℓ. This is equal to 30 %of the total influent BPO (see **Table B.9** in **Appendix B**).Had the VSS of the influent grey and brown WW mix been measured, it would have been possible to calculate the COD/VSS (f_{CV}) and TKN/VSS (f_n) ratios of this influent WW mix and hence prove that these values were low enough to produce the lower than usual composite AEML f_{CV} (1.18 mgCOD/mgVSS) and f_n (0.093 mgN/mgVSS) measured.

In estimating the theoretical aerobic VSS (MLVSS), the typical real WW unbiodegradable particulate ($f_{S'up}$) COD fraction of 0.13 was used (see **Section 4.1.2.6. A**). However, anaverage$f_{S'up}$ of 0.21 was measured for the UCT system (see **Table IV.2**) which,included both influent UPO and influent unutilized BPO. Therefore, as a check, the difference of 0.21 and 0.13 (i.e. 0.08) should equate the ratio of *influent unutilized BPO/*S_{ti} (i.e. 116.4/1020.9, wherethe total influent COD S_{ti}can be read from **Table IV.1**). Doing this yields a 27 % difference between both values, which may be attributed to uncertainties in the experimental measurements. The same check can be done for the influent unbiodegradable soluble COD ($f_{S'us}$). The difference between measured $f_{S'us}$ (0.08, see **Table IV.2**) and theoretical $f_{S'us}$(0.05, see **Section 4.1.2.6. A**) yields a value 0.03 which is 40 % lower than the ratio of *influent unutilized BSO/*S_{ti}(where unutilized BSO is calculated from **Tables IV.1** and **IV.6**). The 40 % difference may be attributed to uncertainties in the experimental measurements.

Note: In calculating the average influent $COD_{unutilized}$, the average of batches 3, 4 and 6 only are considered to obtain a good representative figure for the unutilized BPO. These three batch tests were conducted towards the end of the experimental investigation i.e. closer to the time the aerobic batch tests were done on the effluent from the UCT system (and JHB system). The significant changes in influent $COD_{unutilized}$, from batch test 2 onwards, as seen in **Table IV.4** above, support the evidence of acclimatization problems for microorganisms present in the AS (OHOs and possibly ANOs) (see discussion in **Section 4.2.4**).

4.1.2.9 Alkalinity and SCFA measurements

The 5 pH point titration method was used to determine H_2CO_3**Alkalinity* (*mg* $CaCO_3$*/ℓ*) and the Short Chain Fatty Acids (SCFA in *mgAc/ℓ*) of the influent and the AEML activated sludge. The method is as described by Moosbrugger et al (1992). The Alkalinity measurement was done primarily to confirm the absence of nitrification in the system from the changes in measured Alkalinity between influent and effluent. Therefore, these tests, which are listed in **Table IV.5**, were not done on all the WW batches. From **Table IV.5** it can be seen that the influent and effluent Alk are virtually the same, indicating no loss of Alk due to nitrification (7.14 mgAlk/ℓ per $mgNH_3$-N nitrified + 3.57 mgAlk/ℓ per NO_3-N denitrified). This confirms no nitrification in the UCT system.

Table IV.5: Alkalinity and SCFAs results for the influent and the AEML of the UCT system.

	AvgInfluent		**Avg AEML**	
PAR	***ALK***	***SCFA***	***ALK***	***SCFA***
UNIT	***mg as $CaCO_3$/ℓ***	***mgCOD/ℓ***	***mg as $CaCO_3$/ℓ***	***mgCOD/ℓ***
B 8	*131.3*	*116.0*	*94.6*	*0.0*
B 9	*92.7*	*136.3*	*78.1*	*0.0*
B 10	*66.5*	*90.0*	*70.0*	*0.0*
B 11	*75.2*	*87.1*	*97.1*	*0.0*
B 12	*45.3*	*101.7*	*81.4*	*0.0*
B 13	*40.5*	*122.0*	*86.9*	*0.0*
B 16	*116.8*	*94.4*	*64.9*	*0.0*
Avg=	***81.2***	***106.8***	***81.8***	***0.0***

4.1.2.10 Aerobic batch tests results on the effluent of the UCT system

Aerobic batch tests were done on the filtered effluent from the UCT system (and JHB system) to measure the residual biodegradable soluble COD (S_{bse}), TKN (N_{obse}) and TP (P_{obse}) concentrations. The results of these tests are presented in **Table IV.6**below (see also **Appendix H**).

As can be deduced from **Table IV.6**, nearly 60 % of $S_{bse}$and 25 % of N_{obse} were not degraded in the AS but exited with the effluent possibly as a result of acclimatization problems for microorganisms (OHOs and possibly ANOs) to the influent grey and brown WW mix (see discussion in **Section 4.2.4**).

Table IV.6: Results of aerobic batch tests done on the filtered effluent from the UCT system

PARAMETER	**UCT System (20d SRT)**	
	BT[1]	**Effluent[2]**
S_{use} (mgCOD/ℓ)		*34.9*
TKN_{se} (mgN/ℓ)		*2.1*
FSA (mgN/ℓ)		*1.4*
TP_{se} (mgP/ℓ)		*1.6*
Ortho P (mgP/ℓ)		*1.5*
NO_3 (mgN/ℓ)		*0.7*

[1]0.45µm membrane filtered concentrations at the end of the batch test;[2]From **Table IV.1** or **Table IV.7**for the UCT system over the same WW batches as the JHB system.

4.1.3 Johannesburg system (JHB)

The results presented here are from the 154-day operation of the JHB system operated at 5 day SRT. The system was operated for 15 days (3 x SRT) before reaching steady state (**Figure IV.1**). During the operating period, 8 WW batches were fed. These batches each represent a SSP. Throughout the experiment, the JHB system was fed the same influent as the UCT system. Over the 8 WW batches (8 to 15) the rationale for operating the JHB system was to achieve (1) better P removal at the short SRT, without interference of nitrification (which was confirmed to not be taking place in the long SRT UCT system) and (2) smaller system volume due to the low SRT.

4.1.3.1 Nitrogen (N) mass balance

The N mass balance compares the exiting N fluxes via the effluent, waste sludge stream and nitrate denitrified (from a nitrate balance over the AX and AN reactors) with the N flux entering the system via the influent TKN. The mass balances are calculated to determine the accuracy and reliability of the response data. The N balance in the range 100 ± 10% was considered acceptable and indicated reliable data. For further details on the N mass balance, see **Section 4.1.2.1.**

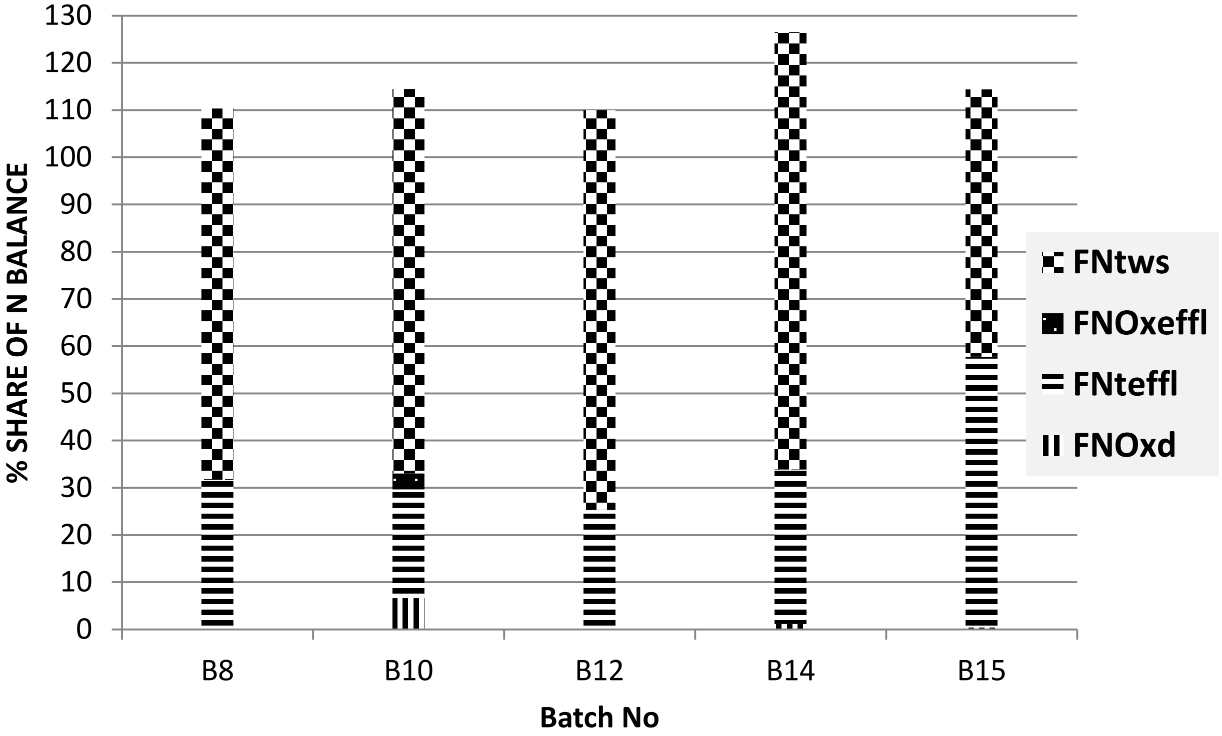


Figure IV.13: Graphical representation of the percentage N mass balance for the steady state WW batches for the JHB system. Note that batches 9, 11 and 13 which are not shown, are WW batches for which only the effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured. Batch 16 was rejected as non-representative of SSP performance.

From **Figure IV.13** N mass balance in the range 100 - 127 %were obtained giving an average mass balance of 115 % for all WW batches. This average is 33 % higher than that obtained for the UCT system over the same WW batches. The higher than 100 % average N balance implies that more N was accounted for exiting the system than entering. In fact, of the total N entering the system, theaverage FN_{teffl} (effluent N) share of the N balance is 34 %. The largest share of the N balance is the nitrogen in the WAS (FN_{tws}) at 79 %while the share of the N denitrified (FNO_{Xd}) is insignificant being equal to 2 %. The percentage sharesfor the UCT system over the same WW batches are 16 % for FN_{teffl}, 63 % for FN_{tws} and 2 % for FNO_{xd}.

4.1.3.2 COD mass balance

The COD balance was calculated by comparing the COD fluxes exiting via the effluent, waste sludge stream and oxygen utilized in the AE reactor (corrected for nitrification) with the COD flux entering the system via the influent COD. The mass balances are calculated to determine the accuracy and reliability of the response data. Mass balances in the range 90 to 110% are considered acceptable and indicate reliable data. **Section 4.1.2.2** contains further details on the COD balance calculation.

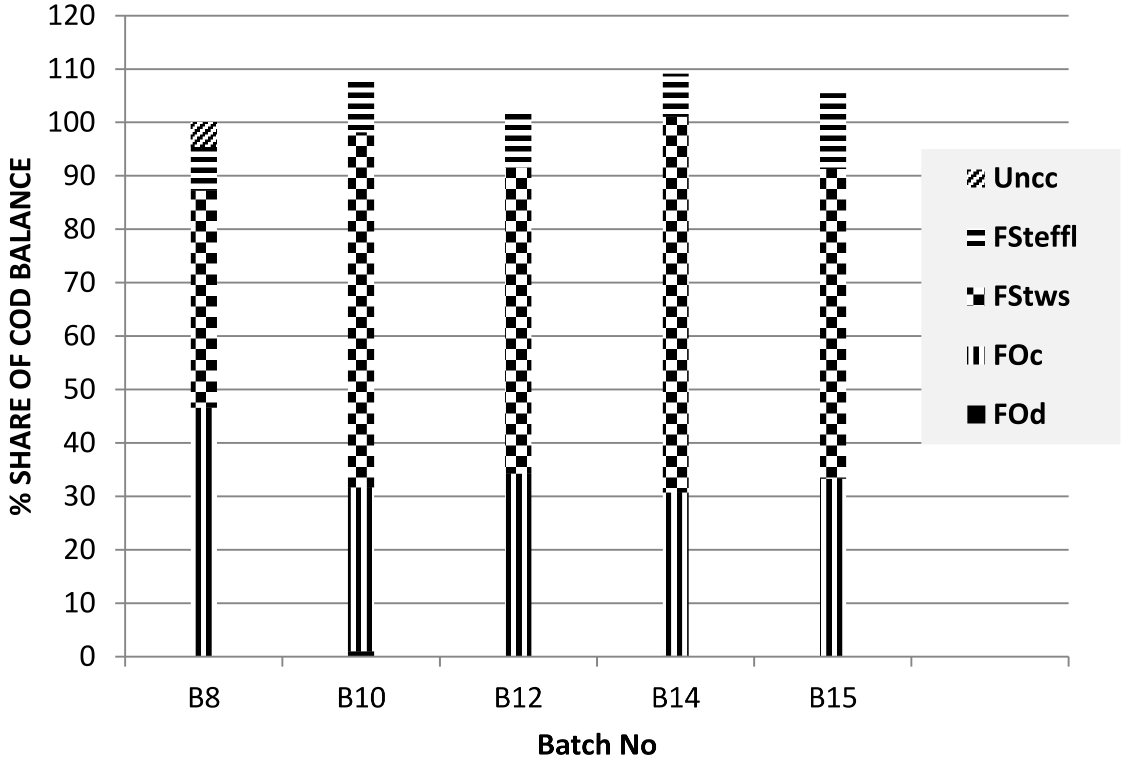


Figure IV.14: Graphical representation of the percentage COD mass balance for the steady state WW batches for the JHB system. Batches 9, 11 and 13 are not presented because only the effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured. Batch 16 was rejected as non-representative of SSP performance.

From **Figure IV.14** COD mass balance in the range 95 - 109 % were obtained giving an average mass balance of 104 % for all WW batches. This average is 3 % lower than that obtained for the UCT system over the same WW batches. Of the total COD entering the system 10 % exits as FS_{teffl}, 35 % as FO_c and 59 % as FS_{tws}. These compare with 10 %, 57 % and 39 % for the UCT system over the same WW batches. The lower SRT of 5 days increased the microorganisms take up of COD for growth (FS_{tws}) by 20%.

4.1.3.3 JHB system COD, N and P removal performance

The overall average influent and effluent COD, TKN, FSA and TP concentrations as well as the respective total removal efficiencies are listed in **Table IV.7**. The total COD, TKN and P removals were low at 80 %, 58 % and 53 % respectively compared with 88 %, 85 % and 82 % for the UCT system over the same WW batches. The average effluent NO_2; NO_3 and Ortho P concentrations were higher than those obtained for the UCT system but still acceptable at 0.3 $mgNO_2$-N/ℓ; 0.4 $mgNO_3$-N/ℓ and 8.5 $mgPO_4$-P/ℓ respectively when compared with the general limits specified by the National Water Act (Act 36 of 1998) for plants discharging up to 2Mℓ/d of effluent in any water resource. The JHB system effluent values were lower than these specified limits by 98 %; 98 % and 15 % respectively. Unexpectedly, all other effluent concentrations i.e. unbiodegradable soluble COD, TKN, FSA, TP, OrthoP and total solids averaged at values much higher than obtained for the UCT system and therefore also higher than the general limits. At the shorter sludge age, the JHB system was expected to have higher concentrations of N and P required for sludge production and consequently lower effluent TKN, FSA, TP and OrthoP concentrations than the UCT system, but the effluent COD, FSA and TSS concentrations were high. Also, they were higher than the specified limits by 42 %, 80 % and 65 % respectively. Aerobic batch tests done on the effluent from the JHB system with WAS harvested from an EBPR system fed real WW from Mitchell's Plain WWTP, revealed that the 0.45 μm membrane filtered effluent COD of 125.1 contained 70 % biodegradable COD (S_{bse}). The same effluent also contained 95 % organic N biodegradable soluble (N_{obse}). This soluble COD (and N) exited in the effluent probably due to constant biomass adaptation to a new WW batch because the WW source was from a very specific and small population group with widely varying diet resulting in widely varying organic constituents between WW batches. The total TSS in the effluent averaged at 70.5 mgTSS/ℓ which was approximately 60 % higher than that obtained for the UCT system over the same WW batches (see **Table IV.7**) and also higher than the general limts.This high TSS (and unfiltered COD) is also due to poor activated sludge development and flocculation.The far greater diversity of OHOs from the real WW EBPR system were able to utilize the biodegradable soluble organics (BSO) exiting the JHB system, which the low diversity and constantly adapting biomass in the JHB system were not able to utilize. The shorter sludge age of the JHB system, with the higher biomass turnover rate than the UCT system, exacerbated this phenomenon, resulting also in reduced utilization of slowly biodegradable particulate organics (BPO), and hence lower N and P concentrations for sludge production. Most of the JHB effluent concentrations are high and do not represent what had been expected from a scenario of 100 % urine diversion and complete utilization of influent biodegradable organics from the grey and brown WW.

Table IV.7: Overall average influent and effluent COD, TKN, FSA and TP concentrations and total COD, N and P removal efficiencies for the JHB system at 5d sludge age and for the UCT system at 20d SRT over the same WW batches.

Parameter	Unit	JHB SYSTEM			UCT SYSTEM	
		Influent	**Effluent**	**Efficiency**	**Effluent**	**Efficieny**
COD	**mg COD/ℓ**	*1014.0*	*200.2*[1] *(125.1*[2]*)*	*80%*	*117.3*[1] *(89.2*[2]*)*	*88%*
TKN	**mg N/ℓ**	*59.6*	*25.7*[1] *(19.0*[2]*)*	*58%*	*9.1*[1] *(6.0*[2]*)*	*85%*
FSA	**mg NH_3-N /ℓ**	*30.8*	*15.1*	*54%*	*4.8*	*83%*
TP	**mgP/ℓ**	*21.5*	*10.2*[1]*(8.5*[2]*)*	*53%*	*3.9*[1]*(3.2*[2]*)*	*82 %*
Ortho P	**mg PO_4-P/ℓ**	—	*8.5*	—	*3.2*	—
NO_2/NO_3	**mg NO_2-(NO_3-) N/ℓ**	*0.0*	*0.3 / 0.4*	*n/a*	*0.1 / 0.2*	*n/a*
SS	**mg SS/ℓ**	—	*70.5*	*n/a*	*29.8*	*n/a*
pH	**n/a**	*5.5 - 6.5*	*6.0 - 7.5*	*n/a*	*6.0 – 7.5*	*n/a*

[1]Unfiltered sample; [2] 0.45 µm membrane filtered sample; values represent the averages for B8, B10, B12, B14 & B15 which represented SSP.

4.1.3.4 Aerobic mixed liquor solids (AETSS and AEVSS) concentrations

The JHB system was operated for 15 days (3 x SRT) before detailed sampling and measurements commenced, to allow it to reach steady state.

Figure IV.15 shows the variations in VSS (TSS) in the AE reactor of the JHB system. Despite the periods of low and high concentrations fluctuation (C'), the VSS and TSS concentrations over a long term period ranged between 2000 – 3500 mg SS/ℓ. The VSS and TSS averaged at 2400 mgVSS/ℓ and 2700 mgTSS/ℓ respectively. These measured concentrations are higher than the model predicted values of 2100 mgVSS/ℓ and 2650 mgTSS/ℓ calculated by the steady state and kinetic NDEBPR BNR system models (Wentzel et al., 1990; 1992). When BPO is not completely utilized in the system, higher VSS concentration (and lower oxygen utilization) than steady state model predictions (which assume complete utilization of BPO) are expected. This probably took place to varying degrees during the investigation resulting in wide fluctuation in VSS (and TSS) concentrations.

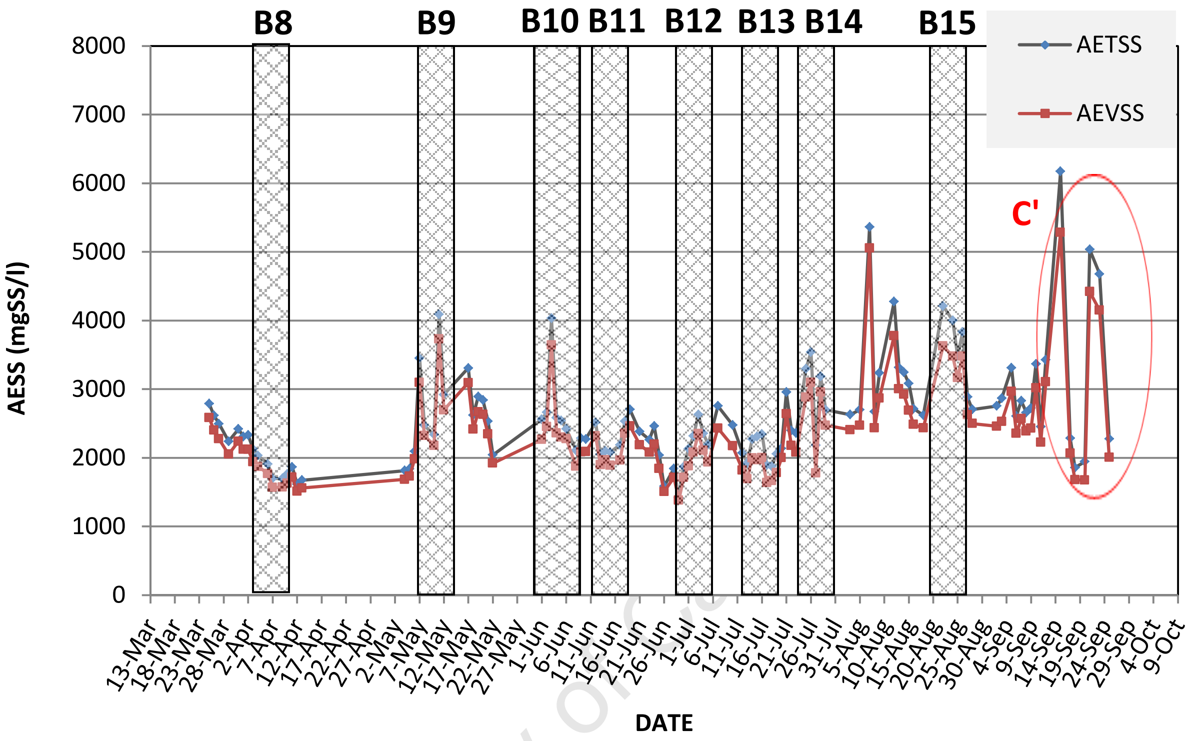


Figure IV.15: Variations of aerobic reactor solids VSS (AEVSS) and TSS (AETSS) for the JHB system, over the entire period of measurement (Mar 2010 – Sept 2010). The circled area *C'* indicates the period of significant SS fluctuation, see discussion in **Section 4.2.1.4**.

The trend in VSS variation – in **Figure IV.15 -** tracks closely that in TSS, with the difference (ISS) being roughly constant for the entire period of measurement, notwithstanding the periods of solids fluctuation. The steady-state VSS/TSS averaged at 0.903 mgVSS/mgTSS with sample standard deviation (SSD) of 0.018 compared with 0.885 (SSD=0.017) obtained for the UCT system over the same WW batches. This value of 0.903 is much higher than expected considering that the EBPR builds up considerable ISS through the storage of polyP and associated counter-ions, (Ekama and Wentzel, 2004). The high VSS/TSS ratio therefore indicates that EBPR was not well developed in the JHB system. It also is a sign that the influent BPO is not completely utilized because OHOs (now not grown to the same mass) make a contribution to the reactor ISS concentration decreasing the VSS/TSS ratio (Ekama and Wentzel, 2004).

4.1.3.5 Diluted sludge volume index (DSVI)

The Diluted Sludge Volume Index (DSVI) averaged at 122 mℓ/gTSSfor the entire experimental period. From **Figure IV.16**, the DSVI varied mostly between 75 – 150 mℓ/gTSS with period D' described as one of significant fluctuation which was caused by fluctuation in TSS concentrations. This fluctuation in TSS concentrations affecting the DSVI is validated by the trend of the DSVI curve that is not similar to the trend of the SV_{30} curve over period D'. Therefore, period D' was identified as a non-steady state period. Its TSS concentration fluctuation may have been induced by factors external to the AS as explained in **Section 4.2.2.4**. When the DSVI shows such significant variations, SST (clarifier) failure can become an operational problem at full-scale BNR WWTPs - if long-term stability is required. However, filamentous organism sludge bulking is not expected because the SRT was only 5 days (see **Section 4.1.2.5**). Nonetheless, microscopic examination should have been done on the AE sludge from the JHB system especially because of the particularity of the feed WW (grey and brown water mix). However, with the low utilization of biodegradable organics (BSO and BPO), the mixed liquor is not typical anyway of that of a real WWTP treating a grey and brown water mix where this is unlikely to take place.

Comparison with the UCT system over the same period (Mar – Oct 2010) showed similar fluctuation in the DSVI over period D (D') thereby giving support to the assumption of externally induced TSS fluctuation (varying degree of utilization of influent BPO and BSO organics).

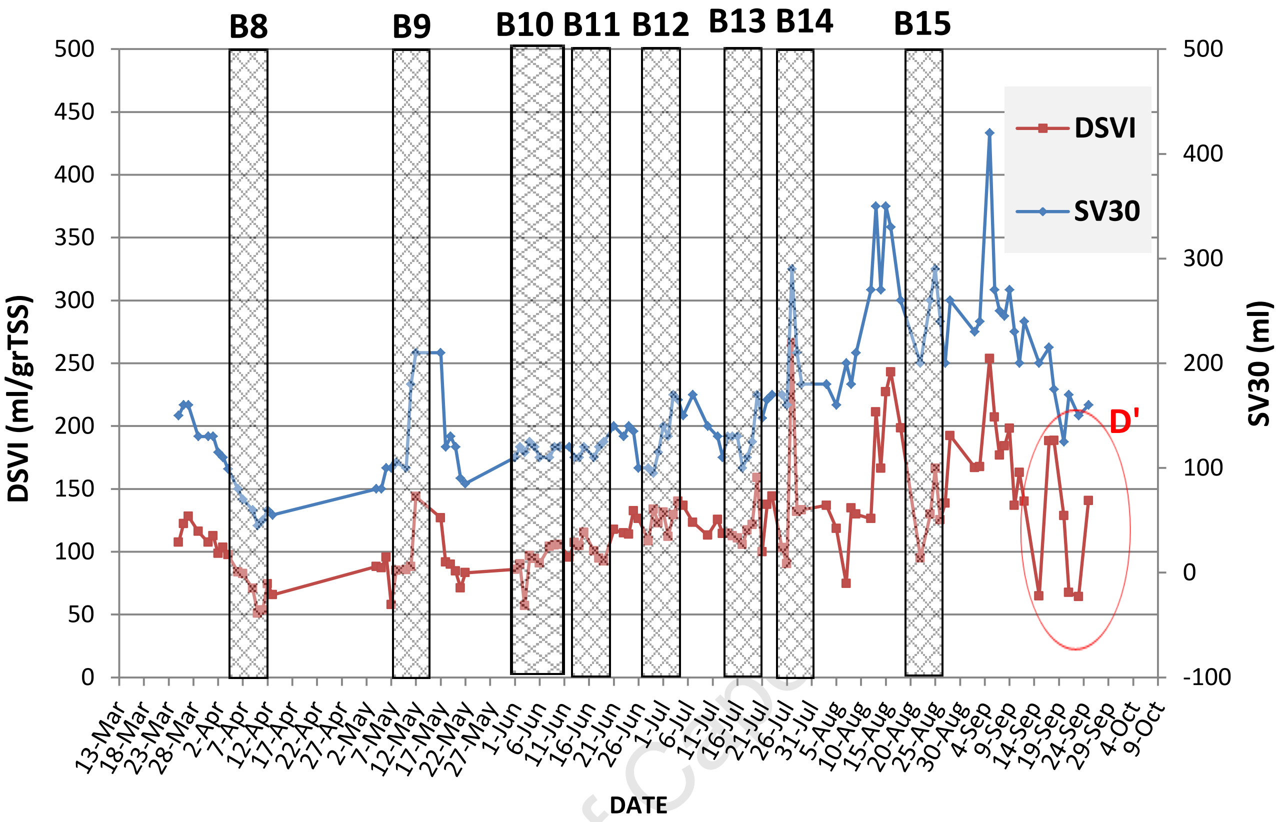


Figure IV.16: DSVI and SV_{30} variations on sludge harvested from the AE reactor of the JHB system, over the entire period of measurement (Mar – Sept 2010). The circled area *D'* indicates the period of significant fluctuation caused by TSS concentration fluctuation.

4.1.3.6 Calculating the influent wastewater (WW) and aerobic reactor mixed liquor (AEML) characteristicsfor the JHB system

Table IV.8 lists the influent and AEML Characteristics for each WW batch as well as the overall average for the experimental investigation.

Table IV.8: Influent WW and AEML Characteristics for the batches of WW over the SSP for the JHB system at 5d sludge age.

BATCH No	**Influent Characteristics**					**AEML Characteristics**			
	TKN/COD	**TP/COD**	**$f_{S'us}$[1]**	**$f_{S'up}$[1]**	**RBCOD[1]**	**VSS/TSS(f_i)**	**COD/VSS (f_{CV})**	**TKN/VSS (f_n)**	**TP/VSS (f_p)**
B8	*0.057*	*0.022*	*0.10*	*0.20*	*0.070*	*0.93*	*1.15*	*0.124*	*0.044*
B9	*0.045*	*0.010*	*0.10*	*n/a*	*n/a*	*0.93*	*n/a*	*n/a*	*n/a*
B10	*0.051*	*0.018*	*0.12*	*0.41*	*0.358*	*0.91*	*1.66*	*0.102*	*0.035*
B11	*0.050*	*0.015*	*0.10*	*n/a*	*n/a*	*0.93*	*n/a*	*n/a*	*n/a*
B12	*0.057*	*0.023*	*0.13*	*0.26*	*0.191*	*0.89*	*1.18*	*0.102*	*0.021*
B13	*0.062*	*0.029*	*0.12*	*n/a*	*n/a*	*0.86*	*n/a*	*n/a*	*n/a*
B14	*0.054*	*0.024*	*0.10*	*0.55*	*0.160*	*0.88*	*1.22*	*0.087*	*0.025*
B15	*0.077*	*0.020*	*0.17*	*0.42*	*0.066*	*0.90*	*1.03*	*0.071*	*0.016*
B16	*0.057*	*0.020*	*0.18*	*0.55*	*0.071*	*0.90*	*1.16*	*0.080*	*0.025*
Avg=	***0.060***	***0.021***	***0.10***	***0.37***	***0.169***	***0.90***	***1.25***	***0.097***	***0.030***

[1] fraction of the total influent COD, *Sti;* n/a designates WW batches for which only effluent concentrations, OUR and solids (TSS, VSS & ISS) were measured; the average includes B8, 10, 12, 14 & B15 which were representative of steady-state period (SSP).

A. *Unbiodegradable soluble $f_{S'us}$and particulate $f_{S'up}$*

The procedure for calculating the $f_{S'us}$ fraction for the JHB system activated sludge is as presented in **Section 4.1.2.6** and was the same as applied to the UCT system results.

The average experimental aerobic MLVSS of 2400 mg VSS/ℓ was higher than the predicted value of 2100 mg VSS/ℓ based on typical influent soluble (S_{us}; $f_{S'us}$) and particulate unbiodegradable organics (S_{up}; $f_{S'up}$) COD fractions of $f_{S'us}$ = 0.05 and $f_{S'up}$ = 0.13 for real unsettled WW. The higher VSS indicates that the grey and brown WW mix had a higher $f_{S'up}$ than 0.13. The determined $f_{S'us}$ and $f_{S'up}$ fractions averaged at $f_{S'us}$ = 0.13 (SSD=0.026) and $f_{S'up}$ =0.37 (SSD=0.138) which are 61 % and 65 % respectively higher than $f_{S'us}$ = 0.05 and $f_{S'up}$ = 0.13 or 31 % and 24 % higher than those values obtained for the UCT system ($f_{S'us}$ = 0.09 (SSD=0.019) and $f_{S'up}$ = 0.28 (SSD=0.043)) over the same WW batches. The $f_{S'us}$ and $f_{S'up}$ values of 0.13 and 0.37 are far outside the ranges (0.04 to 0.10) and (0.07 to 0.20) respectively of typical values expected for real domestic WW in SA (WRC, 1984 as reported by Ramphao, 2004:5.45, 6.15).

Such high $f_{S'us}$ and $f_{S'up}$ fractions indicate a high residual (non utilized) BSO in effluent and BPO in the mixed liquor. This high unutilized BPO also decreases the mixed liquor f_{CV} and f_n ratios because the BPO has lower f_{CV} and f_n than the AS. The $f_{S'us}$ fraction calculated here is based on the measured filtered effluent COD concentrations and ignores the fact that most of this was dissolved biodegradable COD exiting in the effluent that was measured to be 70 % of the filtered effluent COD (see **Section 4.1.3.3**).

B. COD/VSS ratio f_{cv} (mgCOD/mgVSS)

The procedure for calculating the COD/VSS ratio is as explained above in **Section 4.1.2.6**. The average COD/VSS ratio obtained was 1.25 with a SSD of 0.243. This is approximately 13 % higher than the value obtained for the UCT system over the same WW batches (1.09, SSS=0.090) and 12 % lower than the theoretical value of 1.42 derived from the commonly accepted VSS composition formula $C_5H_7NO_2$ (WRC, 1984). The value of 1.25 is just below the lower limit of the range 1.3 – 1.5 mgCOD/mgVSS obtained from extensive experimental research in the UCT Water Reasearch Laboratory – with an average of 1.48 commonly accepted. The fact that the COD balances were between 95 and 109 % (average 100 %) and that most of the COD exits the system via the waste sludge (2/3 rds) at the short sludge age means that the measured COD/VSS ratio of 1.25 is accurate. The low f_{CV} ratio indicates that there is a significant concentration of unutilized BPO with low f_{CV} ratio in the mixed liquor.

C. TKN/VSS ratio f_n(mgN/mgVSS)

In the experimental investigation, the TKN/VSS ratio of the JHB system mixed liquor had an average value of 0.097 with SSD of 0.020 (see **Table IV.8**). This is nearly 5 % higher than the value obtained for the UCT system (0.092, SSD=0.017 over the same WW batches) and yielded a much better N balance of 109 to 126 % (average of 115 %) than the UCT system over the same WW batches (see **Section 4.1.3.1**). With the absence of nitrification and denitrification, the slightly higher than 100 % N balance, indicates that the measured f_n ratio is reliable but should be somewhat lower for 100 % N balance. The 115 % N balance is based on *total* effluent nitrogen N_{teffl} that includes N contained in all particulate solids escaping in the effluent. The N balance based on 0.45µm filtered effluent nitrogen ranged between 100 and 114 % (average of 106 %). Why the measured f_n of the UCT system yielded such a poor N balance (53 – 76 %) is not clear.

4.1.3.7 Excess biological phosphorus removal behaviour (EBPR) across the JHB system

The theory for P removal was explained in **Section 4.1.2.7**. To protect the P removal from the possibility of nitrate entering the AN reactor in the event nitrification takes place in the JHB system, an AX reactor was placed in the underflow recycle flow, the outflow of which entered the AN reactor. Thus, no nitrate was recycled to the AN reactor. Because not all the BSO was utilized in the system, it could not be accepted that all the measured influent RBCOD was converted to volatile fatty acids (VFA) and taken up by the phosphorus accumulating organisms (PAOs) in the AN reactor. In addition, because of this the EBPR models developed for real WW systems could not be used to calculate the BSO converted to VFAs and taken up by PAOs. **Table IV.8** lists the influent WW and aerobic reactor mixed liquor characteristics. The measured P mass changes in each reactor calculated from a P mass balance over each reactor (divided by the influent flow of 15 ℓ/d) are listed in **Table IV.9.** Also calculated for the JHB system was the P mass balance which compares the exiting P flux via the effluent and waste flow with the system influent P flux (**Figure IV.17**). The P unaccounted for ("Uncc") is the P deficit to balance the P at 100%.

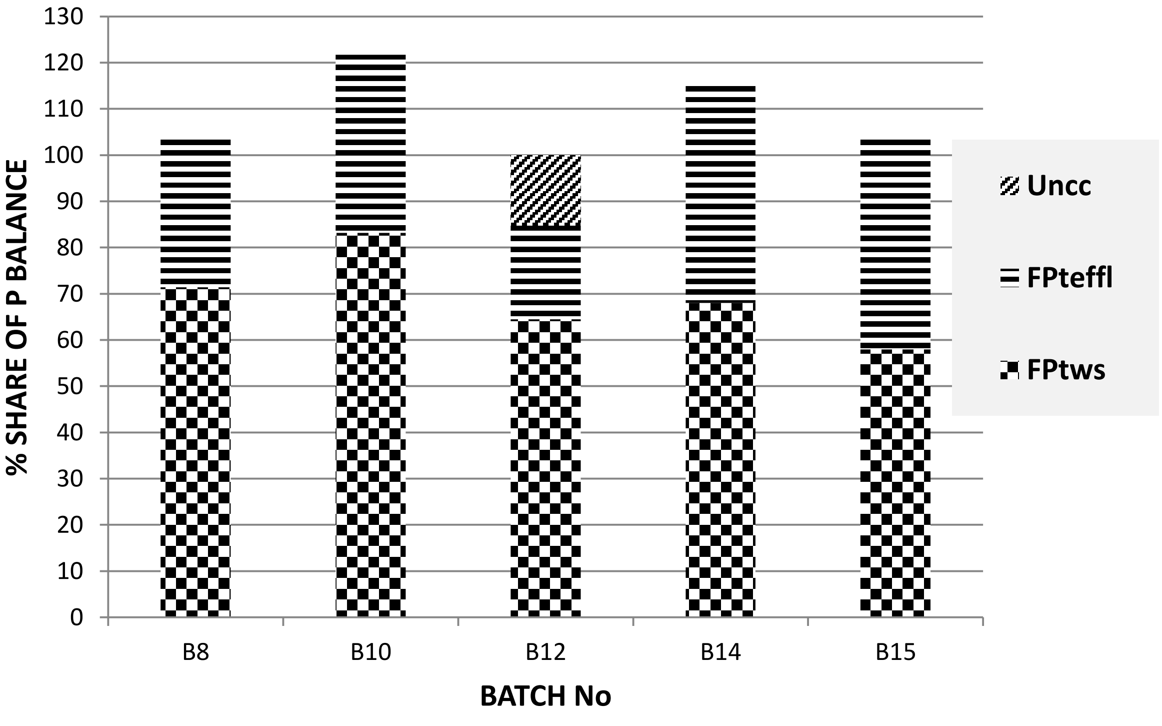


Figure IV.17: Graphical representation of the percentage P mass balance for the steady state WW batches for the JHB system. Batches 9,11 and 13 which are not shown, are WW batches for which only the effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured. Batch 16 was rejected as non-representative of SSP performance.

- The overall P balance, P removal *[(Influent TP – effluent TP)/influent TP]* and P removaℓ/mg RBCOD were 106 %, 53 % and 0.093 (RBCOD = 0.18 of total influent COD), compared with 63 %, 82 % P removal and 0.080 (RBCOD = 0.22 of total influent COD) for the UCT system over the same WW batches; The parameter P removal/influent RBCOD arose because with real WW most of the influent RBCOD was converted to VFA and taken up by PAOs (Wentzel et al., 1985) and so the difference between filtered influent and effluent COD is a reasonable approximation for the influent RBCOD concentration. In this investigation, neither the P removal/mg RBCOD nor the measurement method to approximate the influent RBCOD concentration are valid due to the incomplete utilization of BSO, not only in the AN reactor but also in the AE reactor. The P release and P uptake are therefore better measuresfor observing EBPR in this investigation.

- The sum of P release in the anaerobic and anoxic (2^{nd} anaerobic actually) reactors was 11.5 mgP/ℓ of which 1.8 (16 %) was P release in the AX reactor. Unlike the UCT system – over the same WW batches - the situation of P release in the AN and AX reactors of the JHB system did fluctuate from time to time during the period of measurement where P uptake was observed in the AN reactor for batches 8 (B8) and 15 (B15). As expected and like the UCT system, the JHB system showed consistent P uptake exclusively in the AE reactor for the entire period of measurement (**Table IV.9**). The P removal at 11.4 mgP/ℓ for 1000 mgCOD/ℓ influent is low (only 57 %) of that usually observed (± 20 mgP/ℓ) with real wastewater. The average P removal for the UCT system over the same WW batches was 17.7 mgP/ℓ for 1000 mgCOD/ℓ influent. The lower P removal in the JHB system is due to greater unutilized BPO and BSO resulting in a lower OHO concentration, reduced hydrolysis of BSO to VFA in the AN reactor, lower P release, lower P uptake in the AE reactor, lower PAO concentration and hence lower P removal.

Table IV.9: P mass changes – i.e. P uptake & P release - across each reactor for the WW batches over the SSP for the JHB system at 5d sludge age.

BATCH No	AN reactor		AX reactor		AE reactor	
	P_{uptake}	$P_{release}$	P_{uptake}	$P_{release}$	P_{uptake}	$P_{release}$
	mgP/ℓ influent	**mgP/ℓ influent**	**mgP/ℓ influent**	**mgP/ℓ influent**	**mgP/ℓ influent**	**mgP/ℓ influent**
B8	*6.9*	*0.0*	*0.2*	*0.0*	*8.4*	*0.0*
B9	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B10	*0.0*	*7.6*	*0.2*	*0.0*	*17.5*	*0.0*
B11	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B12	*0.0*	*26.0*	*0.0*	*2.7*	*46.8*	*0.0*
B13	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
B14	*0.0*	*15.0*	*0.0*	*6.5*	*34.6*	*0.0*
B15	*9.6*	*0.0*	*0.0*	*0.0*	*2.9*	*0.0*
B16	*0.0*	*6.3*	*0.0*	*2.5*	*25.6*	*0.0*
Avg=	**3.3**	**9.7**	**0.1**	**1.8**	**22.1**	**0.0**

n/a designates WW batches for which only effluent concentrations, OUR and solids (TSS, VSS and ISS) were measured; the average includes B8, 10, 12, 14 & B15 which were representative of SSP.

4.1.3.8 Nitrification batch tests and unutilized influent biodegradable particulate organics (BPO) in the JHB system

The rationale for operating the JHB system was to achieve, among other things, better P removal at the short SRT of 5 days, without interference of nitrification (which was confirmed to not be taking place in the long SRT UCT system). Therefore, it was deemed unnecessary to conduct nitrification batch tests. However, had this been done,it could have been possible to determine the unutilized influent BPO in the JHB system from the results of such tests, as explained in **Section 4.1.2.8** on the UCT system.Nonetheless, it is possible to confirm the presence of influent BPO in the AEML of the JHB system by analysis of the graph of VSS and OUR variations over time. Periods of low OUR align with high VSS as is shown in **Figure IV.18**. The higher the non utilized BPO, the higher the VSS (due to enmeshed BPO) and the lower the OUR (BPO not utilized for growth). Comparing **Figure IV.18** and

IV.6 suggests further that the JHB system contained a higher concentration of unutilized influent BPO than the UCT system, which is expected at the shorter SRT.

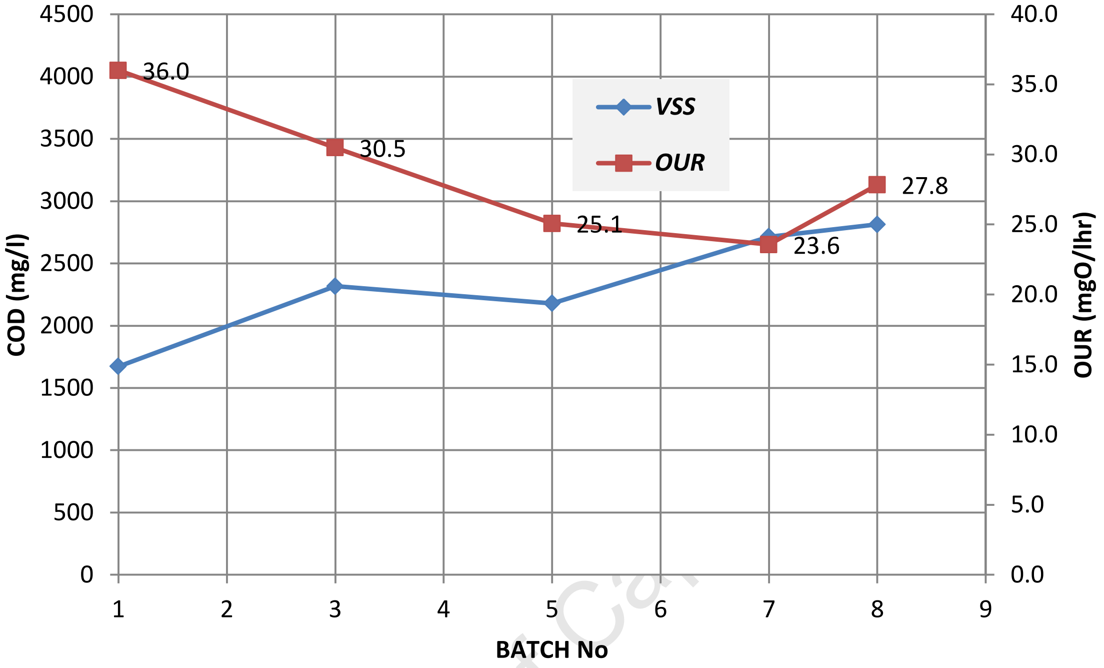


Figure IV.18: AE VSS and OUR variations for the WW batches of the JHB system. The two curves are mirror images of each other thereby providing evidence of the presence of unutilized BPO in the AEML of the system.

4.1.3.9 Alkalinity and SCFA measurements

The 5 pH point titration method was used to determine H_2CO_3**Alkalinity* (*mgCaCO$_3$/ℓ*) and the Short Chain Fatty Acids (SCFA in *mgAc/ℓ*) of the influent and the AEMLAS. The method is as described by Moosbrugger et al(1992). From **Table IV.10** it can be seen that the influent and effluent Alk are virtually the same. The loss of Alk due to nitrification (7.14 mgAlk/ℓ per mgNH_3-N nitrified + 3.57 mgAlk/ℓ per NO_3-N denitrified) was not expected in the JHB system without nitrification. Also, given that no nitrification was confirmed in the long SRT UCT system, *no nitrification* certainly would be expected at the much shorter 5d sludge age.

Table IV.10: Alkalinity as $CaCO_3$ and SCFAs concentrations across the JHB system.

	AvgInfluent		**Avg AEML**	
PAR	***ALK***	***SCFA***	***ALK***	***SCFA***
UNIT	***mg as $CaCO_3$/ℓ***	***mg COD/ℓ***	***mg as $CaCO_3$/ℓ***	***mg COD/ℓ***
B 2	*84.9*	*86.5*	*94.4*	*0.0*
B 3	*111.5*	*145.4*	*83.7*	*0.7*
B 4	*45.3*	*101.7*	*104.6*	*0.0*
B 5	*62.6*	*92.8*	*79.2*	*3.1*
B 7	*33.1*	*128.2*	*45.8*	*2.9*
B 8	*241.5*	*43.1*	*170.8*	*0.0*
B 9	*77.2*	*110.1*	*58.7*	*0.0*
Avg=	***96.5***	***99.6***	***96.4***	***1.3***

Average includes B1, 3, 5, 7 & B8 which were representative of SSP.

4.1.3.10 Results of aerobic batch tests on the effluent of the JHB system

Aerobic batch tests were done on the filtered effluent from the JHB system to measure the residual biodegradable soluble COD (S_{bse}), N (N_{obse}) and P (P_{obse}) concentrations. The results of these tests are presented in **Table IV.11**below (see also **Appendix H**).

Table IV.11: Results of aerobic batch tests done on the filtered effluent from the JHB system. Concentrations measured after 24-hour aeration with Membrane UCT system sludge fed real WW.

PARAMETER	JHB System (5d SRT)
	BT[1] Effluent[2]
S_{use} (mgCOD/ℓ)	*36.6*
TKN_{se} (mgN/ℓ)	*4.8*
FSA (mgN/ℓ)	*4.6*
TP_{se} (mgP/ℓ)	*1.3*
Ortho P (mgP/ℓ)	*1.3*
NO_3 (mgN/ℓ)	0.7

[1] 0.45µm membrane filtered concentrations at the end of the batch test; [2] From **Table IV.7**

As can be deduced from **Tables IV.7** and **IV.11**, nearly 70 % of S_{bse} and 95 % N_{obse} were not degraded in the AS of the JHB system but exited with the effluent possibly as a result of acclimatization problems for microorganisms (OHOs and possibly ANOs) to the influent grey and brown WW mix. The fact that microorganisms could not adapt quickly enough to the characteristics of the influent WW was aggravated by the much shorter sludge age of the JHB system (see discussion in **Section 4.2.4**).

4.2 DISCUSSION ON THE RESULTS OF THE BIOLOGICAL TREATMENT OF GREY-BROWN WATER MIX

The discussion of the experimental results is framed in light of the key questions raised at the beginning of the report namely:

1. With nitrification being the BNRAS size governing bioprocess via the sludge age, will this still be required with WW comprising only brown and grey water?
2. With a significantly reduced P load, will the effluent P concentration also decrease and to what value?
3. With eutrophication prevention requiring ever decreasing effluent N and P concentrations, e.g. 0.1 mgP/ℓ, is achieving such limits related to the N and P loads or by other factors that set the limits of the BNRAS technology?
4. What will be the TKN/COD and TP/COD ratios of urine separated (grey and brown) municipal WW?

In addressing these issues, cognizance needs to be taken of the observation that the utilization of influent BSO and BPO was not complete, which significantly affected the performance of these systems and the measured mixed liquors and effluent concentrations. This effect was far greater in the 5d JHB system than in the 20d UCT system.

4.2.1 Discussion on the performance of the NDBEPR UCT system

4.2.1.1 Absence of nitrification

Six observations pointed to the absence of ND in the UCT system, viz. (1) negligible concentrations of nitrate (NO_3) and nitrite (NO_2) in the AE reactor and effluent; (2) the measured OUR, uncorrected for ND, yielded a good (>90%) COD mass balance; (3) low N content of the AS (f_n = 0.093 mgN/mgVSS); (4) no nitrate generation in nitrification batch tests on sludge harvested from the system; (5) No decrease in Alkalinity which, would have otherwise indicated that ammonia was nitrified and 6) P release in the "anoxic" (actually anaerobic due to the zero nitrate recycled to it). Each of these observations is briefly discussed below.

i. Low aerobic reactor and effluent nitrite (NO_2) and nitrate (NO_3)

Provided the clarifier contains little accumulated sludge to minimize denitrification, the concentrations of NO_2 and NO_3 in the AE reactor and effluent will be the same. This was the case in this investigation. The measured NO_2& NO_3 in the effluent were on averageequal to the concentrations in the AE reactor for all WW batches. The aerobic and effluent nitrite and nitrate were on average 0.15 mgNO_2-N/ℓ& 0.24 mgNO_3-N/ℓ and 0.14 mgNO_2-N/ℓ & 0.32 mgNO_3-N/ℓ respectively. These low NO_2 and NO_3 indicate the absence of nitrification in the AS systems. Such low NO_2 and NO_3 concentrations are probably spurious (should be zero) due to background colour effects in the autoanalyser. Zero NO_2 and NO_3 concentrations in the UCT system were confirmed with parallel tests with the *brucine* method by another laboratory.

ii. Uncorrected measured OUR yields good COD balance

For BNR systems with ND, the OUR measured in the AE reactor (OUR_m) is the sum of the nitrification OUR (OUR_n) and carbonaceous OUR (OUR_c) minus the equivalent OUR recovered by denitrification (OUR_d). If there is no ND in the BNR system, then OUR_n and OUR_d are zero and the measured OUR_m = OUR_c. For 92 % of WW batches (11 out of 12 batches), the measured OUR_m gives good COD mass balances (98 -110 %, see **Figure IV.5**) indicating there is no nitrification-denitrification (ND) in the UCT system.

iii. No nitrate generation in aerobic batch tests

The results of five batch tests on sludge harvested from the AE reactor conducted a month apart show that although the concentration of ammonia decreases over about 24 hours by 9 mgFSA-N/(ℓ) (average of batch tests 4 & 6) at an average ammonia utilization rate of 0.4 mgFSA-N/(ℓ.h), the nitrate generation is negligible, 0.55 mgNO_3-N/(ℓ) at an average production rate of 0.02 mgNO_3-N/(ℓ.h) i.e. only 1/20th of the ammonia decrease. The increase in OUR is only 30% of that expected from the ammonia decrease. In comparison, the results from batch test 5, which was conducted on sludge harvested from the AE reactor of the membrane system – a fully nitrifying system treating normal WW – indicate a nitrate generation rate closely equal (ratio of 1/1.2) to the rate of decrease of ammonia and the increase in OUR for this batch test 5 is greater than 86% of that expected from nitrification of the ammonia. The virtually zero nitrate generated in the UCT system batch tests confirms the absence of nitrification in the AS. The observed decrease in FSA and increase in OUR is probably a response of the OHOs (and PAOs) to the sudden availability of excess ammonia for growth.

iv. No decrease in Alkalinity

There is no decrease in average Alkalinity between the influent and the AEML sludge for all the WW batches. The average influent and effluent Alkalinity remain unchanged at 81 mg$CaCO_3$/ℓ (see **Table IV.5**). Given that *7.14 mg/ℓ as* $CaCO_3$ are needed per mgFSA-N nitrified (Henze et al., 2008), the zero decrease in Alkalinity provides further evidence that there is no nitrification and denitrification in the UCT system.

v. P release in the "anoxic" (actually 2nd anaerobic) reactor

Table IV.3 shows consistent P release in the "AX" reactor throughout the experiment. This can only happen if no external electron acceptor – nitrate in this case - enters the AX reactor such that the OHOs are not capable of using the SBCOD for denitrification. The PAOs also present in the AX reactor take up the VFAs produced from the hydrolyzed RBCOD, which continues in the AX reactor as if it is an AN reactor (Henze et al., 2008:159).

vi. Low nitrogen content of the activated sludge f_n (mgN / mgVSS)

From many years of experimental work, the N content of activated sludge including OHOs and PAOs (f_n) has been accepted at 0.10 mgN/mgVSS in steady state models (Marais and Ekama, 1976; WRC, 1984; Wentzel et al., 1990) and kinetic simulation models (ASM1, Henze et al., 1987; UCTPHO, Wentzel et al., 1992; ASM2, Henze et al., 1995). In this investigation a somewhat lower value was measured on the UCT system sludge (0.093, **Table IV.2**). This does not indicate an N deficiency for the OHOs and PAOs because the average influent TKN/COD ratio of the grey and brown WW mix was twice the maximum expected for complete N removal through sludge production, at 20d sludge age (see **Table II.3** in **Chapter II**), of 0.023 and 0.016 for RWW and SWW respectively. Also, the unutilized influent BPO in the mixed liquor would tend to decrease the f_n ratio. The combination of high influent TKN/COD ratio, long SRT (20 days), effluent FSA > 2 mgNH_3-N/ℓ (3.5 mgNH_3-N/ℓ), low f_n and no nitrification appeared to be anomalous. After investigation, it was found that with no nitrification at such long SRT, the VSS concentration of the sludge was the most sensitive factor affecting the N balance. **Figure IV.19** shows the variation in f_n (mgN/mgVSS) vs the resulting effect on the N balance. An average percentage increase of 55 % in f_n (to 0.135 mgN/mgVSS) yields the best N balance i.e. 100 ± 0.2 % for most of the WW batches. The graph suggests that the average f_n value to close the N balance ought to be around *0.135 mgN/mgVSS.* This indicated that the measured f_n of 0.093 was too low to achieve a 100 % N balance.

The following were attempted to check if possibly higher f_n ratios would result, but none made a significant improvement to the measured $f_n$value: 1) scrubbing and/or brushing the AE reactor's internal walls as well as the propeller before sampling and 2) macerating the AEML sample – after dilution – with a Philips HR2074 juice blender.

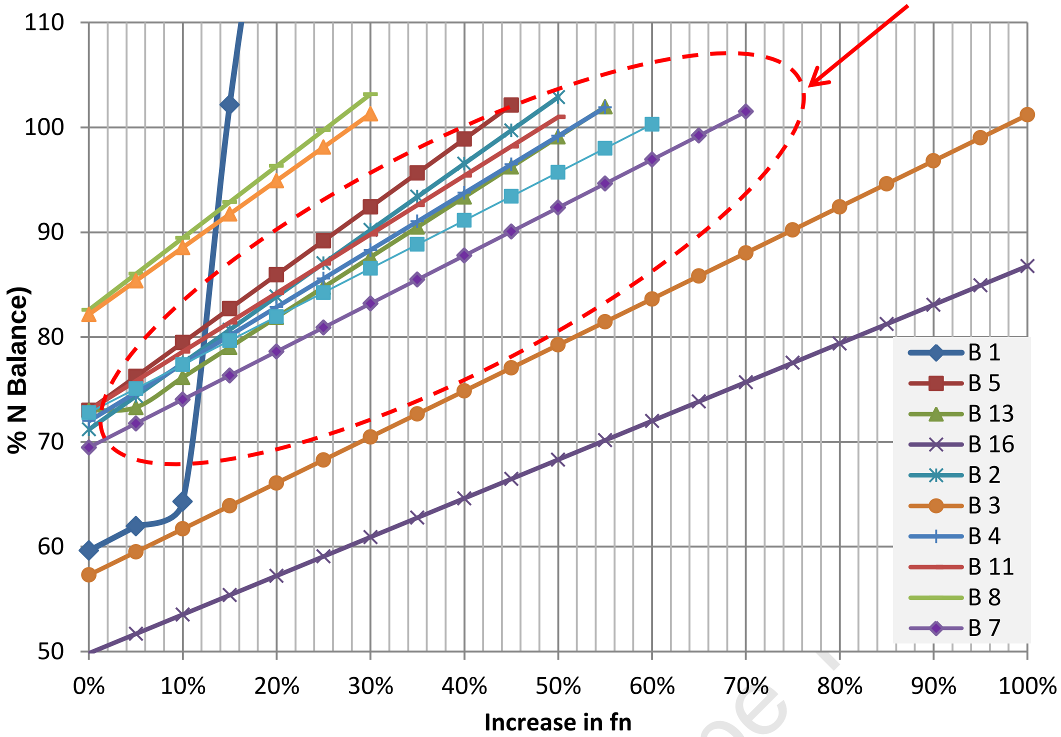


Figure IV.19: Simulation of the percentage increase in f_n and the resulting effect in the N balance. For most of the WW batches a 55 % increase in f_n yields maximum N balance or alternatively the average f_n value is around 0.135 mgN/mgVSS for N balance of 100 ± 0.2 %.

4.2.1.2 Excess biological phosphorus removal behaviour (EBPR) in the UCT system

Although the fraction of influent RBCOD (0.27) in WW feed to the UCT system (measured by difference between membrane filtered influent and effluent COD, which included some unutilized BSO) is sufficient to significantly induce excess P removal, the observed P removal was much lower than expected from the influent RBCOD concentration. Hence, the UCT system exhibited significantly reduced EBPR, which was anomalous. However, this reduced EBPR was not caused by anoxic P uptake (which did not take place – in fact, P release in the "AX" reactor was higher than in the AN reactor) but rather by the loss of RBCOD exiting the AN and AE reactors to the effluent, nearly 55 mgCOD/ℓ (S_{bse}). This was calculated as the difference between the 0.45 µm membrane filtered COD of **Table IV.1** and **Table IV.6**. This loss was caused by an apparent inability of the OHOs to neither (1) completely hydrolyse the BSO to VFA for PAO uptake in the AN reactor nor (2) completely utilize the remaining BSO in the AE reactor. If nitrate were recycled to the AN reactor (which here was not) the loss of RBCOD would be equivalent to a concentration of recycled nitrate to the AN reactor as high as 6 mgNO_3-N/ℓ given that each 1 mgNO_3-N/ℓ recycled reduces the substrate available for P release and removal by 8.6 mgCOD. Or, considering the measured P removal/RBCOD ratio of 0.063, had all the influent RBCOD been taken up by PAOs, the concentration of 55 mgCOD/ℓ would represent an additional 3.4 mgP/ℓ which would have yielded an effluent P of 0.1 mgP/ℓ. The high effluent BSO was attributed to the difficulty of OHOs to adapt to frequent variations in the organic composition of the different grey and brown WW batches, which developed a specific OHO population group for each WW batch that was unable to degrade all the organics of the next WW batch. The WW batches changed regularly, i.e. on a 7 – 10 day-basis per batch and varied depending on the diet of the very small a pool of people (15) producing it on the day it was collected. Consequently, the OHOs could not adapt quickly enough to adjust to every new feed (weekly batch), resulting in a significant unutilized influent BSO and BPO, observed in the UCT (and JHB) system as USO and UPO.

4.2.1.3 Effluent quality of the UCT system

The variability of the influent WW induced the poor mixed liquor sludge characteristics and frequent sludge losses (**Figure IV.21**) with the effluent. Nonetheless, the filtered effluent concentrations of 85.4 mgCOD/ℓ, 4.4 mgTKN-N/ℓ, 3.5 mgNH_3-N/ℓ, 23.3 mgSS/ℓ and 2.1 mgPO_4-P/ℓ are not unreasonable when compared with the concentration limits specified by the National Water Act (Act 36) of 1998 (for plant discharging not more than 2 Mℓ/d). However, they are poor considering what could have been expected from 100 % urine diversion and complete utilization of influent biodegradable organics. The main reason for this poor performance was the apparent inability of the OHO biomass to adapt to the variation in organics of consecutive WW batches.

Persuasive evidence was measured confirming the absence of nitrifiers (ammonia removal) and so the absence of nitrification within the UCT system. But given the anomalies regarding the OHOs observed and presented above, it also seems possible that nitrifiers could not establish themselves in the system for reasons other than there was too little nitrogen in the influent (which there was not really at ~ 3 to 5 mgNH_3-N/ℓ effluent FSA). The main problem also could have been the changing characteristics of the influent WW feed such that it could not sustain nitrifiers in the same way this could not sustain the OHO biomass with sufficient diversity to utilize all the biodegradable organics in each WW batch.

4.2.1.4 Aerobic mixed liquor solids AEVSS (AETSS)

Figure IV.20 shows periods of solids concentration fluctuation *A*, *C* and *D*. While period *C* shows similar trends in the TSS and VSS concentrations curves, period *A* does not. The curve of VSS concentration over period *A* does not track closely that of the TSS concentration over the same period but appears to be too low. It is possible that the ISS mass which is measured as the solids mass after 550℃ incineration (see **Chapter 3, Section 3.2.5**) was measured too high due to a technical problem with the incinerator during period *A* (mid-Nov 2009 – mid-Feb 2010). In fact, the thermostat of the incinerator had a defect such that it was not possible to keep the constant required temperature of 550℃. Some samples were either underheated or overheated at 1000℃, thus resulting in incorrect ISS measurements. A new thermostat was fitted on 19 Feb 2010 and the situation improved. The technical problem with the incinerator is external to the AS and without direct impact on TSS solids accumulation in the UCT system. This is confirmed by the steady trend of the DSVI curve and the fact that the SV_{30} curve follows the trend of DSVI curve over the same period *B*.

However, period *C* shows a situation different to that of period *A* because the VSS concentration curve closely tracks the TSS curve whilst fluctuating significantly. This is possibly due to varying degradation of influent BPO with periods of high VSS and TSS when BPO utilization is low and periods of low VSS and TSS when BPO utilization is high. Another possible factor that may have exacerbated the VSS and TSS fluctuations at the end of the investigation was fluctuations in main power supply which caused the peristaltic feed pump and other electrically-powered components of the UCT system set up to operate faster or slower from day to day. During the last days of operation the on and off times of the feed pump which regulate the constant feed of 15 ℓ/day had to be adjusted frequently (on a daily basis). Failure to do so caused the UCT system to be underfed (when low power supply) or overfed (when high power supply) after 24 hours. On some days, the daily feeding time of the UCT system had to be shifted often by several hours. This also is an external problem to the AS but with direct impact on TSS solids accumulation in the UCT system. Supporting evidence for this is the fluctuation of the DSVI curve and the fact that the SV_{30} curve does not follow the trend of the DSVI curve over the same period *D*.

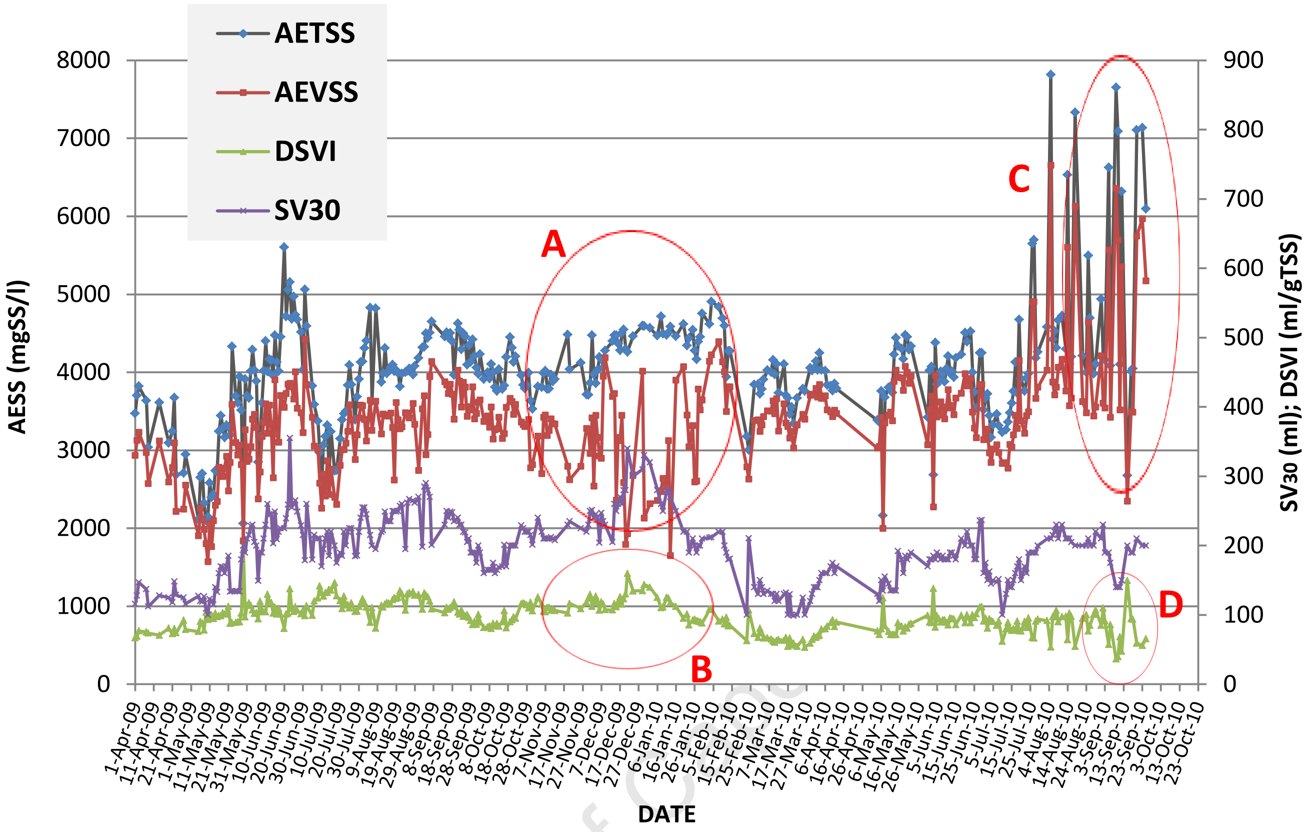
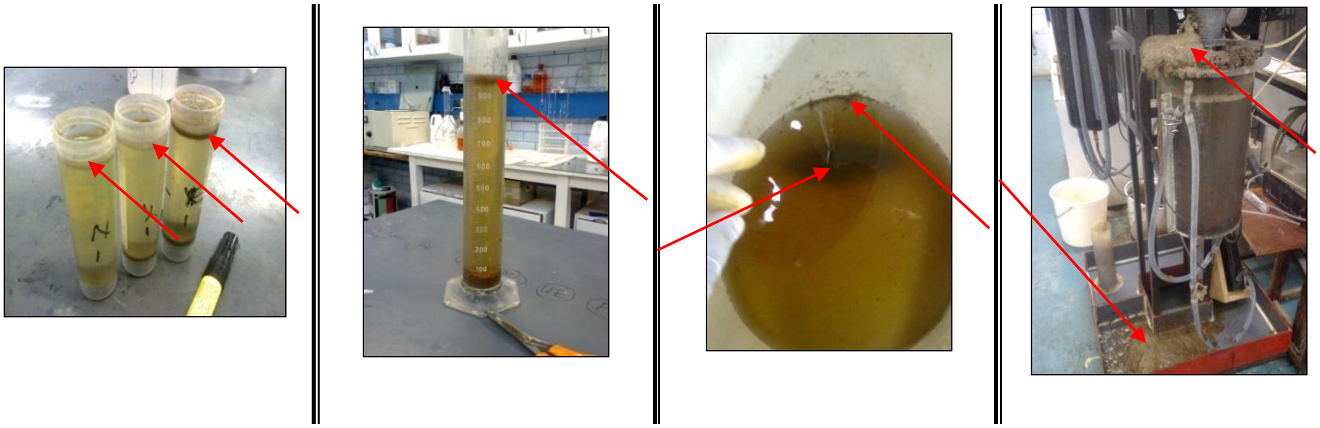


Figure IV.20: VSS (TSS), DSVI and SV_{30} variations over the entire experimental period indicating the periods of fluctuation in the UCT system.

Same variations in VSS (TSS) may also have been due to the varying proportion of dispersed (DS) and suspended solids (SS) in the AS sludge. The DS were lost in the effluent (though included in the unfiltered effluent COD concentration) and through routine testing e.g. while using centrifuge tubes to measure mixed liquor solids (MLSS) (not included in sludge COD and VSS), see**Figure IV.21 a)**below.



a) *b)* *c)* *d)*

Figure IV.21: a) Centrifuge tubes containing significant amount of floating sludge that was discarded as part of the supernatant; b) Diluted Sludge Volume Index test (DSVI) showing the floating solids; c) Effluent bucket containing dispersed (not settleable in settling tank) sludge on a normal operating day; d) AE reactor overflowing foam which contains sludge. The visible normal level of the mixed liquor in the reactor shows that no pipe was clogged.

Foaming incidents such as shown in **Figure IV.21 d)** occurred twice and lasted nearly 1 week each. However, in the last 5 months of operation, a thin layer of foam (1 cm thick) which also resulted in an unclear effluent containing solid particulates resembling breadcrumbs regularly covered the AEML of the UCT system. Itwas assumed that the foam had come from either dishwashing soap or toilet detergents used for cleaning the no-mix units at the CSIR, even though cleaning staff were asked not to do so. Although foaming and pinpoint floc (dispersed suspended solids escaping with effluent) take place sporadically also at full scale WWTP (see **Figure IV.22**), the UCT and JHB systems had these incidents take place in them much more frequently than laboratory systems fed real WW.

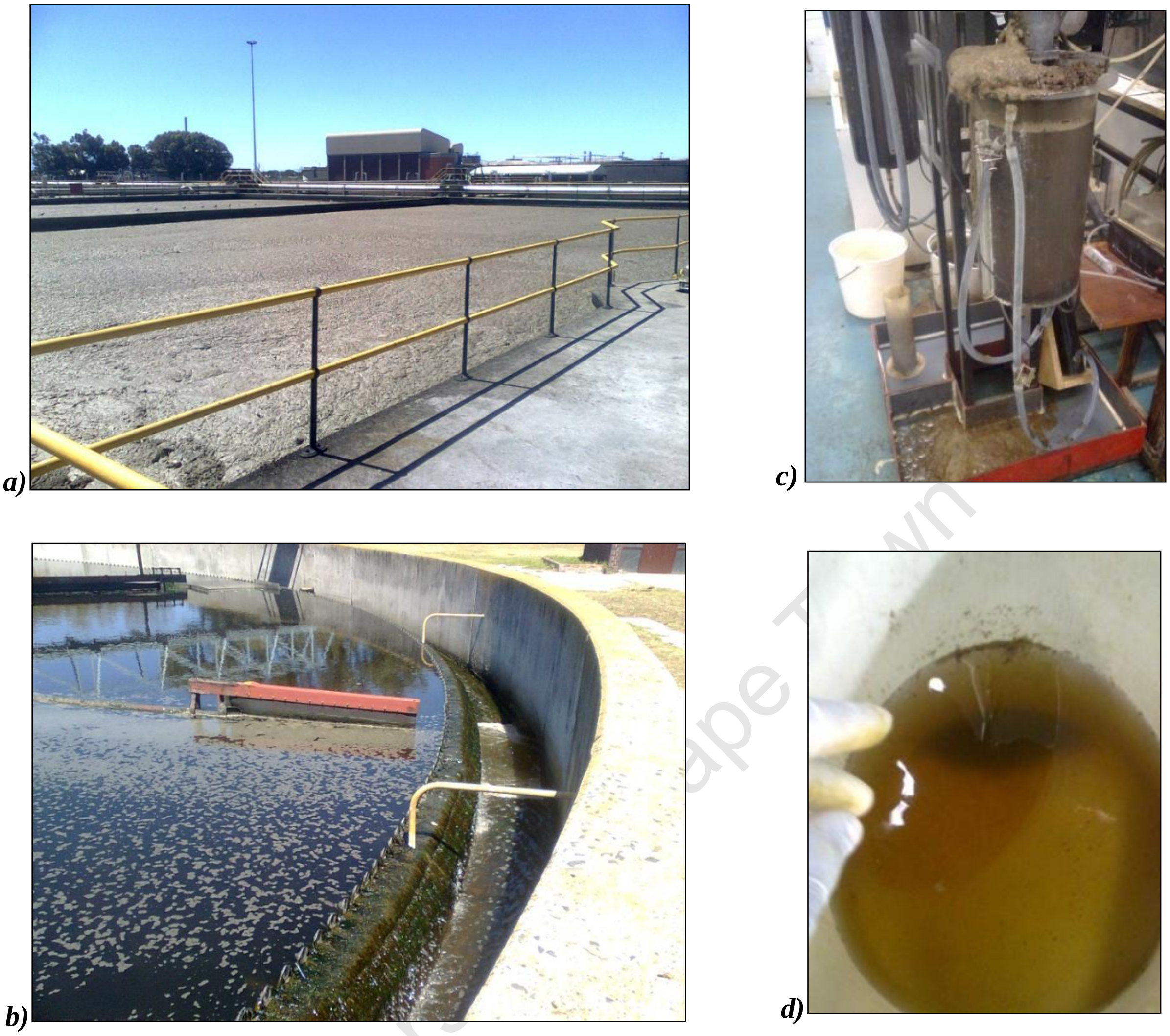


Figure IV.22: a) Operational problem showing a full-scale aerobic reactor (Athlone plant, South Africa) topped with thick layer of foam. The cause was unknown to technical plant operators; b) As a result of a), treated water exiting the clarifier into the effluent contained flocs of foam. Comparable situations with the UCT system in the laboratory are shown in c) & d) (Mbaya, Nov 2010).

4.2.2 Discussion on the results of the JHB system's performance

Following the evidence of no nitrification in the UCT system presented above, the JHB system was set up and run in parallel with the UCT system from January 2010 to the end of October 2010. Due to the many start up problems, the results presented in **Section 4.1.3** are those of the 154 day-operation of the JHB system starting from 25 March 2010 (see **Figure IV.1**). The design and operating parameters are listed in **Table III.1** of **Chapter 3** on materials and methods.

i. *Low aerobic reactor and effluent nitrite (NO_2) and nitrate (NO_3)*

The recorded NO_2& NO_3 in the effluent were on averageequal to the concentrations in the AE reactor for all WW batches as the clarifier was mostly clear of sludge which minimized denitrification there. The aerobic and effluent nitrite and nitrate were on average 0.32 mgNO_2-N/ℓ& 0.41 mgNO_3-N/ℓ and 0.26 mgNO_2-N/ℓ & 0.36 mgNO_3-N/ℓ respectively. These low NO_2 and NO_3 concentrations in the JHB system were to be expected given that the UCT system showed no nitrification. Such low NO_2& NO_3 concentrations (although twice those observed in the UCT system over the same WW batches) are probably spurious (should be zero) due to back colour effects in the autoanalyser.

ii. *No decrease in Alkalinity*

The JHB system showed no decrease in the average Alkalinity between influent and AEML for the WW batches i.e. it remained unchanged at 96 mg$CaCO_3$/ℓ. The no-decrease in Alkalinity was to be expected given that there was no nitrification in the UCT system. The situation in the UCT system over the same WW batches was similar.

iii. *Anoxic P release*

The sum of P release in the anaerobic and anoxic (2nd anaerobic actually) reactors was 11.5 mgP/ℓ of which 1.8 (16 %) was P release in the AX reactor. The JHB system indicated consistent anoxic P release throughout the experiment. This could only happen if no external electron acceptor – nitrate in this case – enters the AX reactor such that the OHOs are not capable of using the SBCOD for denitrification. The PAOs also present in the AX reactor take up the VFAs produced from RBCOD which continues in the AX reactor as if it is an AN reactor. The situation of anoxic P release (50 % of the sum of anaerobic and anoxic P releases) was consistent in the UCT system over the same WW batches.

iv. *Uncorrected measured OUR yields good COD balance*

The COD mass balances were good (95 - 109 %) for 90 % of WW batches (5 out of 6 batches) as a result of the measured OUR_m. Because there was no nitrification the OUR_n and OUR_d were both zero and the measured OUR_m (= OUR_c) was used in calculating the COD mass balances. The situation in the UCT system over the same WW batches was as good (103 – 110 % COD balance for 100 % of WW batches).

v. *Good nitrogen fraction of the sludge f_n (mgN / mgVSS)*

The average f_n (mgN/mgVSS) obtained for all WW batches was 0.097 which is slightly less than the experimental 0.10 derived from steady state and kinetic simulation models. This f_n value subsequently yielded far better N balance than the UCT system over the same WW batches (See **Sections 4.1.3.6.C** and **4.2.2.1**).

4.2.2.1 TKN/VSS ratio f_n (mg N/mgVSS)

The average f_n value obtained was 0.097 mgN/mgVSS which is 3 % less than the experimental f_n value of 0.1 mgN/mgVSS derived from steady state models and kinetic simulation models (see **Section 4.2.1.1: vi**). This yielded a far better N balance than the UCT system over the same WW batches. The average N balance is 115 %. The fact that the N balance is close to 100 % and there was no nitrification and denitrification so that most of the N exits the system as N in the WAS (average FN_{tws} = 79 %) indicates that the measured f_n value is reliable, but slightlylittle too high for 100 % N balance. This indicates that at the decreased sludge age of 5 days (JHB system) (from 20 days, UCT system), the increased flux of OHOs and VSS wasted from the system (gVSS/d) did not result in N deficiency for sludge growth, and the available N from the incoming WW was sufficient for the production of cell mass. There was nearly 20 % more N removed from the JHB system for sludge production (FN_{tws}) compared with that removed from the UCT system over the same WW batches.

4.2.2.2 P behaviour across the JHB system

The system showed poor EBPR (11.3 mgP/ℓ for 1000 mgCOD/ℓ) and 0.093 mgP removed/mgRBCOD for an influent RBCOD of 0.18 (fraction of total influent COD). There was mostly anaerobic P release and aerobic P uptake (60 % of WW batches). The observed anaerobic P uptake (40% of WW batches) represented only 15 % of the P uptake in the AE reactor. Although EBPR was not as good as expected and anaerobic P uptake is anomalous, the predominantly observed anaerobic P release and aerobic P uptake indicate normal EBPR across the JHB system. The low conversion of influent RBCOD due to decreased OHO growth from reduced utilization of influent BPO resulted in lower than expected EBPR.

Although both units were fed the same influent WW (grey and brown water mix), the difference in measured influent RBCOD fraction between the UCT and JHB systems was attributed to the difference in measured 0.45µm membrane filtered effluent COD concentrations. In the case of the JHB system the filtered effluent COD (S_{use}) was on average 32 % higher than that of the UCT indicating not only reduced BSO utilization in the entire system but also by implication reduced BPO utilization. This yielded a low utilized RBCOD concentration given that the RBCOD concentration can be calculated from the following equation (provided it is all utilized in the system, which it was not):

$$RBCOD\ (mgCOD/\ell) = S_{tiFilter} - 8.6 * NO_{3(AN)} * (1+s\text{-}recycle) - S_{use} \textbf{[Eq IV.4]}$$

Where $NO_{3(AN)}$ is the nitrate concentration measured in the AN reactor and which were measured to be equal to zero for both the UCT and the JHB systems. The large difference in effluent unbiodegradable soluble COD (S_{use}) from both systems required further investigation (see **Section 4.2.3**).

4.2.2.3 JHB effluent quality

As explained in the case of the UCT system effluent and sludge characteristics (see **Sections 4.2.1.3** and **4.2.1.4**), the influent WW characteristics (grey and brown water mix) are the main reason for the poor filtered effluent concentrations obtained with the JHB system namely 125.1 mgCOD/ℓ, 19.0mgTKN-N/ℓ, 15.1 mgNH_3-N/ℓ, 70.5 mgSS/ℓ and 8.5 mgPO_4-P/ℓ. These effluent concentration values are not as low as expected from a normally functioning BNR system operating in a scenario of complete urine separation. In addition, they far exceed the effluent limits specified by the National Water Act (Act 36 of 1998) for plant discharging not more than 2 Mℓ/d in a water resource. These effluent concentrations are evaluated further below.

4.2.2.4JHB system aerobic mixed liquor solids AEVSS (AETSS)

Figure IV.23 shows periods of solids concentrations fluctuation *C'*. Causes for the major fluctuation in period *C'* at the end of the investigation are the same as for the UCT system (see **Section 4.2.1.4**) i.e. electrical power fluctuation, periods of foaming and high dispersed suspended solids in effluent and varying degree of influent biodegradable organics utilization.

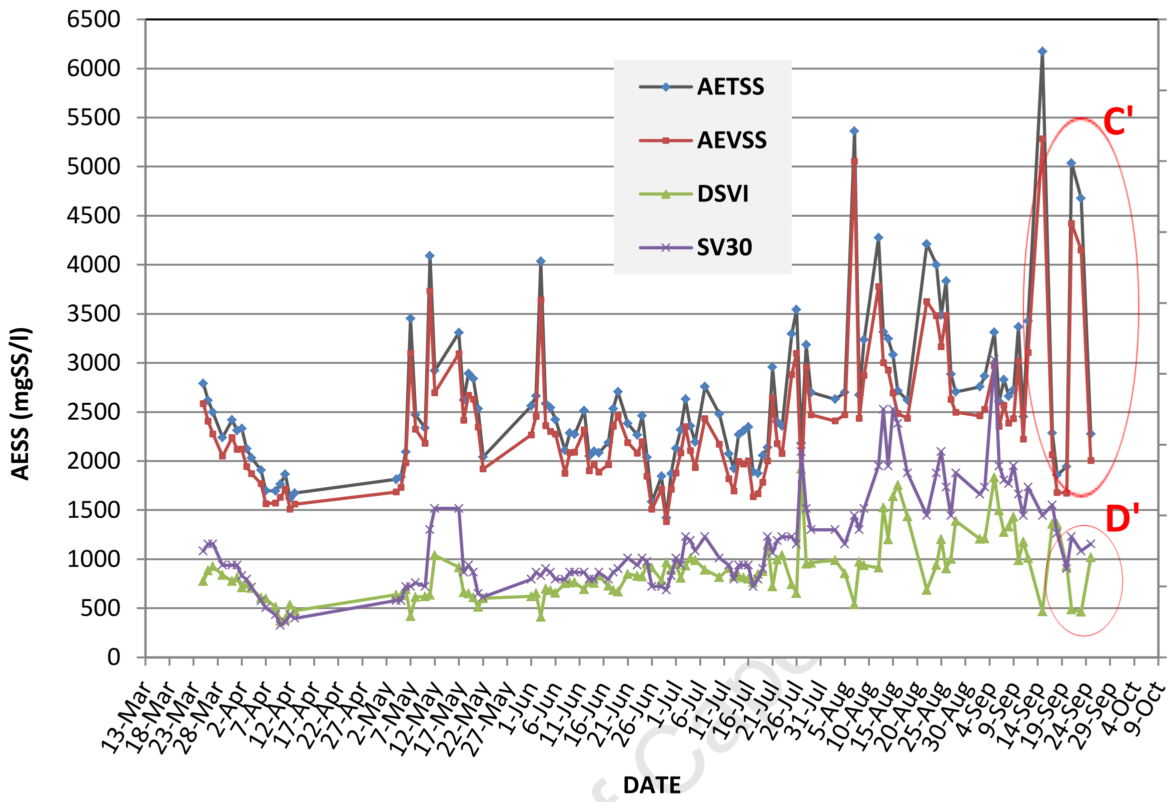


Figure IV.23: VSS (TSS), DSVI and SV_{30} variations over the entire experimental period indicating the periods of fluctuation in the JHB system.

4.2.3 Comparison between the UCT and JHB systems' performance

Ekama et al. (1986), as reported by Ramphao (2004:5.40), state that for long SRT AS systems, and complete utilization of influent BSO and BPO, the influent unbiodegradable soluble COD (S_{usi}) is equal to the effluent unbiodegradable soluble COD (S_{use}). The latter represents the 0.45 µm membrane filtered effluent COD. The fraction $f_{S'us}$ is then equal to S_{use}/S_{ti}; where S_{ti} is the total influent COD. By calculating the $f_{S'us}$ this way, the average obtained for the WW batches (B8 – B15) was 0.092 for the UCT system. This value falls at the upper end of the range (0.04 to 0.10) of typical values for domestic WWs in SA (WRC, 1984). However, the $f_{S'us}$ obtained for the JHB system was nearly 13 % ($f_{S'us}$ = 0.103) higher than that obtained for the UCT system. Considering that both systems were fed the same grey and brown water mix, the nitrate (NO_3) produced in them was zero and given **Equation IV.4**, the difference in $f_{S'us}$ indicated that the measured filtered effluent concentrations were not all unbiodegradable COD but that some biodegradable soluble COD (S_{bse}) was included in the effluent from the JHB (and UCT) system.

Aerobic batch tests were conducted on the effluents from both the JHB and UCT systems in order to determine the unutilized BSO (S_{bse}). The results of these tests are listed in **Tables IV.6**and**IV.11**for the UCT and JHB system respectively. Comparing the unbiodegradable effluent concentrations of the above mentioned tables with those of **Table IV.7** indicates that the JHB system effluent contained nearly 40 % more biodegradable soluble COD (and 50 % more organic N biodegradable soluble, N_{obse}) than the UCT system over the same WW batches, i.e. 88.5 compared with 54.3 mgCOD/ℓ, which were calculated from the difference of 125.1 & 36.6 mgCOD/ℓ and 89.2 & 34.9 mgCOD/ℓ respectively. If the utilization rate of BSO (and BPO) is growth rate kinetics limited (due to the constant acclimatization of OHOs to new WW batches) then a higher unutilized BSO is expected at the shorter sludge. This would also affect the anaerobic fermentation rate of BSO to VFA with consequently much lower EBPR (as observed). When compared with the CAS UCT system of Ramphao (2004), the UCT system performed less well. The CAS UCT released 57 mgCOD/ℓ that could be accepted to be all unbiodegradable soluble COD.

In terms of P removal, the loss of S_{bse} (RBCOD) reduced the P removal by 3.9 mP/ℓ for the UCT system and 10.1 mP/ℓ for the JHB system. Alternatively, had all the RBCOD been fermented and taken up by PAOs within the AS systems, the P removals would have been 100 %thus yielding the low effluent concentrations of 0.1 mgPO_4-P/ℓ (see **Table IV.12**).

Table IV.12: P performance of the UCT and JHB systems for the scenarios of loss and complete utilization of RBCOD (BSO)

SCENARIO	PARAMETER	UCT SYSTEM (20d SRT)	JHB SYSTEM (5d SRT)
	Influent TP (mgP/ℓ)	*21.5*	*21.5*
	Premoved (mgP/mg RBCOD)	*0.080*	*0.093*
With RBCOD (BSO) loss	**% RBCOD (fraction of S_{ti})**	*21.7*	*18.1*
	Premoved/ℓ Influent (mgP/ℓ)	*17.6*	*11.4*
	% Premoved	***82***	***53***
Without RBCOD (BSO) loss	**% RBCOD (fraction of S_{ti})**	*27.1*	*26.9*
	Premoved/ℓ Influent (mgP/ℓ)	*22.0*	*25.4*
	% Premoved	***100***	***100***

S_{ti} is the total Influent COD which is obtained from **Table IV.7**

Therefore, such low effluent concentrations as 0.1 mgPO_4-P/ℓ is a consequence of reducing the influent P load on the plant, due to urine separation. However, in future research, the generation of urine separated influent WW must be given particular attention. In this investigation, the grey and brown water composition were erratic and variable causing OHO acclimatizationproblems in the sense that they were strongly affected by the constantly changing diet of the small community of people generating the waste (15 people).

The COD/TKN/TP ratio of the source separated WW is a WW characteristic which can only be determined from extensive experimental investigation. With the effluent biodegradable COD accounted for, the WW characteristics such as $f_{S'us}$ and $f_{S'up}$ also change to figures that are comparable to typical values expected from domestic WW in South Africa e.g. 34.9 mgCOD/ℓ ($f_{S'us}$ = 0.034)from **Table IV.6** falls just below the lower limit of the range (0.04 to 0.10).

4.2.4 Characteristics of influent WW

In this experimental investigation, the WW treated at laboratory scale consisted of brown and grey water mixed in a 1:1 proportion at laboratory scale. These wastewaters were collected separately from one office block (block D) at the CSIR building in Stellenbosch, Western Cape, South Africa. Block D was fitted with two no-mix urine separation toilets (one in the men's and one in the women's toilets) as well as with one dry (no flush) urinal. Yellow, grey and brown water were separately collected (see **Section 3.1 of Chapter 3** on materials and methods). From the measured performance of the long SRT UCT and short SRT JHB BNR systems, it is concluded that the characteristics of the influent WW are the main reasons for the anomalies observed in the experimental systems. The grey and brown WW were collected over too few days from a too small a pool of people to be sufficiently representative of real municipal or domestic WW urine separated at source. As outlined in **Chapter 2 Section 2.3**, the term municipal refers to two main groups of WW sources, i.e. residential areas and commercial facilities. The former may also include bars and restaurants, apartment houses, resort accommodations, hotels, motels, boarding houses, trailer courts, schools, swimming pools, theaters/movie theatres or summer camps besides private homes. The latter includes offices and buildings mostly. People of different income levels, cultural, social habits have different diets and frequent these places of living, entertainment and work. Research has shown that there is a strong link between the diet of people and the characteristics of the waste generated. The larger the population generating municipal WW, the less variable become its constituents and composition. In the office block at the CSIR, from where the WW treated in this experiment was collected, there were only about 15 people during working hours most young professional researchers and analytical staff. This group falls within the middle-income group of society having income for high quality food rich in nutrients and proteins. The WW generated by this group contained high concentration of N and P relative to COD, was very variable from collected batch to batch and so caused significant acclimatization problems to the OHOs (and possibly also the nitrifiers) in the AS. The quality and composition of every new batch significantly differed from the previous one because it depended on the recent diet of the few people generating it.

The high influent TKN/COD and TP/COD ratios of the CSIR grey and brown water were attributed to 1) the wine-testing activity that took place at the office once a month. Given that wine is rich in nitrogen (N), this increased the concentration of N in the CSIR kitchen greywater (Germanis, 2011) and 2) the misuse of the urine separation toilets that caused urine to enter the faecal chamber. In the 2009 CSIR perception survey on the use of the urine separation toilets, some male staff highlighted the fact that they found it difficult to aim properly while urinating (Germanis, 2009).

There are factors at laboratory level that might bring further evidence of the peculiarity of the particular grey and brown water mix used in this investigation viz., 1) toilet paper, which is mostly biodegradable organics (Beeharry et al., 2001) was sieved out through *0.9 mm* sieve size to prevent pipe blockages in both AS systems and 2) Grey and brown WW were mixed in a 1/1 ratio (by volume). In real WW, the volume composition of municipal or domestic WW maybe 75% greywater and 25 % blackwater i.e. brown and yellowwater (Carden et al., 2007:433). Also, with real WW, there is considerable biological activity for several hours in the sewer, which make organics more easily degradable in the receiving WWTP.

.

Chapter V : CONCLUSION AND RECOMMENDATIONS

INTRODUCTION

The conclusion and recommendations are stated in light of the key questions presented at the beginning of this report, viz

1) With nitrification being the BNRAS size governing bioprocess via the sludge age, will this still be required with WW comprising only brown and grey water?

2) With a significantly reduced P load, will the effluent P concentration also decrease and to what value?

3) With eutrophication prevention requiring ever decreasing effluent N and P concentrations, e.g. *0.1 mgP/ℓ*, is achieving such limits related to the N and P loads or by other factors that set the limits of the BNRAS technology, e.g. affinity constants in Monod kinetics?

4) What will be the COD:TKN:TP ratio of urine separated (grey and brown) municipal WW?

5.1 CONCLUSION

From the observations of the NDBEPR UCT system at 20d SRT and 20˚C operating temperature, it can be concluded that with complete urine separation the BNR size governing nitrification process will not be required. Six factors pointed to the absence of nitrification in the system, viz., (1) virtually zero nitrate in the aerobic reactor and effluent (*<1* $mgNO_3$-*N/ℓ)*; (2) no nitrate generation and associated nitrification OUR could be stimulated in aerobic nitrification batch tests on sludge harvested from the UCT system; (3) no Alkalinity consumption in the aerobic reactor, which would indicate that ammonia was nitrified; 4) the measured OUR, uncorrected for ND, yielded a good (> 95 %) COD mass balance; 5) low N content of the activated sludge (f_n = 0.093 mgN/mgVSS) and 6) P release in the anoxic reactor which indicated that it was a continuation of the anaerobic reactor.However, the absence of nitrifiers may not be due to ammonia limitation because the effluent FSA concentrations were high (3 – 5 mg/ℓ). Activated sludge systems with nitrification achieve much lower effluent FSA concentrations than this. Had the collected WW been from a large population group (lower TKN/COD and TP/COD ratios) and the lab systems operated normally (complete utilization of biodegradable organics), it is likely that low effluent FSA concentrations (less than 1 mgN/ℓ) would have been obtained in the lab systems in the absence of nitrification. The suppression of nitrification and denitrification will unlock great potential at BNRAS WWTPs because the SRT can be reduced. This implies that the size of the plant can be reduced significantly (by nearly ½ as shown in this experimental investigation) or alternatively more WW can be treated for the same overall reactor volume. This will definitely answer the problem of available space for WW treatment works as urbanization increases and increasingly more land is needed for new housing development.

The UCT system's filtered effluent concentrations were 85.4 mgCOD/ℓ, 4.4 mgTKN-N/ℓ, 3.5 $mgNH_3$-N/ℓ, 32.3 mgSS/ℓ and 2.1 $mgPO_4$-P/ℓ and the removal efficiencies (based on unfiltered effluent concentrations) good at 92%, 92%, 86% and 89% for COD, TKN, FSA and TP respectively, at 20d SRT. However, these effluent concentrations are relatively higher than the limit concentrations specified by the National Water Act (Act 36 of 1998) and not good enough to limit receiving water de-oxygenation and eutrophication. But they can be improved considerably. Further investigation revealed that an average of 60 % organic biodegradable soluble COD (S_{bse})and 25 % organic biodegradable soluble N (N_{obse}) were contained in the effluent. This was not attributed to the BNRAS set up because similar units were satisfactorily operated in the past, but to the influent WW. One way to achieve better effluent quality would be to increase the population size from which the WW is collected so that the characteristics of the grey and brown water collected become more consistent. In the current research it was found that the grey and brown water were not sufficiently representative of real domestic or municipal WW because it came from a single office block where only 15 staff members of a specific socio-economic group worked.Furthermore, the grey and brown WW were mixed at laboratory level in a 1:1 ratio unlike in a real situation where the ratio of grey to brown water is 3:1. Theinconsistency of the WW characteristics (organics diversity) may have caused acclimatization problems for microorganisms (OHOs and possibly ANOs) within the AS thereby giving the poor performance observed. The organic types and characteristics of every new collected batchof grey and brown water changed almost weekly depending on the batch of WW collected on that particular week depending on the diet of the small community generating the wastewaters.

From this project, it can be reasonably concluded that lower effluent N and P concentrations, *e.g. 0.1 mgP/ℓ*, from WWTPscan be achieved with lower N and P loads from urine separation. Proper consideration of the characteristics of WW treated would also clarify the anomalies observed in running the UCT and JHB systems in this project.

Hence, all things considered, the COD:TKN:TP ratio of urine separated (grey and brown) municipal WW would certainly be lower than the ratios required for no nitrification and complete utilization of nutrients for sludge growth based on activated sludge characteristics determined from years of experimental research. However, this would be validated in experimental work in which the grey and brown WW are collected from a much larger population.

Likewise, if the quality of the urine separated WW collected was altered to the almost 100 % biodegradability of real domestic WW organics, the results obtained for the JHB system would significantly improve. The filtered effluent quality of the JHB system operated in this investigation was poor at 125.1 mgCOD/ℓ, 19.0mgTKN-N/ℓ, 15.1 mgNH3-N/ℓ, 70.5 mgTSS/ℓ and 8.5 mgPO4-P/ℓat 5d SRT. These effluent concentrations are higher than the limit concentrations specified by the National Water Act (Act 36 of 1998) and not good enough to limit receiving water de-oxygenation and eutrophication. The removal efficiencies (based on unfiltered effluent concentrations) were 86 % COD, 75 % TKN, 51 % FSA and 53 % TP. However, the JHB system represents a 50 % saving in overall reactor size compared to the UCT system, which is a major improvement in WW treatment plant size and costs.

5.2 FUTURE WORK AND RECOMMENDATIONS

This impact of urine separation on BNRAS systems may be improved by:

1. Changing the experimental set up so that the treated WW is a sample representative of the population i.e. 1) the grey and brown water must be mixed in a 3:1 ratio to approach a real domestic or municipal WW scenario and 2) the grey and brown water must be sourced from a much larger and more diversified a pool of people i.e. people with different socio-economic (education, income level) or cultural (culture, religion, etc) identity. That may require running a much larger pilot-scale set-up for grey and brown water collection such as one installed in a new housing development (house village or block of flats) or in public places like airports, shopping malls, libraries, parks etc.

2. Running the same laboratory scale or alternatively a larger pilot scale 5-day SRT JHB system treating the urine separated WW (grey and brown water) from a large diverse population. The pilot scale JHB system could have an overall volume of 2000 m^3 which is comparable to the waste generated by a community of around 21000 people.

3. Analysingthe results of the JHB system by comparison with predictions of the models for BNRAS systems and analysingboth the separated urine and the brownwater samples for micropollutants such as hormones, environmental estrogens and/or pharmaceutical residues which were not done in this investigation.

The urine separation concept is still in its early stages and the prospects of achieving more sustainable urban water management with it are very good e.g. increased WWTP capacity, improved effluent quality and reduction in energy consumption. However, in order to quickly advance these prospects some risks need to be taken (capital risks); Also, strong political will, significant financial investment and large scale public education are required to embark on the source separation of urine route in urban sanitation, because any deviation from the current water borne sanitation will beless convenient for users but better for the environment. Adoption of urine separation sanitation by middle- and high-income urban groups will change the perception that urine separation is an inferior system only for low-income communities.

REFERENCES

Ab Razak, I.A. & Christensen, E.R. 2001.Water quality before and after deep tunnel operation in Milwaukee, Wisconsin.*Water research*.35(11):2683-2692.

American Public Health Association. 1989. *Standard methods for the evaluation of water and wastewater*.Washington D.C., USA: APHA.

Armitage, N., Carden, K., Sichone, O. & Winter, K. 2007. The use and disposal of greywater in non-sewered areas of South Africa: Part 2 – Greywater management options. *Water SA*. 33:433-441.

Austin, L.M. 2006.Operational safety of urine diversion toilets in Durban, South Africa.*32nd WEDC International Conference, Colombo, Sri Lanka*.2006. 13-17. Available: http://researchspace.csir.co.za/dspace/bitstream/10204/839/1/Austin_2006_D.pdf

Balkema, A.J., Preisig, H.A., Otterpohl, R. & Lambert, F.J.D. 2002.Indicators for the sustainability assessment of wastewater treatment systems.*Urban water*.4(2):153-161.

Beal, C., Gardner, T., Ahmed, W., Walton, C. & Hamlyn-Harris, D. 2009.Urine-separation and reuse trials.*Water: Journal of the Australian water association.* 35(1):66-69.

Beeharry, A.O. 2001.Evaluation of batch test for measurement of active biomass in activated sludge mixed liquor.Master Thesis. University of Cape Town, Department of Civil Engineering.(Unpublished).

Burkhard, R., Deletic, A. & Craig, A. 2000. Techniques for water and wastewater management: a review of techniques and their integration in planning. *Urban water*.2(3):197-221.

Cadbury, D. 1997. *The feminization of nature: our future at risk.* Hamish Hamilton Ltd., London.

Carden, K., Armitage, N., Winter, K., Sichone, O., Rivett, U. & Kahonde, J. 2010. The use and disposal of greywater in the non-sewered areas of South Africa: Part 1–Quantifying the greywater generated and assessing its quality. *Water S.A.* 33(4):433-441.

Catunda, P.F.C. & Van Haandel, A.C. 1992. Activated sludge settling part I: Experimental determination of activated sludge settleability.*Water S.A.* 18(3):165-172.

Clayton, J.A., Ekama, G.A. & Wentzel, M.C. 1991.Denitrification kinetics in biological nitrogen and phosphorus removal activated sludge systems treating municipal waste waters.*Water science and technology*.23(4-6):1025-1035.

Del Mistro, R. 2007. State of cities.Civ 4040F Course notes. University of Cape Town, Department of Civil Engineering.(Unpublished).

Depledge, M.H. & Billinghurst, Z. 1999. Ecological significance of endocrine disruption in marine invertebrates.*Marine pollution bulletin*.39(1-12):32-38.

Eberhard, R.G.,Peters, C.R., Palmer, I.H. & Marais, G.v.R. 1992.Evaluation of sanitation systems with a focus on social aspects.*Seminar on water and sanitation for developing urban communities.*Jun 1992.

Ekama, G.A. 2010. The role and control of sludge age in biological nutrient removal activated sludge systems. *Water science and technology*.61(7):1645-1652.

Ekama, G.A., Marais, G.v.R., Siebritz, I.P., Pitman, A.R., Keay, G.F.P., Buchan, L., Gerber, A. & Smollen, M. 1984.*Theory, Design and Operation of Nutrient Removal Activated Sludge Processes: A Collaborative Information Document.* Water Research Commission.

Ekama, G.A. & Wentzel, M.C. 1999. Denitrification kinetics in biological N and P removal activated sludge systems treating municipal wastewaters. *Water science and technology*.39(6):69-77.

Ekama, G.A., Wentzel, M.C. & Sötemann, S.W. 2006.Tracking the inorganic suspended solids through biological treatment units of wastewater treatment plants.*Water research*.40(19):3587-3595.

Foucher, S., Battaglia-Brunet, F., Ignatiadis, I. & Morin, D. 2001.Treatment by sulfate-reducing bacteria of Chessy acid-mine drainage and metals recovery.*Chemical engineering science*.56(4):1639-1645.

Gaydon, P.& Water Research Commission. 2007. *Evaluation of sewage treatment package plants for rural, peri-urban and community use.* Gezina, South Africa: Water Research Commission.

Gounden, T., Pfaff, B., Macleod, N. & Buckley, C. 2006. Provision of free sustainable basic sanitation: the Durban experience.*32nd WEDC International Conference.*Colombo, Sri Lanka:2006.

Graham, N. 2003. A review of infrastructure services for the upgrading of South African informal settlements. Master Thesis. University of Cape Town, Department of Civil Engineering.(Unpublished).

Hanaeus, J., Hellstroem, D. & Johansson, E. 1997.A study of a urine separation system in an ecological village in northern Sweden.*Water science & technology*.35(9):153-160.

He, Q., Gou, H., Dai, Z. & Hao, Y. 2006.Discussion on the Water-Saving Technology of the Green Community.*Proceedings of the Sixth International Conference for Enhanced Building Operations*. Shenzhen, China, 6 – 9 November 2006.

Health Library for Disasters, 2011.Retrieved from http://helid.digicollection.org/en/d/Js2669e/7.6.6.html (Accessed 7 August 2011).

Henze, M., Grady Jr, C.P.L., Gujer, W., Marais, G.R. & Matsuo, T. 1987.*Activated Sludge Model No. 1. IAWPRC Scientific and Technical Reports No. 1.*Bristol, UK: JW arrowsmith ltd.

Henze, M., Van Loosdrecht, M.C.M., Ekama, G.A. & Brdjanovic, D. 2008.*Biological wastewater treatment: principles, modelling and design.* London: IWA Publishing.

Höglund, C., Vinneras, B., Stenström, T.A. & Jönsson, H. 2000. Variation of chemical and microbial parameters in collection and storage tanks for source separated human urine. *J. Environ.Sci.Health.*A35(8):1463-1475.

Hollender, J., Zimmermann, S.G., Koepke, S., Krauss, M., McArdell, C.S., Ort, C., Singer, H., Von Gunten, U. & Siegrist, H. 2009. Elimination of organic micropollutants in a municipal wastewater treatment plant upgraded with a full-scale post-ozonation followed by sand filtration. *Environmental science & technology*.43(20):7862-7869.

Hu, Z., Wentzel, M.C. & Ekama, G.A. 2001. External nitrification in biological nutrient removal activated sludge systems. *Water science & technology*.43(1):251-260.

Jefferson, B., Palmer, A., Jeffrey, P., Stuetz, R. & Judd, S. 2004. Grey water characterisation and its impact on the selection and operation of technologies for urban reuse. *Water science & technology*.50(2):157-164.

Jönsson, H., Stenström, T.A., Svensson, J. & Sundin, A. 1997. Source separated urine-nutrient and heavy metal content, water saving and faecal contamination. *Water science and technology*.35(9):145-152.

Kirchmann, H. & Pettersson, S. 1994. Human urine-chemical composition and fertilizer use efficiency. *Nutrient cycling in agroecosystems*.40(2):149-154.

Kirsten, M. & Development Bank of Southern Africa.2006. *The DBSA infrastructure barometer, 2006.* Halfway House, Midrand: Development Bank of Southern Africa.

Kreuzinger, N.,Clara, M., Strenn, B. & Kroiss, H. 2004.Relevance of the sludge retention time(SRT) as design criteria for wastewater treatment plants for the removal of endocrine disruptors and pharmaceuticals from wastewater.*Water science & technology*.50(5):149-156.

Kroiss, H., Klager, F., Winkler,S., Wandl,G. & Svardal, K. 2004. Nutrient removal process development and full scale implementation at the 4 million p.e. main treatment plant of Vienna, Austria. *Water science and technology : A journal of the international association on water pollution research.* 50(7):19-26.

Landman, J.P., Bhorat, H., Van der Berg, S. & Van Aardt, C. 2003.“*Breaking the grip of poverty and inequality in South Africa: 2004-2014”*.Retrieved fromhttp://www.sarpo.org.za/documents/d000649/p661-Povertyreport3b.pdf (Accessed 13 september 2009).

Larsen, T.A. & Gujer, W. 1996. Separate management of anthropogenic nutrient solutions (human urine). *Water science and technology*.34(3-4):87-94.

Lienert, J., Gudel, K. & Escher, B.I. 2007.Screening method for ecotoxicological hazard assessment of 42 pharmaceuticals considering human metabolism and excretory routes.*Environ.sci.technol.* 41(12):4471-4478.

Little, C., Wentzel, M.C. & Ekama, G.A. 2002.Economic evaluation of the external nitrification system with particular reference to the Potsdam WWTP Milnerton.*Proceedings of 7th WISA Biennial conference,* paper 034.

Lofrano, G. & Brown, J. 2010. Wastewater management through the ages: A history of mankind. *Science of the total environment.* 408(2010):5254-5264.

Lu, H., Tang, D.T.W., Chen, G.H., van Loosdrecht, M.C.M. & Ekama, G. 2011. Pilot scale evaluation of SANI< sup> R</sup> process for sludge minimization and greenhouse gas reduction in saline sewage treatment. *Water science & technology*.63(10):2149-2154.

Ludzack, F.J. & Ettinger, M.B. 1962.Controlling operation to minimize activated sludge effluent nitrogen.*Water pollution control federation*.34(9):920-931.

Marais, G.R. & Ekama, G.A. 1976.The activated sludge process.Part 1-Steady state behaviour.*Water SA.* 2(4):164-200.

Matthiessen, P. 2003. Topic 4.1: Historical perspective on endocrine disruption in wildlife. *Pure and applied chemistry*.75(11/12):2197-2206.

Maurer, M., Pronk, W. & Larsen, T.A. 2006. Treatment processes for source-separated urine. *Water research*.40(17):3151-3166.

Moosbrugger, H. & Frank, D. 1992.*Clusteranalytische Methoden in der Persönlichkeitsforschung*.Bern, Gö ttingen: Huber.

Morel, A. & Diener, S. 2006. *Greywater management in low and middle-income countries, review of different treatment systems for households or neighborhoods.*Dubendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (EAWAG).

Network, S.A.C. 2006.*State of the cities report.* Braamfontein, South Africa: South African Cities Network.

Nikkicarman, 2011.*“Berry Berry Project”*.Retrieved from http://nikkicarman.blogspot.com/2011/05/carbon-nitrogen-phosphorus-and-sulfur.html (Accessed 15 January 2011).

Oosthuizen, N.L., Bell, J. &South Africa Department of Water affairs and Forestry (DWAF). 1980. *Guidelines to facilitate legal compliance with respect to industrial waste management.* Pretoria South Africa: Government Printer.

Oosthuizen, N.L., Bell, J. & South Africa Water Research Commission. 2009. *Guidelines to facilitate legal compliance with respect to industrial waste management : report to the Water Research Commission.* Gezina South Africa: Water Research Commission.

Otterpohl, R., Grottker, M. & Lange, J. 1997.Sustainable water and waste management in urban areas.*Water science and technology*.35(9):121-133.

Ramphao, M.C. 2004. The performance of biological nitrogen and phosphorus removal with ultra-filtration membranes for solid-liquid separation.Master Thesis. University of Cape Town, Department of Civil Engineering.(Unpublished).

Randall, C.W. & Sen, D. 1996. Full-scale evaluation of an integrated fixed-film activated sludge (IFAS) process for enhanced nitrogen removal. *Water science and technology*.33(12):155-162.

Randall, E.W., Wilkinson, A. & Ekama, G.A. 1991.An instrument for the direct determination of oxygen utilisation rate.*Water S. A.* 17(1):11-18.

Ren, N.Q., Chua, H., Chan, S.Y., Tsang, Y.F. & Sin, N. 2007.Effects of COD/SO42-ratios on an acidogenic sulfate-reducing reactor.*Ind.eng.chem.res.* 46(6):1661-1666.

Rossi, L., Lienert, J. & Larsen, T.A. 2009.Real-life efficiency of urine source separation.*Journal of environmental management.*90(5):1909-1917.

Sawyer, C.N., McCarty, P.L. & Parkin, G.F. 2003.*Chemistry for environmental engineering and science.*New York: McGraw-Hill.

Sen, D., Mitta, P. & Randall, C. 1994. Performance of fixed film media integrated in activated sludge reactors to enhance nitrogen removal. *Water science and technology*.30(11):13-24.

Schmieg, S. 2011. *“One Step Beyond”*.Retrieved from http://1stepbeyond.wordpress.com/recipes/toilets/ (Accessed 12 January 2011).

Siebritz, I.P., Ekama,G.A., Marais, G.v.R. & South Africa Water Research Commission. 1983. *Biological excess phosphorus removal in the activated sludge process.* Cape Town: University of Cape Town.

Snyman, H.G. & Herselman, J.E. 2006.*Premise for the Development of Volume 1 and 2 of the South African Sludge Guidelines.*Pretoria, South Africa: Water Research Commission K5/1453/1/06.

Soewondo, P. & Yulianto, A. 2008.The effect of aeration mode on submerged aerobic bio filter reactor for grey water treatment. *Journal of applied sciences in environmental sanitation.*3(3):169-175.

Srinivas, H. 2011. *"Differentiating Management of Water Resources and Waste in Urban Areas".* Retrieved from http://www.gdrc.org/uem/waste/oldenburg.html (Accessed 23 January 2011)

Statistics South Africa. 2003. *Census 2001.* Pretoria: Statistics South Africa.

Technicon Autoanalyzer Methodology, Industrial Method 33~59W. 1969. Tarrytown, New York: Technicon Corporation

The Economist. 2010. Seing the wood. Special report. 396(8701):3-6.

The Living Principles, 2011.Retrieved from http://www.livingprinciples.org/flush-with-inequality-sanitation-in-south-africa/ (Accessed 12 January 2011).

Tilley, E., Atwater, J. & Mavinic, D. 2008. Recovery of struvite from stored human urine. *Environmental technology*.29(7):797-806.

Vinnerås, B. 2001.Faecal separation and urine diversion for nutrient management of household biodegradable waste and wastewater. Master Thesis. Swedish University of Agricultural Sciences, Department of Agricultural Engineering. (Unpublished)

Vinnerås, B., Björklund, A. & Jönsson, H. 2003.Thermal composting of faecal matter as treatment and possible disinfection method--laboratory-scale and pilot-scale studies.*Bioresource technology*.88(1):47-54.

Vinnerås, B. & Jönsson, H. 2002.The performance and potential of faecal separation and urine diversion to recycle plant nutrients in household wastewater.*Bioresource technology*.84(3):275-282.

Wandl, G., Schaar, H., Papp, M. & Svardal, K. 2009. The first two years of full scale operation of the two-stage Main Wastewater Treatment Plant of Vienna. *Water practice & technology*.4(1):170-177.

Wanner, J., Kucman, K. & Grau, P. 1988. Activated sludge process combined with biofilm cultivation. *Water research.*22(2):207-215.

Wentzel, M.C., Dold, P.L. & Ekama, G.A. 1985.Kinetics of biological phosphorus release.*Water science & technology*.17(11-12):57-71.

Wentzel, M.C., Ekama, G.A., Dold, P.L. & Marais, G.R. 1990.Biological excess phosphorus removal.Steady state process design.*Water S.A.* 16(1):29-48.

Wentzel, M.C., Ekama, G.A. & Loewenthal, R.E. 2010.Fundamentals of biological behaviour and wastewater measurement parameters.Civ 5045Z course notes. University of Cape Town, Department of Civil Engineering. Water Research Group. (Unpublished).

Wentzel, M.C., Ekama, G.A. & Marais, G.R. 1992.Processes and Modelling of Nitrification Denitrification Biological Excess Phosphorus Removal Systems--A Review.*Water science and technology WSTED 4.*25(6):59-82.

Wentzel, M.C., Mbewe, A. & Ekama, G.A. 1995. Batch test for measurement of readily biodegradable COD and active organism concentrations in municipal waste waters. *Water S.A.* 21(2):117-124.

Wilsenach, J. 2009.Urine separation [workshop]. CSIR, Stellenbosch. July 28.

Wilsenach, J. 2006. *Treatment of source separated urine and its effects on wastewater systems.* Ph.D. Thesis. Delft University of Technology, Delft, Netherlands.

Wilsenach, J. & Loosdrecht, M. 2002. Separate urine collection and treatment: options for sustainable wastewater systems and mineral recovery. Utrecht, Netherlands: STOWA.

Wilsenach, J. & Van Loosdrecht, M. 2003. Impact of separate urine collection on wastewater treatment systems.*Water science & technology*.48(1):103-110.

World Bank, 2010.*"Gross Domestic Product 2009.World Development Indicators database".*Retrieved fromhttp: //siteresources.worldbank.org/DATASTATISTICS/Resources/GDP_PPP.pdf. (Accessed05 October 2010).

WRC Project: JNPWT 39. 2009.Effects of urine separation and treatment on wastewater effluent quality, Deliverable 6, Perception Survey.

Zhirong, H., Wentzel, M.C. & Ekama, G.A. 2001. External nitrification in biological nutrient removal activated sludge systems. *Water science & technology*.43(1):251-260.

APPENDICES

APPENDIX A

DAILY MAINTENANCE AND OPERATION OF URINE, GREY AND BROWN WATER COLLECTION SYSTEMS

WRC Project: JNPWT 39 08 May 2008

Effects of Urine Separation and Treatment on WW Effluent Quality.

Re: Job Description for Operator of urine separation toilet WW collection system

---

WW Standard sampling Procedures:

1. Grinder pump operating guide & brown water sampling

- Before starting pump, make sure
    - Blue flexible recycle pipe is not twisted, and that it is well connected at both ends to the collection tank.
    - water level is above the minimum level for pumping.
- Turn pump ON.
- Check and ensure everything is working.
- After completing all other tasks on grey and urine sampling, only then sample brown water:
    1. Record volume of brown water in the tank, with pump switched OFF (to include brown water in hose and to avoid stirring effects on water level).
    2. Collect 150 ml of sample in 500 ml brown bottle while pump is running by opening sample valve, then label sample bottle with date and time (sample every week on Monday, Tuesday, & Thursday = 3 x 150 = 450 ml composite sample).
    3. After taking each sample empty the brown water tank.
    4. Reset toilet door counter to zero.
- Once tank is empty, flush tank out using hose pipe water. **When finished remember to close outlet valve to sewer**.
- On Thursday afternoon book in sample of the week and place in fridge.

Days operating grinder pump:

- Monday morning, Tuesday afternoon, Thursday afternoon
- Estimated time 1 hour/day.
- Contact electrician if pump is not working.

2. Separated urine sampling procedure

- FIRST, record volume of urine, date, time and people counters on clip-board.

2.1 Mens urine from waterless urinals – if the undiluted urine reactor needs a urine batch then - :

- disconnect urine downpipe and overflow pipe which lead into urine collection tank.
- place urine downpipe into 5 L bucket temporarily.
- pour urine slowly into 25 L square container (so that solid precipitate remains in collection tank), and liaise with Morgan.
- urine at the bottom of collection tank with precipitate will be thrown down the drain.
- reconnect downpipe and overflow to urine collection tank (no sample needs to be taken to the lab – Morgan will do that).

If the reactor **doesnot** need a urine batch, then discard urine without taking a sample.

2.2 Ladies urine from No-Mix toilets (take 3 samples per week, on Mon, Tues, Thurs)

- open sampling valve and drain **all** urine into open grey bucket, while stirring with PVC plank to suspend all solids and get a representative sample.
- sub-sample 150 ml into 500 ml brown plastic bottle.
- place sample bottle in closed white bucket next to collection tanks.
- leave urine which you can not remove in the bottom of the urine tank.
- label sample bottle with date.
- on Thursday afternoon book in sample of the week and place in fridge.

2.3 Mens urine from No-Mix toilets (take 3 samples per week, on Mon, Tues, Thurs)

- disconnect urine downpipe and overflow pipe which lead into urine collection tank.
- place urine downpipe into 5L bucket temporarily.
- pour**all** urine into open grey bucket after stirring with PVC plank to suspend all solids and get a representative sample.

- sub-sample 150 ml into 500 ml brown plastic bottle, again while stirring.
- place sample bottle in closed white bucket next to collection tanks.
- label sample bottle with date.
- on Thursday afternoon book in sample of the week and place in fridge.

- **Days collecting urine samples:**

Monday morning, Tuesday afternoon, Thursday afternoon

Estimated time required 45 min/day (Operator to confirm).

3.1 Grey water sampling procedure

(FIRST record volume of grey water, date, and time before discarding)

- completely empty grey water into 25 L white buckets
- move buckets using trolley/wheel barrow to store room and transfer grey water into 150 L blue drums
- when in doubt, check with Jason how many buckets are required.
- when no grey water is collected, pour grey water down the drain on LHS.
- no grey water sample needs to be submitted to the lab (Project leader will do this).

Monday morning, Tuesday afternoon, Thursday afternoon

Estimated time required 25 min/day (operator to confirm).

When collecting grey water for processing, the discharge line on the right is used to fill 25L containers. These are either taken to CSIR Process Lab to fill the grey water reactor, or decanted into 150 L drums and transported to UCT Water Lab to be used as feed for the mixed WW reactors.

Every 2 weeks:

WW to be transported to UCT by operator (Civil Engineering building, contact person Andre Mbaya) using CSIR truck.

WW to be transported consists of grey water, brown water and urine in separate containers:

1. Grey water is collected by filling up the 150 L drums one week in advance. Once full, these drums will be loaded on CSIR bakkie. These drums must be closed and tied down to the bakkie. Careful handling is necessary to prevent damage to outlet taps.

2. Urine from the no-mix toilets will be decanted into the 25 L square containers. This urine will be collected over a one week period on Mondays, Tuesdays and Thursdays before being delivered.

3. Brown water is collected on the day of delivery from the 200 L WW container while operating the grinder pump. 25 L white buckets should used to store and deliver the brown water to UCT.

For emergencies, brown water stored in 25 L white buckets can be keep cool in the empty freezer in the compressor room by B-block or the walk-in fridges. This freezer should be kept slightly open to prevent the WW from freezing.

APPENDIX B

OPERATIONAL DATA FOR THE UCT SYSTEM

TABLE OF CONTENTS

Table B.1:UCT average COD concentrations and OUR data for each sewage batch.

UCT SYSTEM AVERAGE COD (*mg COD/ℓ*) AND OUR (*mg O/ℓhr*) DATA

BATCH No	**INFLUENT (I)**			**FILTERED INFLUENT (FI)**			**AEROBIC MIXED LIQUOR (AEML)**			**UNFILTERED EFFLUENT (UE)**			**FILTERED EFFLUENT (FE)**			**OUR**		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**
1	*1032.3*	*113.9*	*12*	*444.8*	*51*	*12*	*4260.9*	*214*	*12*	*125.6*	*14*	*12*	*87.0*	*13*	*12*	*23.4*	*0.2*	*12*
2	*1018.6*	*62.1*	*5*	*379.6*	*52*	*5*	*4747.7*	*199*	*5*	*93.4*	*11*	*5*	*69.4*	*12*	*5*	*23.9*	*0.7*	*5*
3	*1101.9*	*87.0*	*4*	*300.0*	*19*	*4*	*4168.3*	*662*	*4*	*122.4*	*12*	*4*	*100.0*	*4*	*4*	*23.6*	*0.0*	*4*
4	*1019.8*	*88.7*	*5*	*412.9*	*43*	*5*	*4033.1*	*98*	*5*	*116.3*	*27*	*5*	*104.0*	*25*	*5*	*23.0*	*0.5*	*5*
5	*1036.1*	*67.7*	*7*	*391.3*	*36*	*7*	*4248.9*	*417*	*7*	*93.2*	*9*	*7*	*75.9*	*8*	*7*	*23.7*	*1.3*	*7*
6	*991.9*	*199.9*	*6*	*322.0*	*68*	*6*	*3355.8*	*386*	*6*	*76.7*	*26*	*6*	*74.7*	*21*	*6*	*23.1*	*7.2*	*3*
7	*979.8*	*102.5*	*6*	*373.0*	*51*	*6*	*3187.4*	*508*	*6*	*93.7*	*15*	*6*	*71.1*	*19*	*6*	*25.3*	*1.0*	*6*
8	*974.1*	*122.5*	*6*	*329.0*	*80*	*6*	*4052.5*	*295*	*6*	*150.7*	*11*	*6*	*73.2*	*10*	*6*	*25.2*	*2.1*	*6*
9	*1019.8*	*121.6*	*5*	*431.0*	*34*	*5*	*4690.0*	*367*	*5*	*125.0*	*11*	*5*	*91.0*	*15*	*5*	*25.4*	*0.9*	*5*
10	*1288.3*	*95.9*	*4*	*530.3*	*45*	*4*	n/a			*145.7*	*11*	*4*	*81.0*	*3*	*4*	*n/a*		
11	*1036.3*	*156.8*	*5*	*357.3*	*133*	*5*	*3761.0*	*227*	*5*	*141.3*	*11*	*5*	*81.7*	*13*	*5*	*24.4*	*3.7*	*5*
12	*978.4*	*103.3*	*5*	*273.6*	*71*	*5*	n/a			*125.2*	*13*	*5*	*110.9*	*12*	*5*	*n/a*		
13	*1019.8*	*57.3*	*5*	*250.4*	*52*	*5*	*3880.5*	*76*	*5*	*144.2*	*18*	*5*	*103.4*	*15*	*5*	*23.4*	*1.6*	*5*
14	*943.8*	*69.2*	*5*	*279.9*	*102*	*5*	n/a			*141.6*	*11*	*5*	*113.9*	*12*	*5*	*n/a*		
15	*1012.0*	*111.1*	*4*	*223.9*	*35*	*4*	n/a			*144.7*	*17*	*4*	*110.9*	*20*	*4*	*n/a*		
16	*961.3*	*79.4*	*3*	*177.3*	*32*	*3*	*3693.3*	*233*	*3*	*168.7*	*9*	*3*	*127.3*	*10*	*3*	*19.2*	*0.8*	*3*

n/a refers to sewage batches for which daily effluent concentrations, settleable solids (TSS, VSS and ISS) and DSVI only were measured while the JHB system was fully tested

Table B.2: UCT average TKN concentrations for each sewage batch.

UCT SYSTEM AVERAGE TKN (*mg N/ℓ*)															
BATCH No	**INFLUENT (I)**			**FILTERED INFLUENT (FI)**			**AEROBIC MIXED LIQUOR (AEML)**			**UNFILTERED EFFLUENT (UE)**			**FILTERED EFFLUENT (FE)**		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**
1	*54.7*	*2.2*	*12*	*31.4*	*3.0*	*12*	*271.0*	*20.7*	*12*	*5.9*	*0.9*	*12*	*2.4*	*1.2*	*12*
2	*50.4*	*2.2*	*5*	*26.6*	*1.3*	*5*	*345.3*	*15.2*	*5*	*3.8*	*0.8*	*5*	*2.3*	*0.9*	*5*
3	*66.1*	*3.4*	*4*	*36.7*	*5.9*	*4*	*306.8*	*7.9*	*4*	*5.2*	*0.8*	*4*	*3.8*	*0.5*	*4*
4	*49.5*	*2.6*	*5*	*34.2*	*1.0*	*5*	*283.9*	*6.7*	*5*	*4.9*	*1.0*	*5*	*2.5*	*1.7*	*5*
5	*45.2*	*3.2*	*7*	*25.3*	*2.1*	*7*	*310.6*	*15.7*	*7*	*4.3*	*0.7*	*7*	*3.3*	*0.8*	*7*
6	*66.5*	*2.7*	*6*	*34.7*	*0.7*	*6*	*324.5*	*9.2*	*6*	*4.4*	*1.1*	*6*	*5.0*	*2.0*	*6*
7	*68.4*	*1.7*	*6*	*42.4*	*7.3*	*6*	*327.9*	*10.4*	*6*	*6.1*	*1.5*	*6*	*5.0*	*0.9*	*6*
8	*63.6*	*14.4*	*6*	*25.0*	*2.8*	*6*	*463.8*	*59.2*	*6*	*7.9*	*2.0*	*6*	*5.0*	*1.8*	*6*
9	*46.0*	*6.1*	*5*	*31.0*	*6.5*	*5*	*321.1*	*23.7*	*5*	*9.0*	*3.2*	*5*	*5.8*	*2.9*	*5*
10	*62.9*	*2.8*	*4*	*42.7*	*2.5*	*4*		*n/a*		*7.0*	*2.5*	*4*	*6.7*	*0.0*	*4*
11	*49.1*	*1.1*	*5*	*32.8*	*1.7*	*5*	*291.7*	*8.8*	*5*	*9.2*	*3.2*	*5*	*7.0*	*0.3*	*5*
12	*55.2*	*1.8*	*5*	*34.3*	*0.9*	*5*		*n/a*		*8.5*	*2.9*	*5*	*6.8*	*0.0*	*5*
13	*49.5*	*1.0*	*5*	*33.3*	*1.5*	*5*	*305.0*	*41.1*	*5*	*10.2*	*0.5*	*5*	*6.3*	*0.3*	*5*
14	*55.2*	*3.1*	*5*	*34.7*	*2.7*	*5*		*n/a*		*8.9*	*1.9*	*5*	*6.8*	*0.0*	*5*
15	*74.1*	*1.7*	*4*	*50.2*	*4.4*	*4*		*n/a*		*9.5*	*2.0*	*4*	*5.0*	*0.0*	*4*
16	*63.9*	*1.3*	*3*	*34.8*	*4.6*	*3*	*250.4*	*6.0*	*3*	*7.6*	*0.6*	*3*	*4.0*	*0.5*	*3*

n/a refers to sewage batches for which daily effluent concentrations, settleable solids (TSS, VSS and ISS) and DSVI only were measured while the JHB system was fully tested

Table B.3: UCT average FSA concentrations for each sewage batch.

UCT SYSTEM AVERAGE FSA (*mg NH_3-N/ℓ*)						
BATCH No	**FILTERED INFLUENT (FI)**			**FILTERED EFFLUENT (FE)**		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**
1	*23.8*	*3.4*	*12*	*2.4*	*0.2*	*12*
2	*20.6*	*1.3*	*5*	*3.2*	*1.3*	*5*
3	*30.6*	*1.7*	*4*	*2.6*	*0.4*	*4*
4	*27.2*	*3.2*	*5*	*2.4*	*0.7*	*5*
5	*18.4*	*1.5*	*7*	*2.3*	*0.3*	*7*
6	*28.4*	*0.9*	*6*	*2.2*	*0.8*	*6*
7	*29.4*	*4.6*	*6*	*4.0*	*1.0*	*6*
8	*23.5*	*9.1*	*6*	*5.1*	*2.5*	*6*
9	*23.3*	*3.6*	*5*	*5.6*	*1.0*	*5*
10	*29.7*	*2.8*	*4*	*3.4*	*0.5*	*4*
11	*20.7*	*6.7*	*5*	*4.8*	*0.2*	*5*
12	*24.7*	*3.5*	*5*	*8.5*	*1.1*	*5*
13	*26.3*	*0.8*	*5*	*3.9*	*0.2*	*5*
14	*26.7*	*1.7*	*5*	*3.7*	*0.4*	*5*
15	*42.3*	*0.9*	*4*	*2.6*	*0.2*	*4*
16	*28.8*	*0.0*	*3*	*1.9*	*0.0*	*3*

Table B.4: UCT average Nitrite concentrations for each sewage batch.

UCT SYSTEM AVERAGE NITRITE (*mg* NO_2*-N/ℓ*)															
BATCH No	**INFLUENT (I)**			**AN REACTOR (AN)**			**ANOXIC REACTOR (AX)**			**AEROBIC REACTOR (AE)**			**FILTERED EFFLUENT (FE)**		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**
1	*0.05*	*0.0*	*12*	*0.00*	*0.0*	*12*	*0.02*	*0.1*	*12*	*0.07*	*0.1*	*12*	*0.10*	*0.1*	*12*
2	*0.18*	*0.1*	*5*	*0.00*	*0.0*	*5*	*0.14*	*0.0*	*5*	*0.20*	*0.0*	*5*	*0.18*	*0.2*	*5*
3	*0.18*	*0.1*	*4*	*0.00*	*0.0*	*4*	*0.11*	*0.0*	*4*	*0.30*	*0.0*	*4*	*0.23*	*0.2*	*4*
4	*0.14*	*0.1*	*4*	*0.00*	*0.0*	*4*	*0.11*	*0.0*	*4*	*0.17*	*0.0*	*4*	*0.22*	*0.2*	*4*
5	*0.19*	*0.1*	*7*	*0.00*	*0.0*	*7*	*0.13*	*0.0*	*7*	*0.13*	*0.0*	*7*	*0.18*	*0.2*	*7*
6	*0.10*	*0.0*	*6*	*0.00*	*0.0*	*6*	*0.07*	*0.0*	*6*	*0.09*	*0.0*	*6*	*0.15*	*0.2*	*6*
7	*0.08*	*0.0*	*6*	*0.00*	*0.0*	*6*	*0.07*	*0.0*	*6*	*0.08*	*0.0*	*6*	*0.15*	*0.2*	*6*
8	*0.05*	*0.0*	*6*	*0.05*	*0.0*	*6*	*0.05*	*0.0*	*6*	*0.43*	*0.2*	*6*	*0.34*	*0.3*	*6*
9	*0.02*	*0.0*	*5*	*0.02*	*0.0*	*5*	*0.02*	*0.0*	*5*	*0.03*	*0.0*	*5*	*0.03*	*0.0*	*5*
10	*0.00*	*0.0*	*4*	*n/a*			*n/a*			*n/a*			*0.00*	*0.0*	*4*
11	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.13*	*0.1*	*5*	*0.04*	*0.0*	*5*
12	*0.00*	*0.0*	*5*	*n/a*			*n/a*			*n/a*			*0.01*	*0.0*	*5*
13	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.05*	*0.1*	*5*	*0.02*	*0.0*	*5*
14	*0.07*	*0.1*	*5*	*n/a*			*n/a*			*n/a*			*0.09*	*0.0*	*5*
15	*0.00*	*0.0*	*4*	*n/a*			*n/a*			*n/a*			*0.00*	*0.0*	*4*
16	*0.00*	*0.0*	*3*	*0.00*	*0.0*	*3*	*0.00*	*0.0*	*3*	*0.02*	*0.0*	*3*	*0.07*	*0.0*	*3*

n/a refers to sewage batches for which daily effluent concentrations, settleable solids (TSS, VSS and ISS) and DSVI only were measured while the JHB system was fully tested

Table B.5: UCT average Nitrate concentrations for each sewage batch.

UCT SYSTEM AVERAGE NITRATE (*mg* NO_3*-N/ℓ*)

BATCH No	INFLUENT (I)			AN REACTOR (AN)			ANOXIC REACTOR (AX)			AEROBIC REACTOR (AE)			FILTERED EFFLUENT (FE)		
	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N
1	0.00	0.0	12	0.00	0.0	12	0.00	0.1	12	0.33	0.1	12	0.49	0.2	12
2	0.00	0.1	5	0.00	0.0	5	0.00	0.0	5	0.17	0.1	5	0.19	0.1	5
3	0.00	0.2	4	0.00	0.0	4	0.00	0.0	4	0.54	0.1	4	0.50	0.1	4
4	0.00	1.6	4	0.00	0.0	4	0.00	0.0	4	0.47	0.1	4	0.85	0.3	4
5	0.00	2.9	7	0.00	0.0	7	0.00	0.0	7	0.00	0.0	7	0.00	0.1	7
6	0.00	0.0	6	0.00	0.0	6	0.00	0.0	6	0.33	0.1	6	0.33	0.1	6
7	0.00	0.0	6	0.00	0.0	6	0.00	0.0	6	0.35	0.1	6	0.47	0.1	6
8	0.00	0.0	6	0.00	0.0	6	0.00	0.0	6	0.32	0.3	6	0.46	0.2	6
9	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5
10	0.00	0.0	4	n/a			n/a			n/a			0.66	0.5	4
11	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5	0.19	0.1	5	0.26	0.3	5
12	0.00	0.0	5	n/a			n/a			n/a			0.10	0.1	5
13	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5	0.00	0.0	5
14	0.00	0.0	5	n/a			n/a			n/a			0.01	0.0	5
15	0.03	0.0	4	n/a			n/a			n/a			0.38	0.1	4
16	0.00	0.0	3	0.00	0.0	3	0.00	0.0	3	0.50	0.2	3	0.53	0.2	3

n/a refers to sewage batches for which daily effluent concentrations, settleable solids (TSS, VSS and ISS) and DSVI only were measured while the JHB system was fully tested

Table B.6: UCT average TP concentrations for each sewage batch.

UCT SYSTEM AVERAGE TOTAL PHOSPHORUS (*mg PO_4-P/ℓ*)

BATCH No	INFLUENT (I)			AN REACTOR (AN)			ANOXIC REACTOR (AX)			FILTERED AEROBIC (AE)			AEROBIC MIXED LIQUOR (ML)			FILTERED EFFLUENT (FE)		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**
1	*15.5*	*2.3*	*12*	*26.8*	*1.7*	*12*	*23.7*	*2.9*	*12*	*0.8*	*0.8*	*12*	*80.9*	*17.9*	*12*	*1.4*	*0.8*	*12*
2	*19.5*	*6.5*	*5*	*23.7*	*1.4*	*5*	*8.4*	*0.7*	*5*	*0.7*	*3.5*	*5*	*131.0*	*37.4*	*5*	*0.6*	*1.4*	*5*
3	*24.2*	*5.7*	*4*	*20.6*	*0.8*	*4*	*8.7*	*3.8*	*4*	*3.7*	*1.4*	*4*	*156.5*	*26.8*	*4*	*2.1*	*0.3*	*4*
4	*14.8*	*6.6*	*5*	*17.5*	*1.3*	*5*	*6.0*	*0.8*	*5*	*1.2*	*0.6*	*5*	*102.5*	*2.4*	*5*	*1.0*	*0.7*	*5*
5	*14.1*	*1.2*	*7*	*31.0*	*2.2*	*7*	*12.3*	*1.2*	*7*	*1.0*	*0.3*	*7*	*106.8*	*23.6*	*7*	*0.8*	*0.3*	*7*
6	*21.0*	*6.3*	*6*	*31.4*	*1.4*	*6*	*16.5*	*0.8*	*6*	*2.7*	*0.8*	*6*	*98.4*	*6.2*	*6*	*2.4*	*0.9*	*6*
7	*17.3*	*7.1*	*6*	*31.8*	*0.4*	*6*	*14.2*	*1.6*	*6*	*2.1*	*1.1*	*6*	*100.8*	*13.4*	*6*	*2.0*	*1.1*	*6*
8	*23.2*	*6.5*	*6*	*30.2*	*5.5*	*6*	*18.3*	*8.9*	*6*	*7.7*	*8.4*	*6*	*135.4*	*11.3*	*6*	*2.4*	*0.8*	*6*
9	*11.5*	*2.2*	*5*	*23.7*	*0.7*	*5*	*17.0*	*1.2*	*5*	*12.0*	*0.8*	*5*	*98.1*	*6.8*	*5*	*6.2*	*3.7*	*5*
10	*21.9*	*1.1*	*4*		*n/a*			*n/a*			*n/a*			*n/a*		*1.2*	*0.0*	*4*
11	*17.3*	*2.9*	*5*	*23.6*	*1.4*	*5*	*11.6*	*1.7*	*5*	*2.7*	*1.5*	*5*	*96.9*	*2.7*	*5*	*3.0*	*2.9*	*5*
12	*21.0*	*1.5*	*5*		*n/a*			*n/a*			*n/a*			*n/a*		*3.5*	*0.0*	*5*
13	*21.9*	*5.2*	*5*	*25.7*	*1.4*	*5*	*12.9*	*2.9*	*5*	*1.0*	*0.4*	*5*	*109.3*	*12.9*	*5*	*1.1*	*0.9*	*5*
14	*23.0*	*1.8*	*5*		*n/a*			*n/a*			*n/a*			*n/a*		*8.3*	*0.0*	*5*
15	*23.6*	*6.5*	*4*		*n/a*			*n/a*			*n/a*			*n/a*		*0.8*	*0.0*	*4*
16	*27.3*	*1.6*	*3*	*27.6*	*0.3*	*3*	*12.7*	*0.8*	*3*	*5.7*	*0.5*	*3*	*108.1*	*7.6*	*3*	*5.7*	*0.7*	*3*

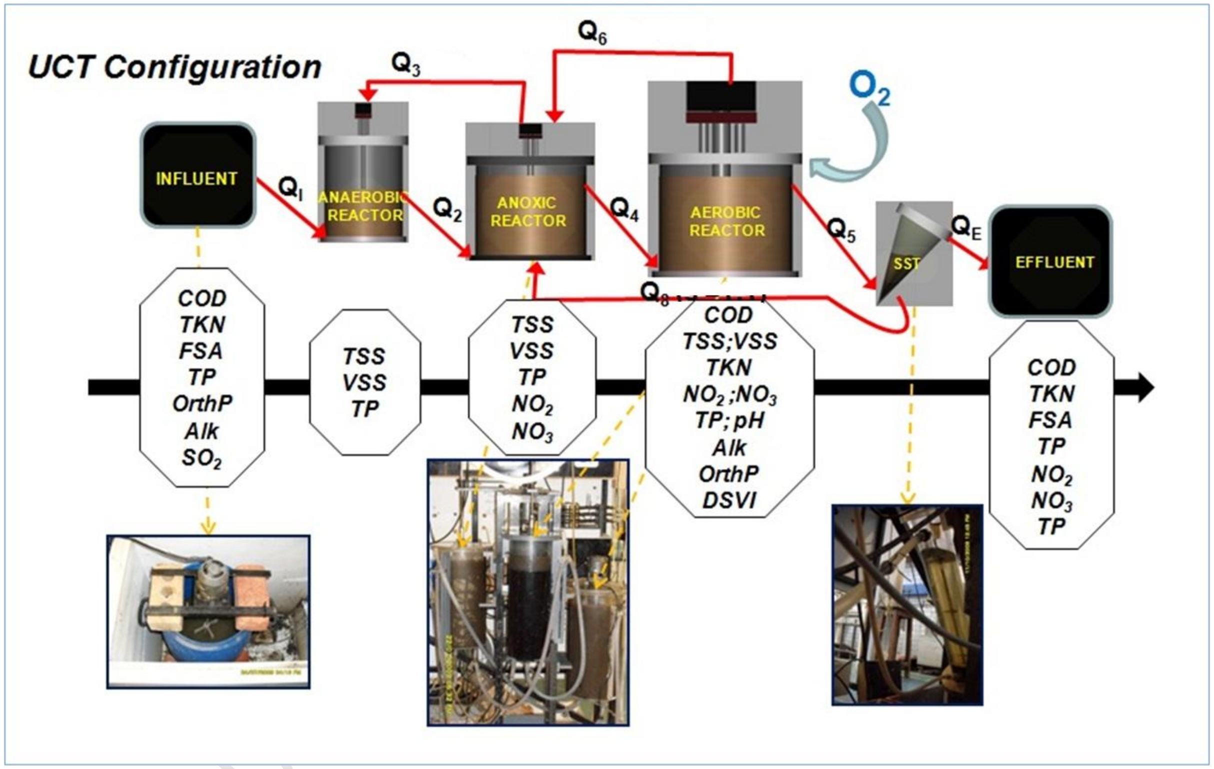
n/a refers to sewage batches for which daily effluent concentrations, settleable solids (TSS, VSS and ISS) and DSVI only were measured while the JHB system was fully tested

Table B.7: UCT average VSS and TSS concentrations for each sewage batch.

UCT SYSTEM AVERAGE AEROBIC VSS (*mg VSS/ℓ*) AND TSS (*mg TSS/ℓ*)						
BATCH No	**AEVSS**			**AETSS**		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**
1	*3436*	*250.9*	*12*	*3988*	*112.4*	*12*
2	*3702*	*182.0*	*5*	*4344*	*229.0*	*5*
3	*3276*	*113.2*	*4*	*3901*	*136.3*	*4*
4	*3229*	*255.3*	*4*	*3820*	*128.6*	*4*
5	*3332*	*95.2*	*7*	*3893*	*93.5*	*7*
6	*3172*	*503.8*	*6*	*4140*	*215.1*	*6*
7	*2476*	*615.6*	*6*	*4423*	*112.5*	*6*
8	*4006*	*308.0*	*6*	*4518*	*331.6*	*6*
9	*3915*	*119.9*	*5*	*4319*	*126.3*	*5*
10	*3592*	*245.4*	*4*	*4024*	*239.7*	*4*
11	*3591*	*118.4*	*5*	*4051*	*103.4*	*5*
12	*3064*	*179.1*	*5*	*3465*	*234.4*	*5*
13	*3257*	*431.9*	*5*	*3822*	*435.0*	*5*
14	*4155*	*693.6*	*5*	*4754*	*844.8*	*5*
15	*3834*	*566.5*	*4*	*4456*	*716.9*	*4*
16	*3787*	*369.7*	*3*	*4426*	*445.2*	*3*

Actual Flow Data

In order to obtain the actual flows (as opposed to the design flows) within the pipes of a particular biological system, one needed to manually measure it. This was done by using a stop watch and a recipient such as a cylinder. The watch was used for timing and the cylinder for containing and subsequently measuring the fluid collected over the recorded time. The flow (ℓ/s) would then be given as the ratio of the volume of sludge collected (± 250 ml) and the recorded time (10 min). Flows were measured because the voltage of the main power supply fluctuated. The flows used in the mass balance calculations for a batch of sewage are the average actual flows for that particular batch.



The flows measured were Q_3 ;Q_6 and Q_8. The remaining flows were calculated as follow:

- $Q_w \quad = \quad V_{uct\ system} / SRT$

Where:

$V_{\text{uct system}}$ = overall reactor volume $=(V_{\text{actual}} * V_{\text{equivalent of mass}})_{\text{anaerobic}} + (V_{\text{actual}} * V_{\text{equivalent of mass}})_{\text{anoxic}} + (V_{\text{actual}} * V_{\text{equivalent of mass}})_{\text{aerobic}}$

$= (7*0.5)+(10*1)+(15*1)$

$= 28.5$ l

SRT = sludge age = 20 days

- $Q_e = Q_i - Q_w$
- $Q_2 = Q_i + Q_3$
- $Q_4 = Q_2 + Q_6 + Q_8 - Q_3$
- $Q_5 = Q_4 - Q_6 - Q_w$

Table B.8: Actual average flow data for each sewage batch of the UCT system

BATCH No	**Pump On/Off time**									
DESIGN FLOW	***Flow***	**Qi**	**Q2**	**Q3**		**Q5**	**Q6**	**Qe**	**Q8**	**Qw**
		1	**1+r**	**r**	**1+a+s**	**1+s**	**a**		**s**	
	Flow/Qi	**1.0**	**2.0**	**1.0**	**4.0**	**1.9**	**2.0**	**0.9**	**1.0**	
	ℓ/s	0.0002	0.0003	0.0002	0.0007	0.0003	0.0003	0.0002	0.0002	0.0000
	ℓ/d	***15.0***	***30.0***	***15.0***	***60.0***	***28.6***	***30.0***	***13.6***	***15.0***	***1.425***
1	**25 sec /75 sec**									
	Flow/Qi	***1***	***3***	***2.30***	***9***	***3***	***5.44***	***1***	***2.24***	
	ℓ/s	0.0002	0.0006	0.0004	0.0015	0.0005	0.0009	0.0002	0.0004	0.0000
	ℓ/d	***15***	***49.1***	***34.2***	***129.2***	***46.8***	***81.0***	***13.5***	***33.4***	***1.425***
2	**25 sec /59 sec**									
	Flow/Qi	***1***	***3***	***1.50***	***7***	***3***	***3.82***	***1***	***2.18***	
	ℓ/s	0.0002	0.0004	0.0003	0.0012	0.0005	0.0007	0.0002	0.0004	0.0000
	ℓ/d	***15***	***37.2***	***22.3***	***104.2***	***45.9***	***56.9***	***13.5***	***32.4***	***1.425***

3	**25 sec /59 sec**									
	Flow/Qi	***1***	***3***	***1.50***	***7***	***3***	***3.82***	***1***	***2.18***	
	ℓ/s	0.0002	0.0004	0.0003	0.0012	0.0005	0.0007	0.0002	0.0004	0.0000
	ℓ/d	***15***	***37.2***	***22.3***	***104.2***	***45.9***	***56.9***	***13.5***	***32.4***	***1.425***
4	**25 sec /59 sec**									
	Flow/Qi	***1***	***3***	***1.50***	***7***	***3***	***3.82***	***1***	***2.18***	
	ℓ/s	0.0002	0.0004	0.0003	0.0012	0.0005	0.0007	0.0002	0.0004	0.000
	ℓ/d	***15***	***37.20***	***22.32***	***104.16***	***45.86***	***56.88***	***13.46***	***32.40***	***1.425***
5	**25 sec /75 sec**									
	Flow/Qi	***1***	***3***	***2.30***	***9***	***3***	***5.44***	***1***	***2.24***	
	ℓ/s	0.0002	0.0006	0.0004	0.0015	0.0005	0.0009	0.0002	0.0004	0.0000
	ℓ/d	***15***	***49.1***	***34.2***	***129.2***	***46.8***	***81.0***	***13.5***	***33.4***	***1.425***
6	**25 sec /75 sec**									
	Flow/Qi	***1***	***3***	***2.30***	***9***	***3***	***5.44***	***1***	***2.24***	
	ℓ/s	0.0002	0.0006	0.0004	0.0015	0.0005	0.0009	0.0002	0.0004	0.0000
	ℓ/d	***15***	***49.1***	***34.2***	***129.2***	***46.8***	***81.0***	***13.5***	***33.4***	***1.425***
7	**25 sec /75 sec**									
	Flow/Qi	***1***	***3***	***2.30***	***9***	***3***	***5.44***	***1***	***2.24***	
	ℓ/s	0.0002	0.0006	0.0004	0.0015	0.0005	0.0009	0.0002	0.0004	0.0000
	ℓ/d	***15***	***49.1***	***34.2***	***129.2***	***46.8***	***81.0***	***13.5***	***33.4***	***1.425***
8	**25 sec /62 sec**									
	Flow/Qi	***1***	***3***	***1.50***	***7***	***3***	***3.82***	***1***	***2.18***	
	ℓ/s	0.0002	0.0004	0.0003	0.0012	0.0005	0.0007	0.0002	0.0004	0.0000
	ℓ/d	***15***	***37.2***	***22.3***	***104.2***	***45.9***	***56.9***	***13.5***	***32.4***	***1.425***
9	**25 sec /29 sec**									
	Flow/Qi	***1***	***2***	***1.08***	***5***	***2***	***2.55***	***1***	***1.05***	
	ℓ/s	0.0002	0.0004	0.0002	0.0008	0.0003	0.0004	0.0002	0.0002	0.0000
	ℓ/d	***15***	***30.9***	***16.0***	***68.5***	***29.1***	***37.9***	***13.5***	***15.6***	***1.425***
10	**25 sec /62 sec**									

	Flow/Qi	*1*	*3*	*1.50*	*7*	*3*	*3.82*	*1*	*2.18*	
	ℓ/s	0.0002	0.0004	0.0003	0.0012	0.0005	0.0007	0.0002	0.0004	0.0000
	ℓ/d	*15*	*37.2*	*22.3*	*104.2*	*45.9*	*56.9*	*13.5*	*32.4*	*1.425*
11	**25 sec /59 sec**									
	Flow/Qi	*1*	*2*	*1.38*	*6*	*3*	*2.79*	*1*	*1.78*	
	ℓ/s	0.0002	0.0004	0.0002	0.0010	0.0005	0.0005	0.0002	0.0003	0.0000
	ℓ/d	*15*	*35.5*	*20.6*	*83.0*	*40.0*	*41.6*	*13.5*	*26.5*	*1.425*
12	**25 sec /59 sec**									
	Flow/Qi	*1*	*2*	*1.38*	*6*	*3*	*2.79*	*1*	*1.78*	
	ℓ/s	0.0002	0.0004	0.0002	0.0010	0.0005	0.0005	0.0002	0.0003	0.0000
	ℓ/d	*15*	*35.5*	*20.6*	*83.0*	*40.0*	*41.6*	*13.5*	*26.5*	*1.425*
13	**25 sec /59 sec**									
	Flow/Qi	*1*	*2*	*1.38*	*6*	*3*	*2.79*	*1*	*1.78*	
	ℓ/s	0.0002	0.0004	0.0002	0.0010	0.0005	0.0005	0.0002	0.0003	0.0000
	ℓ/d	*15*	*35.5*	*20.6*	*83.0*	*40.0*	*41.6*	*13.5*	*26.5*	*1.425*
14	**25 sec /59 sec**									
	Flow/Qi	*1*	*2*	*1.38*	*6*	*3*	*2.79*	*1*	*1.78*	
	ℓ/s	0.0002	0.0004	0.0002	0.0010	0.0005	0.0005	0.0002	0.0003	0.0000
	ℓ/d	*15*	*35.5*	*20.6*	*83.0*	*40.0*	*41.6*	*13.5*	*26.5*	*1.425*
15	**26 sec /59 sec**									
	Flow/Qi	*1*	*2*	*1.38*	*6*	*3*	*2.79*	*1*	*1.78*	
	ℓ/s	0.0002	0.0004	0.0002	0.0010	0.0005	0.0005	0.0002	0.0003	0.0000
	ℓ/d	*15*	*35.5*	*20.6*	*83.0*	*40.0*	*41.6*	*13.5*	*26.5*	*1.425*
16	**25 sec /39 sec**									
	Flow/Qi	*1*	*3*	*1.85*	*7*	*3*	*3.73*	*1*	*2.39*	
	ℓ/s	0.0002	0.0005	0.0003	0.0012	0.0006	0.0006	0.0002	0.0004	0.0000
	ℓ/d	*15*	*42.4*	*27.6*	*106.0*	*49.0*	*55.5*	*13.5*	*35.6*	*1.425*

Table B.9: Influent WW COD characterization for the UCT system (20d SRT)

	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B11**	**B13**	***Avg =***
S_{ti}	*1032.3*	*1018.6*	*1101.9*	*1019.8*	*1036.1*	*991.9*	*979.8*	*974.1*	*1019.8*	*1036.3*	*1019.8*	***1020.9***
S_{si}	*444.8*	*379.6*	*300.0*	*412.9*	*391.3*	*322.0*	*373.0*	*329.0*	*431.0*	*357.3*	*250.4*	***362.8***
S_{pi}	*587.5*	*637.0*	*802.0*	*607.0*	*644.8*	*669.8*	*606.8*	*645.1*	*588.8*	*679.0*	*769.4*	***657.9***
S_{usi}	*87.0*	*69.4*	*100.0*	*104.0*	*75.9*	*74.7*	*71.1*	*73.2*	*91.0*	*81.7*	*110.9*	***85.4***
S_{bsi}	*357.8*	*310.2*	*199.9*	*308.9*	*315.4*	*247.3*	*301.9*	*255.8*	*340.0*	*275.6*	*139.5*	***277.5***
S_{upi}	*185.9*	*273.9*	*221.9*	*205.0*	*209.2*	*160.7*	*141.3*	*243.5*	*269.2*	*199.4*	*242.4*	***213.9***
S_{bpi}	*401.6*	*365.1*	*580.0*	*401.9*	*435.6*	*509.1*	*465.6*	*401.6*	*319.7*	*479.6*	*527.0*	***444.3***
S_{bi}	*759.3*	*675.3*	*779.9*	*710.8*	*751.1*	*756.4*	*767.5*	*657.3*	*659.7*	*755.2*	*666.5*	***721.7***
S_{ui}	*272.9*	*343.3*	*322.0*	*309.1*	*285.1*	*235.5*	*212.3*	*316.7*	*360.2*	*281.1*	*353.3*	***299.2***

Note: Table B.9 data ignore the biodegradable soluble COD (~60 % of measured 0.45µm membrane filtered effluent) exiting in the effluent of the UCT system.Refer to Appendix F for COD, N and P characterization procedures.

Table B.10: AN, AX and AE daily solids (TSS, VSS and ISS) variations for the UCT system (20d SRT)

Date	AN				AX				AE					
	TSS	ISS	VSS	VSS/TSS	TSS	ISS	VSS	VSS/TSS	TSS	ISS	VSS	VSS/TSS	SV_{30}	DSVI
				f_i				f_i				f_i		
–	mg/L	mg/L	mg/L	—	mg/L	mg/L	mg/L	—	mg/L	mg/L	mg/L	—	ml	ml/gTSS
1-Apr-09	1696	204	1492	0.88	3370	504	2866	0.85	3472	536	2936	**0.85**	116	67
2-Apr-09	1706	226	1480	0.87	3390	502	2888	0.85	3704	574	3130	**0.85**	128	69
3-Apr-09	1742	216	1526	0.88	3660	574	3086	0.84	3820	588	3232	**0.85**	147	77
7-Apr-09	1760	270	1490	0.85	3692	582	3110	0.84	3638	668	2970	**0.82**	137	75
8-Apr-09	1700	218	1482	0.87	3100	440	2660	0.86	3036	464	2572	**0.85**	112	74
14-Apr-09	1616	216	1400	0.87	3048	446	2602	0.85	3614	494	3120	**0.86**	128	71
19-Apr-09	1484	140	1344	0.91	2842	470	2372	0.83	3096	500	2596	**0.84**	125	81
21-Apr-09	1552	210	1342	0.86	4558	656	3902	0.86	3242	462	2780	**0.86**	118	73
22-Apr-09	1810	226	1584	0.88	4660	666	3994	0.86	3676	582	3094	**0.84**	148	81
23-Apr-09	1382	200	1182	0.86	4300	646	3654	0.85	2684	468	2216	**0.83**	129	74
27-Apr-09	1596	178	1418	0.89	3902	626	3276	0.84	2708	462	2246	**0.83**	125	92
28-Apr-09	1656	206	1450	0.88	3812	522	3290	0.86	2946	394	2552	**0.87**	116	79

5-May-09	*1302*	*66*	*1236*	*0.95*	*1988*	*168*	*1820*	*0.92*	*2114*	*208*	*1906*	***0.90***	*127*	*76*
6-May-09	*1404*	*156*	*1248*	*0.89*	*2156*	*290*	*1866*	*0.87*	*2650*	*394*	*2256*	***0.85***	*120*	*91*
7-May-09	*1254*	*130*	*1124*	*0.90*	*2524*	*528*	*1996*	*0.79*	*2702*	*588*	*2114*	***0.78***	*119*	*88*
8-May-09	*2078*	*266*	*1812*	*0.87*	*2272*	*316*	*1956*	*0.86*	*2322*	*336*	*1986*	***0.86***	*126*	*78*
9-May-09	*1930*	*258*	*1672*	*0.87*	*2250*	*310*	*1940*	*0.86*	*2102*	*300*	*1802*	***0.86***	*109*	*104*
10-May-09	*1134*	*166*	*968*	*0.85*	*4328*	*796*	*3532*	*0.82*	*2146*	*574*	*1572*	***0.73***	*100*	*93*
11-May-09	*1660*	*234*	*1426*	*0.86*	*4742*	*1212*	*3530*	*0.74*	*2584*	*524*	*2060*	***0.80***	*123*	*95*
12-May-09	*1464*	*296*	*1168*	*0.80*	*4182*	*1186*	*2996*	*0.72*	*2396*	*630*	*1766*	***0.74***	*120*	*100*
13-May-09	*1452*	*100*	*1352*	*0.93*	*4814*	*586*	*4228*	*0.88*	*2436*	*338*	*2098*	***0.86***	*115*	*94*
14-May-09	*1554*	*152*	*1402*	*0.90*	*4732*	*658*	*4074*	*0.86*	*2736*	*440*	*2296*	***0.84***	*140*	*102*
15-May-09	*1986*	*242*	*1744*	*0.88*	*4920*	*852*	*4068*	*0.83*	*2732*	*390*	*2342*	***0.86***	*133*	*97*
16-May-09	*2238*	*274*	*1964*	*0.88*	*2912*	*376*	*2536*	*0.87*	*3244*	*460*	*2784*	***0.86***	*160*	*99*
17-May-09	*1764*	*296*	*1468*	*0.83*	*3616*	*826*	*2790*	*0.77*	*3444*	*752*	*2692*	***0.78***	*170*	*99*
18-May-09	*1596*	*214*	*1382*	*0.87*	*4156*	*706*	*3450*	*0.83*	*3282*	*618*	*2664*	***0.81***	*169*	*103*
19-May-09	*1972*	*176*	*1796*	*0.91*	*3848*	*442*	*3406*	*0.89*	*3166*	*396*	*2770*	***0.87***	*160*	*101*
20-May-09	*1836*	*172*	*1664*	*0.91*	*4118*	*448*	*3670*	*0.89*	*3320*	*396*	*2924*	***0.88***	*170*	*102*
21-May-09	*1862*	*270*	*1592*	*0.85*	*3208*	*856*	*2352*	*0.73*	*3298*	*818*	*2480*	***0.75***	*185*	*112*

22-May-09	1830	178	1652	0.90	4058	480	3578	0.88	3194	350	2844	**0.89**	134	88
23-May-09	2280	270	2010	0.88	3028	316	2712	0.90	4332	746	3586	**0.83**	134	89
25-May-09	2062	238	1824	0.88	3428	616	2812	0.82	3696	596	3100	**0.84**	134	89
26-May-09	2004	256	1748	0.87	4122	606	3516	0.85	3610	670	2940	**0.81**	134	90
27-May-09	2168	308	1860	0.86	4166	1000	3166	0.76	3944	878	3066	**0.78**	134	90
28-May-09	1808	218	1590	0.88	4130	738	3392	0.82	3514	700	2814	**0.80**	180	102
29-May-09	3918	556	3362	0.86	3736	502	3234	0.87	2062	224	1838	**0.89**	200	194
30-May-09	2074	310	1764	0.85	4030	622	3408	0.85	3914	652	3262	**0.83**	190	97
31-May-09	2082	232	1850	0.89	5528	1230	4298	0.78	3698	840	2858	**0.77**	210	114
1-Jun-09	1928	248	1680	0.87	4662	812	3850	0.83	3672	786	2886	**0.79**	215	117
2-Jun-09	1912	300	1612	0.84	4728	1026	3702	0.78	4014	970	3044	**0.76**	228	114
3-Jun-09	2046	282	1764	0.86	3960	572	3388	0.86	4288	890	3398	**0.79**	230	107
4-Jun-09	2390	160	2230	0.93	3734	498	3236	0.87	4026	566	3460	**0.86**	205	102
5-Jun-09	2116	228	1888	0.89	4700	690	4010	0.85	3886	594	3292	**0.85**	200	103
6-Jun-09	1748	190	1558	0.89	2636	436	2200	0.83	2848	470	2378	**0.83**	149	94
7-Jun-09	1844	242	1602	0.87	4216	638	3578	0.85	3178	456	2722	**0.86**	190	120
8-Jun-09	2106	214	1892	0.90	3482	414	3068	0.88	3608	432	3176	**0.88**	190	105

9-Jun-09	2142	302	1840	0.86	4560	720	3840	0.84	4018	660	3358	**0.84**	210	105
10-Jun-09	2380	316	2064	0.87	4348	692	3656	0.84	4400	802	3598	**0.82**	230	105
11-Jun-09	2256	280	1976	0.88	5158	810	4348	0.84	4010	792	3218	**0.80**	260	130
12-Jun-09	2332	284	2048	0.88	4092	596	3496	0.85	4166	586	3580	**0.86**	245	118
13-Jun-09	2378	298	2080	0.87	5356	802	4554	0.85	4156	820	3336	**0.80**	245	118
14-Jun-09	4080	892	3188	0.78	5886	1936	3950	0.67	3958	1310	2648	**0.67**	203	103
15-Jun-09	2344	232	2112	0.90	4812	620	4192	0.87	4474	572	3902	**0.87**	249	111
16-Jun-09	2458	258	2200	0.90	4146	756	3390	0.82	4130	920	3210	**0.78**	209	101
17-Jun-09	2232	282	1950	0.87	5162	888	4274	0.83	4016	912	3104	**0.77**	220	110
18-Jun-09	2460	286	2174	0.88	4578	660	3918	0.86	4456	752	3704	**0.83**	225	101
20-Jun-09	3002	1286	1716	0.57	5414	1876	3538	0.65	5602	2050	3552	**0.63**	225	80
21-Jun-09	2042	302	1740	0.85	4598	920	3678	0.80	4718	990	3728	**0.79**	239	101
22-Jun-09	2150	308	1842	0.86	4782	1012	3770	0.79	5058	1210	3848	**0.76**	259	102
23-Jun-09	2104	240	1864	0.89	4830	738	4092	0.85	5156	1296	3860	**0.75**	355	138
24-Jun-09	1922	284	1638	0.85	4460	710	3750	0.84	4684	872	3812	**0.81**	255	109
25-Jun-09	2044	290	1754	0.86	4822	1070	3752	0.78	4970	1314	3656	**0.74**	260	105
26-Jun-09	1998	236	1762	0.88	4600	650	3950	0.86	4736	730	4006	**0.85**	265	112

27-Jun-09	1830	222	1608	0.88	4294	748	3546	0.83	4674	1136	3538	**0.76**	249	107
29-Jun-09	2808	390	2418	0.86	4080	662	3418	0.84	4514	1034	3480	**0.77**	229	101
30-Jun-09	2338	318	2020	0.86	3978	710	3268	0.82	4032	804	3228	**0.80**	215	107
1-Jul-09	3000	292	2708	0.90	5030	610	4420	0.88	5060	634	4426	**0.87**	178	99
2-Jul-09	2002	240	1762	0.88	4058	512	3546	0.87	4594	750	3844	**0.84**	260	113
5-Jul-09	1982	196	1786	0.90	3474	396	3078	0.89	3828	404	3424	**0.89**	180	99
6-Jul-09	1980	270	1710	0.86	3358	468	2890	0.86	3586	532	3054	**0.85**	215	120
8-Jul-09	1822	158	1664	0.91	3254	382	2872	0.88	3376	358	3018	**0.89**	210	124
9-Jul-09	1744	206	1538	0.88	2814	360	2454	0.87	2966	390	2576	**0.87**	210	142
10-Jul-09	2012	222	1790	0.89	2408	308	2100	0.87	2578	320	2258	**0.88**	170	132
11-Jul-09	1682	180	1502	0.89	2896	350	2546	0.88	3068	374	2694	**0.88**	195	127
12-Jul-09	1844	206	1638	0.89	2942	462	2480	0.84	3176	762	2414	**0.76**	210	132
13-Jul-09	1848	210	1638	0.89	3136	402	2734	0.87	3320	454	2866	**0.86**	220	133
14-Jul-09	1600	140	1460	0.91	2652	238	2414	0.91	2710	276	2434	**0.90**	185	137
15-Jul-09	2268	330	1938	0.85	3248	442	2806	0.86	3240	480	2760	**0.85**	220	136
17-Jul-09	1870	180	1690	0.90	2590	266	2324	0.90	2736	338	2398	**0.88**	200	146
18-Jul-09	1634	212	1422	0.87	2550	372	2178	0.85	2748	440	2308	**0.84**	175	127

20-Jul-09	*1832*	*164*	*1668*	*0.91*	*2908*	*290*	*2618*	*0.90*	*3148*	*342*	*2806*	***0.89***	*190*	*121*
21-Jul-09	*1972*	*172*	*1800*	*0.91*	*3220*	*320*	*2900*	*0.90*	*3390*	*380*	*3010*	***0.89***	*185*	*109*
22-Jul-09	*1916*	*184*	*1732*	*0.90*	*3434*	*384*	*3050*	*0.89*	*3470*	*460*	*3010*	***0.87***	*220*	*127*
23-Jul-09	*1972*	*142*	*1830*	*0.93*	*3362*	*316*	*3046*	*0.91*	*3502*	*410*	*3092*	***0.88***	*200*	*114*
24-Jul-09	*2198*	*246*	*1952*	*0.89*	*3304*	*486*	*2818*	*0.85*	*3834*	*590*	*3244*	***0.85***	*220*	*115*
25-Jul-09	*2212*	*228*	*1984*	*0.90*	*3910*	*444*	*3466*	*0.89*	*4094*	*510*	*3584*	***0.88***	*225*	*110*
26-Jul-09	*2338*	*184*	*2154*	*0.92*	*4020*	*392*	*3628*	*0.90*	*3842*	*450*	*3392*	***0.88***	*225*	*117*
28-Jul-09	*2062*	*264*	*1798*	*0.87*	*3690*	*506*	*3184*	*0.86*	*3390*	*508*	*2882*	***0.85***	*185*	*105*
29-Jul-09	*2112*	*272*	*1840*	*0.87*	*3570*	*464*	*3106*	*0.87*	*3688*	*492*	*3196*	***0.87***	*186*	*105*
30-Jul-09	*2168*	*244*	*1924*	*0.89*	*3926*	*486*	*3440*	*0.88*	*3914*	*500*	*3414*	***0.87***	*220*	*112*
31-Jul-09	*2186*	*258*	*1928*	*0.88*	*4026*	*530*	*3496*	*0.87*	*4128*	*548*	*3580*	***0.87***	*240*	*116*
1-Aug-09	*2322*	*232*	*2090*	*0.90*	*4040*	*504*	*3536*	*0.88*	*4136*	*566*	*3570*	***0.86***	*255*	*123*
2-Aug-09	*2340*	*294*	*2046*	*0.87*	*4230*	*722*	*3508*	*0.83*	*4310*	*914*	*3396*	***0.79***	*255*	*118*
3-Aug-09	*2346*	*326*	*2020*	*0.86*	*4244*	*1054*	*3190*	*0.75*	*4404*	*1284*	*3120*	***0.71***	*245*	*111*
5-Aug-09	*2512*	*306*	*2206*	*0.88*	*5682*	*2430*	*3252*	*0.57*	*4828*	*1188*	*3640*	***0.75***	*215*	*89*
6-Aug-09	*2052*	*380*	*1672*	*0.81*	*3528*	*338*	*3190*	*0.90*	*3624*	*370*	*3254*	***0.90***	*200*	*110*
8-Aug-09	*2822*	*668*	*2154*	*0.76*	*3398*	*1094*	*2304*	*0.68*	*4820*	*1190*	*3630*	***0.75***	*195*	*81*

11-Aug-09	2822	304	2518	0.89	3738	574	3164	0.85	3874	662	3212	**0.83**	220	114
12-Aug-09	2370	218	2152	0.91	3930	432	3498	0.89	3986	522	3464	**0.87**	222	111
13-Aug-09	1392	162	1230	0.88	3554	664	2890	0.81	4310	858	3452	**0.80**	249	116
14-Aug-09	2132	178	1954	0.92	3970	440	3530	0.89	3988	546	3442	**0.86**	235	118
15-Aug-09	2116	202	1914	0.90	3868	492	3376	0.87	4020	582	3438	**0.86**	235	117
16-Aug-09	2040	170	1870	0.92	3842	444	3398	0.88	4064	586	3478	**0.86**	235	116
17-Aug-09	2146	240	1906	0.89	3926	650	3276	0.83	4098	804	3294	**0.80**	250	122
18-Aug-09	2126	466	1660	0.78	3948	1236	2712	0.69	4014	1396	2618	**0.65**	250	125
19-Aug-09	2258	144	2114	0.94	3972	348	3624	0.91	4028	416	3612	**0.90**	249	124
20-Aug-09	2228	232	1996	0.90	3932	472	3460	0.88	3990	598	3392	**0.85**	250	125
21-Aug-09	2190	164	2026	0.93	3660	408	3252	0.89	3816	540	3276	**0.86**	257	135
22-Aug-09	2316	256	2060	0.89	3748	492	3256	0.87	3984	684	3300	**0.83**	260	131
24-Aug-09	2532	230	2302	0.91	3692	436	3256	0.88	4002	522	3480	**0.87**	195	107
25-Aug-09	2358	156	2202	0.93	3858	444	3414	0.88	4020	542	3478	**0.87**	262	130
26-Aug-09	2364	220	2144	0.91	4016	588	3428	0.85	4048	632	3416	**0.84**	267	132
28-Aug-09	2414	20	2394	0.99	3790	326	3464	0.91	3968	366	3602	**0.91**	265	134
29-Aug-09	2458	336	2122	0.86	4020	726	3294	0.82	4082	748	3334	**0.82**	262	128
31-Aug-09	2780	324	2456	0.88	4136	966	3170	0.77	4184	1440	2744	**0.66**	270	129

2-Sep-09	*2384*	*224*	*2160*	*0.91*	*3866*	*784*	*3082*	*0.80*	*4320*	*788*	*3532*	***0.82***	*198*	*108*
3-Sep-09	*2614*	*218*	*2396*	*0.92*	*4260*	*666*	*3594*	*0.84*	*4328*	*628*	*3700*	***0.85***	*285*	*132*
4-Sep-09	*2758*	*660*	*2098*	*0.76*	*4352*	*1628*	*2724*	*0.63*	*4498*	*1554*	*2944*	***0.65***	*290*	*129*
5-Sep-09	*2854*	*374*	*2480*	*0.87*	*4038*	*878*	*3160*	*0.78*	*4440*	*1240*	*3200*	***0.72***	*280*	*126*
6-Sep-09	*2518*	*188*	*2330*	*0.93*	*4312*	*450*	*3862*	*0.90*	*4506*	*562*	*3944*	***0.88***	*270*	*120*
7-Sep-09	*2536*	*232*	*2304*	*0.91*	*4374*	*474*	*3900*	*0.89*	*4650*	*512*	*4138*	***0.89***	*201*	*109*
14-Sep-09	*2718*	*254*	*2464*	*0.91*	*4314*	*544*	*3770*	*0.87*	*4460*	*582*	*3878*	***0.87***	*230*	*103*
15-Sep-09	*2566*	*244*	*2322*	*0.90*	*4262*	*602*	*3660*	*0.86*	*4512*	*672*	*3840*	***0.85***	*250*	*111*
16-Sep-09	*2698*	*280*	*2418*	*0.90*	*4176*	*642*	*3534*	*0.85*	*4448*	*720*	*3728*	***0.84***	*240*	*108*
17-Sep-09	*2874*	*310*	*2564*	*0.89*	*4224*	*586*	*3638*	*0.86*	*4504*	*656*	*3848*	***0.85***	*249*	*111*
18-Sep-09	*2546*	*286*	*2260*	*0.89*	*4130*	*574*	*3556*	*0.86*	*4398*	*678*	*3720*	***0.85***	*248*	*113*
19-Sep-09	*2644*	*304*	*2340*	*0.89*	*4386*	*642*	*3744*	*0.85*	*3964*	*564*	*3400*	***0.86***	*235*	*119*
21-Sep-09	*3092*	*296*	*2796*	*0.90*	*4394*	*596*	*3798*	*0.86*	*4626*	*598*	*4028*	***0.87***	*240*	*104*
22-Sep-09	*2836*	*332*	*2504*	*0.88*	*4246*	*582*	*3664*	*0.86*	*4546*	*658*	*3888*	***0.86***	*230*	*101*
23-Sep-09	*2794*	*376*	*2418*	*0.87*	*4070*	*632*	*3438*	*0.84*	*4294*	*738*	*3556*	***0.83***	*230*	*107*
24-Sep-09	*2778*	*304*	*2474*	*0.89*	*4160*	*550*	*3610*	*0.87*	*4500*	*630*	*3870*	***0.86***	*220*	*98*
25-Sep-09	*2748*	*318*	*2430*	*0.88*	*4064*	*628*	*3436*	*0.85*	*4458*	*650*	*3808*	***0.85***	*219*	*98*
26-Sep-09	*2520*	*298*	*2222*	*0.88*	*3894*	*590*	*3304*	*0.85*	*4096*	*660*	*3436*	***0.84***	*205*	*100*

27-Sep-09	2684	486	2198	0.82	4118	886	3232	0.78	4344	786	3558	**0.82**	210	97
28-Sep-09	3408	444	2964	0.87	4080	582	3498	0.86	4134	614	3520	**0.85**	190	92
29-Sep-09	2468	262	2206	0.89	4326	606	3720	0.86	4420	608	3812	**0.86**	190	86
30-Sep-09	2724	340	2384	0.88	4084	662	3422	0.84	4210	806	3404	**0.81**	190	90
1-Oct-09	2694	306	2388	0.89	3998	574	3424	0.86	4060	588	3472	**0.86**	175	86
2-Oct-09	2452	170	2282	0.93	3948	330	3618	0.92	3976	358	3618	**0.91**	200	101
3-Oct-09	2412	260	2152	0.89	4104	508	3596	0.88	4234	590	3644	**0.86**	190	90
5-Oct-09	2344	260	2084	0.89	3922	528	3394	0.87	3912	540	3372	**0.86**	160	82
7-Oct-09	2512	230	2282	0.91	4044	474	3570	0.88	3998	560	3438	**0.86**	165	83
8-Oct-09	2562	306	2256	0.88	3984	658	3326	0.83	3920	624	3296	**0.84**	165	84
9-Oct-09	2714	300	2414	0.89	4130	500	3630	0.88	4104	548	3556	**0.87**	165	80
10-Oct-09	2544	320	2224	0.87	3914	694	3220	0.82	3996	850	3146	**0.79**	175	88
11-Oct-09	2502	280	2222	0.89	3916	530	3386	0.86	3808	546	3262	**0.86**	160	84
12-Oct-09	2300	256	2044	0.89	3770	494	3276	0.87	3762	486	3276	**0.87**	165	88
13-Oct-09	2486	294	2192	0.88	3894	556	3338	0.86	4038	616	3422	**0.85**	169	84
15-Oct-09	2498	262	2236	0.90	3768	528	3240	0.86	3786	632	3154	**0.83**	170	90
16-Oct-09	2508	248	2260	0.90	3948	608	3340	0.85	3832	618	3214	**0.84**	201	106
17-Oct-09	2960	318	2642	0.89	4272	572	3700	0.87	4194	642	3552	**0.85**	170	81

19-Oct-09	2726	306	2420	0.89	4276	838	3438	0.80	4448	782	3666	**0.82**	200	90
20-Oct-09	2698	340	2358	0.87	4114	648	3466	0.84	4316	690	3626	**0.84**	200	93
21-Oct-09	2508	328	2180	0.87	4114	590	3524	0.86	4128	668	3460	**0.84**	200	97
22-Oct-09	2636	296	2340	0.89	4124	566	3558	0.86	4202	616	3586	**0.85**	200	95
25-Oct-09	2682	266	2416	0.90	3908	542	3366	0.86	3960	596	3364	**0.85**	229	116
26-Oct-09	2546	292	2254	0.89	3750	474	3276	0.87	3838	508	3330	**0.87**	225	117
27-Oct-09	2526	252	2274	0.90	3688	448	3240	0.88	3792	488	3304	**0.87**	220	116
28-Oct-09	2410	226	2184	0.91	3794	472	3322	0.88	3836	498	3338	**0.87**	220	115
29-Oct-09	2664	332	2332	0.88	3836	602	3234	0.84	3996	600	3396	**0.85**	220	110
30-Oct-09	2470	356	2114	0.86	3574	864	2710	0.76	3636	860	2776	**0.76**	215	118
31-Oct-09	2438	362	2076	0.85	3402	802	2600	0.76	3532	716	2816	**0.80**	202	106
3-Nov-09	2364	226	2138	0.90	3810	548	3262	0.86	3818	636	3182	**0.83**	240	126
5-Nov-09	2272	230	2042	0.90	3588	794	2794	0.78	3810	1110	2700	**0.71**	220	115
6-Nov-09	2444	188	2256	0.92	3848	502	3346	0.87	3988	564	3424	**0.86**	210	105
7-Nov-09	2426	204	2222	0.92	3882	506	3376	0.87	4020	566	3454	**0.86**	210	104
8-Nov-09	2278	230	2048	0.90	3652	572	3080	0.84	3784	596	3188	**0.84**	210	111
9-Nov-09	2210	240	1970	0.89	3616	510	3106	0.86	3790	536	3254	**0.86**	210	111
10-Nov-09	2366	222	2144	0.91	3858	524	3334	0.86	3968	566	3402	**0.86**	212	107

11-Nov-09	2374	277	2097	0.88	3792	486	3306	0.87	3884	543	3341	**0.86**	210	108
12-Nov-09	2363	213	2149	0.91	3786	533	3253	0.86	3913	575	3338	**0.85**	208	106
19-Nov-09	2568	586	1982	0.77	4054	1490	2564	0.63	4484	1688	2796	**0.62**	230	103
20-Nov-09	3148	844	2304	0.73	3544	1290	2254	0.64	4038	1414	2624	**0.65**	235	116
26-Nov-09	2196	326	1870	0.85	3836	1202	2634	0.69	4122	1326	2796	**0.68**	225	109
29-Nov-09	2134	112	2022	0.95	3514	454	3060	0.87	3716	436	3280	**0.88**	220	118
30-Nov-09	2148	184	1964	0.91	3852	494	3358	0.87	3710	446	3264	**0.88**	230	124
1-Dec-09	2296	254	2042	0.89	3694	1066	2628	0.71	3862	902	2960	**0.77**	250	129
2-Dec-09	2252	176	2076	0.92	3856	634	3222	0.84	4476	1062	3414	**0.76**	251	112
3-Dec-09	2370	378	1992	0.84	3870	1032	2838	0.73	3974	1432	2542	**0.64**	240	121
4-Dec-09	2200	150	2050	0.93	3798	408	3390	0.89	3860	410	3450	**0.89**	245	127
5-Dec-09	2348	206	2142	0.91	3904	1074	2830	0.72	4032	868	3164	**0.78**	240	119
6-Dec-09	2134	282	1852	0.87	3860	1200	2660	0.69	4194	1266	2928	**0.70**	204	107
7-Dec-09	2130	284	1846	0.87	3866	1214	2652	0.69	4170	1272	2898	**0.69**	247	118
8-Dec-09	2162	1274	888	0.41	3980	376	3604	0.91	4058	108	3950	**0.97**	235	116
9-Dec-09	2362	46	2316	0.98	3986	104	3882	0.97	4278	90	4188	**0.98**	230	108
13-Dec-09	2380	208	2172	0.91	3964	490	3474	0.88	4400	710	3690	**0.84**	205	107
14-Dec-09	2350	172	2178	0.93	4214	634	3580	0.85	4474	748	3726	**0.83**	260	116

15-Dec-09	*2472*	*946*	*1526*	*0.62*	*4220*	*2038*	*2182*	*0.52*	*4476*	*2116*	*2360*	**0.53**	*250*	*112*
16-Dec-09	*2398*	*296*	*2102*	*0.88*	*4138*	*1334*	*2804*	*0.68*	*4366*	*1200*	*3166*	**0.73**	*260*	*119*
17-Dec-09	*2396*	*212*	*2184*	*0.91*	*4154*	*954*	*3200*	*0.77*	*4280*	*1158*	*3122*	**0.73**	*270*	*126*
18-Dec-09	*2548*	*840*	*1708*	*0.67*	*4402*	*1422*	*2980*	*0.68*	*4502*	*1054*	*3448*	**0.77**	*260*	*116*
19-Dec-09	*2524*	*874*	*1650*	*0.65*	*4378*	*1818*	*2560*	*0.58*	*4550*	*1962*	*2588*	**0.57**	*280*	*123*
20-Dec-09	*2418*	*1190*	*1228*	*0.51*	*4244*	*2328*	*1916*	*0.45*	*4300*	*2508*	*1792*	**0.42**	*280*	*130*
21-Dec-09	*2378*	*1084*	*1294*	*0.54*	*4328*	*2354*	*1974*	*0.46*	*4262*	*2334*	*1928*	**0.45**	*340*	*160*
24-Dec-09	*2522*	*840*	*1682*	*0.67*	*4512*	*1764*	*2748*	*0.61*	*4464*	*1780*	*2684*	**0.60**	*300*	*134*
29-Dec-09	*2476*	*202*	*2274*	*0.92*	*4436*	*952*	*3484*	*0.79*	*4598*	*584*	*4014*	**0.87**	*310*	*135*
30-Dec-09	*2522*	*1310*	*1212*	*0.48*	*4426*	*2390*	*2036*	*0.46*	*4592*	*2462*	*2130*	**0.46**	*330*	*144*
2-Jan-10	*2450*	*1014*	*1436*	*0.59*	*4308*	*2160*	*2148*	*0.50*	*4568*	*2254*	*2314*	**0.51**	*320*	*140*
6-Jan-10	*2460*	*1036*	*1424*	*0.58*	*4400*	*1968*	*2432*	*0.55*	*4470*	*2114*	*2356*	**0.53**	*280*	*125*
8-Jan-10	*2376*	*870*	*1506*	*0.63*	*4492*	*1944*	*2548*	*0.57*	*4716*	*2244*	*2472*	**0.52**	*260*	*110*
9-Jan-10	*2378*	*788*	*1590*	*0.67*	*4252*	*1894*	*2358*	*0.55*	*4496*	*1856*	*2640*	**0.59**	*250*	*111*
11-Jan-10	*2324*	*814*	*1510*	*0.65*	*4232*	*1928*	*2304*	*0.54*	*4478*	*1946*	*2532*	**0.57**	*280*	*125*
12-Jan-10	*2762*	*680*	*2082*	*0.75*	*4242*	*1298*	*2944*	*0.69*	*4506*	*1382*	*3124*	**0.69**	*280*	*124*
13-Jan-10	*2468*	*1392*	*1076*	*0.44*	*4438*	*2854*	*1584*	*0.36*	*4586*	*2936*	*1650*	**0.36**	*270*	*118*
16-Jan-10	*2452*	*156*	*2296*	*0.94*	*4222*	*1036*	*3186*	*0.75*	*4464*	*566*	*3898*	**0.87**	*250*	*112*

20-Jan-10	3946	438	3508	0.89	4460	496	3964	0.89	4620	546	4074	**0.88**	220	95
22-Jan-10	2456	244	2212	0.90	4208	616	3592	0.85	4342	890	3452	**0.80**	220	101
23-Jan-10	2440	264	2176	0.89	4166	1170	2996	0.72	4438	1394	3044	**0.69**	190	86
25-Jan-10	2696	414	2282	0.85	4314	994	3320	0.77	4546	1228	3318	**0.73**	210	92
26-Jan-10	2488	802	1686	0.68	4096	1532	2564	0.63	4276	1682	2594	**0.61**	200	94
27-Jan-10	2670	766	1904	0.71	4080	1588	2492	0.61	4166	1560	2606	**0.63**	190	91
28-Jan-10	2556	222	2334	0.91	4198	502	3696	0.88	4392	606	3786	**0.86**	200	91
29-Jan-10	2600	180	2420	0.93	4236	384	3852	0.91	4454	936	3518	**0.79**	200	90
30-Jan-10	2702	300	2402	0.89	4488	780	3708	0.83	4754	1108	3646	**0.77**	210	88
3-Feb-10	2812	344	2468	0.88	4344	414	3930	0.90	4618	476	4142	**0.90**	212	108
4-Feb-10	2966	188	2778	0.94	4646	538	4108	0.88	4906	682	4224	**0.86**	212	108
8-Feb-10	2830	188	2642	0.93	4582	464	4118	0.90	4838	446	4392	**0.91**	220	91
10-Feb-10	2816	206	2610	0.93	4576	476	4100	0.90	4692	560	4132	**0.88**	220	94
11-Feb-10	2780	274	2506	0.90	4564	544	4020	0.88	4598	592	4006	**0.87**	200	87
12-Feb-10	2176	150	2026	0.93	3628	352	3276	0.90	3942	446	3496	**0.89**	190	96
13-Feb-10	2382	176	2206	0.93	3970	398	3572	0.90	4274	460	3814	**0.89**	180	84
14-Feb-10	2354	174	2180	0.93	3970	398	3572	0.90	4274	460	3814	**0.89**	181	85
23-Feb-10	1908	136	1772	0.93	3008	336	2672	0.89	3176	388	2788	**0.88**	100	63

24-Feb-10	*2186*	*138*	*2048*	*0.94*	*2908*	*294*	*2614*	*0.90*	*3006*	*374*	*2632*	**0.88**	*211*	*107*
27-Feb-10	*2516*	*176*	*2340*	*0.93*	*3680*	*402*	*3278*	*0.89*	*3842*	*458*	*3384*	**0.88**	*140*	*73*
1-Mar-10	*2442*	*160*	*2282*	*0.93*	*3788*	*410*	*3378*	*0.89*	*3848*	*456*	*3392*	**0.88**	*130*	*68*
2-Mar-10	*2368*	*192*	*2176*	*0.92*	*3650*	*412*	*3238*	*0.89*	*3724*	*482*	*3242*	**0.87**	*150*	*81*
3-Mar-10	*2368*	*186*	*2182*	*0.92*	*3584*	*412*	*3172*	*0.89*	*3786*	*462*	*3324*	**0.88**	*140*	*74*
4-Mar-10	*2428*	*194*	*2234*	*0.92*	*3776*	*434*	*3342*	*0.89*	*3908*	*476*	*3432*	**0.88**	*130*	*67*
6-Mar-10	*2484*	*198*	*2286*	*0.92*	*3782*	*474*	*3308*	*0.87*	*4028*	*522*	*3506*	**0.87**	*135*	*67*
8-Mar-10	*2464*	*196*	*2268*	*0.92*	*3916*	*450*	*3466*	*0.89*	*4002*	*500*	*3502*	**0.88**	*130*	*65*
9-Mar-10	*2608*	*222*	*2386*	*0.91*	*3934*	*492*	*3442*	*0.87*	*4158*	*524*	*3634*	**0.87**	*130*	*63*
10-Mar-10	*2588*	*236*	*2352*	*0.91*	*3878*	*478*	*3400*	*0.88*	*3972*	*504*	*3468*	**0.87**	*120*	*60*
11-Mar-10	*2526*	*170*	*2356*	*0.93*	*3950*	*378*	*3572*	*0.90*	*4104*	*442*	*3662*	**0.89**	*130*	*63*
12-Mar-10	*2408*	*200*	*2208*	*0.92*	*3674*	*460*	*3214*	*0.87*	*3736*	*490*	*3246*	**0.87**	*120*	*64*
15-Mar-10	*2528*	*210*	*2318*	*0.92*	*3918*	*442*	*3476*	*0.89*	*4104*	*506*	*3598*	**0.88**	*130*	*63*
16-Mar-10	*2324*	*134*	*2190*	*0.94*	*3964*	*350*	*3614*	*0.91*	*3708*	*358*	*3350*	**0.90**	*132*	*67*
17-Mar-10	*2222*	*128*	*2094*	*0.94*	*3374*	*280*	*3094*	*0.92*	*3668*	*362*	*3306*	**0.90**	*100*	*55*
18-Mar-10	*2230*	*146*	*2084*	*0.93*	*3284*	*296*	*2988*	*0.91*	*3464*	*308*	*3156*	**0.91**	*130*	*66*
19-Mar-10	*2196*	*136*	*2060*	*0.94*	*3266*	*282*	*2984*	*0.91*	*3556*	*314*	*3242*	**0.91**	*100*	*56*
20-Mar-10	*2136*	*140*	*1996*	*0.93*	*3138*	*264*	*2874*	*0.92*	*3344*	*314*	*3030*	**0.91**	*99*	*59*

22-Mar-10	2424	176	2248	0.93	3548	306	3242	0.91	3668	342	3326	**0.91**	100	55
25-Mar-10	2486	140	2346	0.94	3646	274	3372	0.92	3790	328	3462	**0.91**	125	65
26-Mar-10	2260	144	2116	0.94	3520	294	3226	0.92	3762	362	3400	**0.90**	100	53
29-Mar-10	2570	186	2384	0.93	4034	348	3686	0.91	4056	350	3706	**0.91**	120	59
30-Mar-10	2580	158	2422	0.94	3922	324	3598	0.92	4022	304	3718	**0.92**	130	65
31-Mar-10	2410	146	2264	0.94	3968	168	3800	0.96	4050	342	3708	**0.92**	140	69
1-Apr-10	2726	168	2558	0.94	4334	298	4036	0.93	4144	350	3794	**0.92**	140	68
2-Apr-10	2498	160	2338	0.94	3924	314	3610	0.92	4030	348	3682	**0.91**	140	69
3-Apr-10	2526	188	2338	0.93	4112	298	3814	0.93	4250	406	3844	**0.90**	150	71
4-Apr-10	2394	142	2252	0.94	3872	306	3566	0.92	4030	364	3666	**0.91**	160	79
6-Apr-10	2394	170	2224	0.93	3976	300	3676	0.92	4018	318	3700	**0.92**	160	80
7-Apr-10	2336	140	2196	0.94	3622	286	3336	0.92	3840	320	3520	**0.92**	160	83
9-Apr-10	2364	160	2204	0.93	3570	266	3304	0.93	3828	336	3492	**0.91**	170	89
10-Apr-10	2388	156	2232	0.93	3648	270	3378	0.93	3764	334	3430	**0.91**	175	93
11-Apr-10	3688	294	3394	0.92	2538	164	2374	0.94	3854	340	3514	**0.91**	160	83
12-Apr-10	2544	164	2380	0.94	3690	270	3420	0.93	3792	320	3472	**0.92**	170	90
4-May-10	2102	144	1958	0.93	3258	314	2944	0.90	3386	358	3028	**0.89**	130	77
5-May-10	2118	122	1996	0.94	3252	244	3008	0.92	3362	312	3050	**0.91**	120	71

6-May-10	2266	126	2140	0.94	3482	276	3206	0.92	3762	338	3424	**0.91**	150	80
7-May-10	2020	132	1888	0.93	4668	334	4334	0.93	2162	162	2000	**0.93**	135	125
8-May-10	2300	182	2118	0.92	3480	336	3144	0.90	3678	328	3350	**0.91**	155	84
10-May-10	2282	134	2148	0.94	3540	282	3258	0.92	3804	352	3452	**0.91**	145	76
11-May-10	2288	136	2152	0.94	3592	296	3296	0.92	3816	328	3488	**0.91**	135	72
12-May-10	2144	150	1994	0.93	3480	282	3198	0.92	3740	360	3380	**0.90**	135	72
13-May-10	2124	152	1972	0.93	3802	322	3480	0.92	4228	346	3882	**0.92**	135	72
14-May-10	2158	154	2004	0.93	3896	336	3560	0.91	4440	414	4026	**0.91**	135	71
15-May-10	2474	194	2280	0.92	3804	348	3456	0.91	4340	402	3938	**0.91**	192	88
17-May-10	2546	174	2372	0.93	4064	372	3692	0.91	4304	376	3928	**0.91**	180	84
18-May-10	2534	180	2354	0.93	3910	354	3556	0.91	4170	400	3770	**0.90**	160	77
19-May-10	2536	184	2352	0.93	4184	354	3830	0.92	4480	402	4078	**0.91**	185	83
20-May-10	2580	196	2384	0.92	4198	366	3832	0.91	4454	456	3998	**0.90**	180	81
21-May-10	2568	178	2390	0.93	4022	370	3652	0.91	4290	430	3860	**0.90**	185	86
22-May-10	2664	178	2486	0.93	4090	334	3756	0.92	4336	384	3952	**0.91**	190	88
31-May-10	2612	240	2372	0.91	3344	358	2986	0.89	3424	352	3072	**0.90**	170	99
1-Jun-10	2446	206	2240	0.92	3838	400	3438	0.90	4024	504	3520	**0.87**	180	89
2-Jun-10	2634	168	2466	0.94	3974	362	3612	0.91	4072	378	3694	**0.91**	180	88

3-Jun-10	2872	230	2642	0.92	3716	376	3340	0.90	2684	410	2274	**0.85**	185	138
4-Jun-10	2724	206	2518	0.92	3858	418	3440	0.89	4380	420	3960	**0.90**	180	82
5-Jun-10	2546	182	2364	0.93	3722	394	3328	0.89	3848	420	3428	**0.89**	190	99
6-Jun-10	2588	184	2404	0.93	3746	388	3358	0.90	3902	450	3452	**0.88**	185	95
7-Jun-10	2612	176	2436	0.93	3564	306	3258	0.91	4010	388	3622	**0.90**	180	90
8-Jun-10	2538	196	2342	0.92	3792	398	3394	0.90	3978	480	3498	**0.88**	185	93
9-Jun-10	2482	208	2274	0.92	3862	416	3446	0.89	3878	476	3402	**0.88**	180	93
10-Jun-10	2492	200	2292	0.92	3866	420	3446	0.89	4048	494	3554	**0.88**	180	89
11-Jun-10	2468	182	2286	0.93	3938	410	3528	0.90	4208	430	3778	**0.90**	180	86
12-Jun-10	2448	180	2268	0.93	3904	380	3524	0.90	3986	442	3544	**0.89**	190	95
13-Jun-10	2522	184	2338	0.93	3870	378	3492	0.90	4012	436	3576	**0.89**	190	95
14-Jun-10	2404	216	2188	0.91	3728	466	3262	0.88	3936	478	3458	**0.88**	185	94
15-Jun-10	2676	254	2422	0.91	4050	468	3582	0.88	4184	516	3668	**0.88**	180	86
18-Jun-10	2740	232	2508	0.92	4070	438	3632	0.89	4228	496	3732	**0.88**	210	99
20-Jun-10	2860	232	2628	0.92	4246	464	3782	0.89	4506	524	3982	**0.88**	200	89
21-Jun-10	2746	250	2496	0.91	4224	516	3708	0.88	4394	568	3826	**0.87**	220	100
23-Jun-10	2860	304	2556	0.89	4206	518	3688	0.88	4524	602	3922	**0.87**	200	88
24-Jun-10	2802	282	2520	0.90	4088	604	3484	0.85	4000	512	3488	**0.87**	200	100

25-Jun-10	2526	250	2276	0.90	3552	450	3102	0.87	3746	460	3286	**0.88**	180	96
26-Jun-10	2390	186	2204	0.92	3446	360	3086	0.90	3544	384	3160	**0.89**	180	102
28-Jun-10	2526	188	2338	0.93	4112	298	3814	0.93	4250	406	3844	**0.90**	236	111
29-Jun-10	2526	188	2338	0.93	4112	298	3814	0.93	4250	406	3844	**0.90**	237	112
30-Jun-10	2378	202	2176	0.92	3324	340	2984	0.90	3516	378	3138	**0.89**	160	91
1-Jul-10	2326	204	2122	0.91	3482	392	3090	0.89	3672	448	3224	**0.88**	175	95
2-Jul-10	2910	350	2560	0.88	3298	372	2926	0.89	3722	452	3270	**0.88**	150	81
3-Jul-10	2280	246	2034	0.89	3330	414	2916	0.88	3444	478	2966	**0.86**	163	94
4-Jul-10	2890	172	2718	0.94	2900	288	2612	0.90	3164	320	2844	**0.90**	145	92
5-Jul-10	2398	158	2240	0.93	2936	260	2676	0.91	3324	308	3016	**0.91**	150	90
7-Jul-10	2132	208	1924	0.90	3118	320	2798	0.90	3466	396	3070	**0.89**	148	85
8-Jul-10	2774	248	2526	0.91	2918	272	2646	0.91	3316	346	2970	**0.90**	151	91
10-Jul-10	1998	170	1828	0.91	2656	298	2358	0.89	3230	396	2834	**0.88**	100	62
12-Jul-10	2160	160	2000	0.93	3126	334	2792	0.89	3264	424	2840	**0.87**	130	80
13-Jul-10	2216	266	1950	0.88	3088	332	2756	0.89	3360	588	2772	**0.82**	150	89
14-Jul-10	2232	156	2076	0.93	3396	348	3048	0.90	3482	406	3076	**0.88**	140	80
15-Jul-10	2348	218	2130	0.91	3094	334	2760	0.89	3606	564	3042	**0.84**	140	78
16-Jul-10	2480	232	2248	0.91	3472	462	3010	0.87	3758	562	3196	**0.85**	150	80

17-Jul-10	*2430*	*236*	*2194*	*0.90*	*3306*	*394*	*2912*	*0.88*	*4128*	*680*	*3448*	***0.84***	*160*	*78*
18-Jul-10	*2380*	*190*	*2190*	*0.92*	*3788*	*450*	*3338*	*0.88*	*3732*	*452*	*3280*	***0.88***	*170*	*91*
19-Jul-10	*2466*	*194*	*2272*	*0.92*	*4112*	*298*	*3814*	*0.93*	*4676*	*526*	*4150*	***0.89***	*180*	*77*
20-Jul-10	*2296*	*164*	*2132*	*0.93*	*3548*	*342*	*3206*	*0.90*	*3918*	*538*	*3380*	***0.86***	*150*	*77*
22-Jul-10	*2280*	*166*	*2114*	*0.93*	*3546*	*354*	*3192*	*0.90*	*3760*	*542*	*3218*	***0.86***	*170*	*90*
23-Jul-10	*2436*	*220*	*2216*	*0.91*	*3762*	*398*	*3364*	*0.89*	*3924*	*480*	*3444*	***0.88***	*160*	*82*
24-Jul-10	*2442*	*172*	*2270*	*0.93*	*3598*	*360*	*3238*	*0.90*	*3984*	*492*	*3492*	***0.88***	*190*	*95*
26-Jul-10	*4140*	*422*	*3718*	*0.90*	*4532*	*484*	*4048*	*0.89*	*5648*	*742*	*4906*	***0.87***	*190*	*67*
27-Jul-10	*4042*	*436*	*3606*	*0.89*	*4436*	*494*	*3942*	*0.89*	*5698*	*794*	*4904*	***0.86***	*190*	*67*
28-Jul-10	*4000*	*432*	*3568*	*0.89*	*4692*	*496*	*4196*	*0.89*	*4182*	*516*	*3666*	***0.88***	*190*	*91*
29-Jul-10	*4672*	*366*	*4306*	*0.92*	*4464*	*438*	*4026*	*0.90*	*4260*	*452*	*3808*	***0.89***	*200*	*94*
3-Aug-10	*3158*	*274*	*2884*	*0.91*	*4698*	*516*	*4182*	*0.89*	*4580*	*552*	*4028*	***0.88***	*210*	*92*
5-Aug-10	*5436*	*436*	*5000*	*0.92*	*4864*	*608*	*4256*	*0.87*	*7816*	*1162*	*6654*	***0.85***	*210*	*54*
6-Aug-10	*2570*	*204*	*2366*	*0.92*	*4580*	*478*	*4102*	*0.90*	*4420*	*544*	*3876*	***0.88***	*215*	*97*
7-Aug-10	*2694*	*204*	*2490*	*0.92*	*4612*	*522*	*4090*	*0.89*	*4530*	*820*	*3710*	***0.82***	*220*	*97*
8-Aug-10	*5064*	*412*	*4652*	*0.92*	*5082*	*564*	*4518*	*0.89*	*4314*	*506*	*3808*	***0.88***	*230*	*107*
9-Aug-10	*2960*	*180*	*2780*	*0.94*	*4654*	*562*	*4092*	*0.88*	*4668*	*602*	*4066*	***0.87***	*210*	*90*
11-Aug-10	*3404*	*234*	*3170*	*0.93*	*6190*	*674*	*5516*	*0.89*	*4724*	*558*	*4166*	***0.88***	*230*	*97*

13-Aug-10	*5872*	*498*	*5374*	*0.92*	*5192*	*608*	*4584*	*0.88*	*4300*	*538*	*3762*	**0.87**	*210*	*98*
14-Aug-10	*4880*	*400*	*4480*	*0.92*	*4768*	*548*	*4220*	*0.89*	*6530*	*928*	*5602*	**0.86**	*210*	*64*
15-Aug-10	*5000*	*450*	*4550*	*0.91*	*4368*	*884*	*3484*	*0.80*	*4106*	*534*	*3572*	**0.87**	*210*	*102*
16-Aug-10	*4620*	*420*	*4200*	*0.91*	*4354*	*464*	*3890*	*0.89*	*4198*	*530*	*3668*	**0.87**	*205*	*98*
18-Aug-10	*5728*	*624*	*5104*	*0.89*	*4440*	*498*	*3942*	*0.89*	*7332*	*1202*	*6130*	**0.84**	*200*	*55*
22-Aug-10	*3738*	*380*	*3358*	*0.90*	*4190*	*520*	*3670*	*0.88*	*4212*	*586*	*3626*	**0.86**	*200*	*95*
24-Aug-10	*3210*	*304*	*2906*	*0.91*	*4940*	*622*	*4318*	*0.87*	*4000*	*520*	*3480*	**0.87**	*200*	*100*
25-Aug-10	*3226*	*312*	*2914*	*0.90*	*4618*	*558*	*4060*	*0.88*	*5496*	*852*	*4644*	**0.84**	*210*	*76*
26-Aug-10	*3178*	*308*	*2870*	*0.90*	*4270*	*508*	*3762*	*0.88*	*4698*	*646*	*4052*	**0.86**	*200*	*85*
28-Aug-10	*4692*	*530*	*4162*	*0.89*	*4474*	*580*	*3894*	*0.87*	*3982*	*540*	*3442*	**0.86**	*200*	*100*
29-Aug-10	*3380*	*324*	*3056*	*0.90*	*4444*	*532*	*3912*	*0.88*	*4104*	*550*	*3554*	**0.87**	*220*	*107*
1-Sep-10	*3568*	*388*	*3180*	*0.89*	*4472*	*584*	*3888*	*0.87*	*4940*	*728*	*4212*	**0.85**	*210*	*85*
2-Sep-10	*3572*	*346*	*3226*	*0.90*	*4348*	*544*	*3804*	*0.87*	*4178*	*572*	*3606*	**0.86**	*230*	*110*
3-Sep-10	*3584*	*426*	*3158*	*0.88*	*4212*	*610*	*3602*	*0.86*	*4160*	*618*	*3542*	**0.85**	*190*	*91*
5-Sep-10	*4156*	*492*	*3664*	*0.88*	*4924*	*656*	*4268*	*0.87*	*6624*	*1052*	*5572*	**0.84**	*190*	*57*
6-Sep-10	*3816*	*442*	*3374*	*0.88*	*4340*	*568*	*3772*	*0.87*	*4086*	*664*	*3422*	**0.84**	*175*	*86*
9-Sep-10	*4694*	*506*	*4188*	*0.89*	*4164*	*582*	*3582*	*0.86*	*7652*	*1292*	*6360*	**0.83**	*140*	*37*
10-Sep-10	*4810*	*452*	*4358*	*0.91*	*5188*	*650*	*4538*	*0.87*	*7088*	*1388*	*5700*	**0.80**	*140*	*40*

11-Sep-10	*3224*	*278*	*2946*	*0.91*	*4274*	*518*	*3756*	*0.88*	*4100*	*582*	*3518*	***0.86***	*140*	*68*
12-Sep-10	*3252*	*224*	*3028*	*0.93*	*4084*	*472*	*3612*	*0.88*	*6320*	*968*	*5352*	***0.85***	*150*	*47*
15-Sep-10	*4514*	*408*	*4106*	*0.91*	*5418*	*612*	*4806*	*0.89*	*2676*	*330*	*2346*	***0.88***	*200*	*149*
17-Sep-10	*4220*	*420*	*3800*	*0.90*	*5100*	*606*	*4494*	*0.88*	*4012*	*520*	*3492*	***0.87***	*190*	*95*
18-Sep-10	*4024*	*618*	*3406*	*0.85*	*2912*	*298*	*2614*	*0.90*	*4048*	*558*	*3490*	***0.86***	*190*	*94*
20-Sep-10	*4098*	*484*	*3614*	*0.88*	*5010*	*654*	*4356*	*0.87*	*7108*	*1362*	*5746*	***0.81***	*210*	*59*
23-Sep-10	*5426*	*668*	*4758*	*0.88*	*4548*	*496*	*4052*	*0.89*	*7134*	*1166*	*5968*	***0.84***	*200*	*56*
25-Sep-10	*3932*	*492*	*3440*	*0.87*	*2836*	*304*	*2532*	*0.89*	*6098*	*924*	*5174*	***0.85***	*200*	*66*
3-Oct-10	*2808*	*238*	*2570*	*0.92*	*3626*	*398*	*3228*	*0.89*	*3982*	*454*	*3528*	***0.89***	*190*	*95*

APPENDIX C

OPERATIONAL DATA FOR THE JHB SYSTEM

TABLE OF CONTENTS

Table C.1:JHB system average COD and average OUR data for each sewage batch.

JHB SYSTEM AVERAGE COD (*mg COD/ℓ*) AND AVERAGE OUR (*mg O/ℓhr*) DATA

BATCH No	INFLUENT (I)			FILTERED INFLUENT (FI)			AEROBIC MIXED LIQUOR (AEML)			UNFILTERED EFFLUENT (UE)			FILTERED EFFLUENT (FE)			OUR		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**	**AVE**	**SSD**	**N**
8	*997.0*	*116.1*	*4*	*172.0*	*67.4*	*4*	*2015.0*	*134.5*	*4*	*144.0*	*30.0*	*4*	*102.0*	*38.6*	*4*	*36.0*	*3.9*	4
9	*1024.1*	*103.5*	*4*	*409.0*	*29.6*	*4*		*n/a*			*n/a*		*105.0*	*16.2*	*4*		*n/a*	
10	*1194.2*	*95.9*	*4*	*566.7*	*45.2*	*4*	*3992.3*	*521.4*	*4*	*195.3*	*27.0*	*4*	*139.7*	*12.5*	*4*	*30.5*	*6.0*	4
11	*960.8*	*174.0*	*5*	*466.4*	*148.4*	*5*		*n/a*			*n/a*		*94.1*	*19.0*	*5*		*n/a*	
12	*944.7*	*103.3*	*5*	*301.8*	*71.4*	*5*	*2691.7*	*540.1*	*5*	*196.0*	*34.4*	*5*	*121.5*	*20.8*	*5*	*25.1*	*4.0*	5
13	*809.1*	*59.0*	*5*	*266.1*	*57.8*	*5*		*n/a*			*n/a*		*94.1*	*19.0*	*5*		*n/a*	
14	*982.3*	*69.2*	*5*	*280.1*	*101.7*	*5*	*3426.7*	*455.3*	*5*	*186.7*	*24.8*	*5*	*122.4*	*11.5*	*5*	*23.6*	*3.7*	5
15	*951.8*	*111.1*	*4*	*226.9*	*34.8*	*4*	*3052.2*	*726.3*	*4*	*279.1*	*31.8*	*4*	*163.7*	*23.0*	*4*	*27.8*	*4.1*	4
16	*1000.0*	*48.5*	*3*	*252.0*	*52.0*	*3*	*3443.3*	*213.9*	*3*	*226.7*	*12.2*	*3*	*181.3*	*22.7*	*3*	*26.9*	*4.5*	3

n/a refers to sewage batches for which daily filtered (0.45 µm membrane) effluent concentrations, settleable solids and DSVI only were measured while the UCT system was fully tested

Table C.2:JHB system average TKN concentrations for each sewage batch.

JHB SYSTEM AVERAGE TKN (*mg N/ℓ*)															
BATCH No	**INFLUENT (I)**			**FILTERED INFLUENT (FI)**			**AEROBIC MIXED LIQUOR (AEML)**			**UNFILTERED EFLUENT (UE)**			**FILTERED EFFLUENT (FE)**		
	AVE	***SSD***	***N***	***AVE***	***SSD***	***N***	***AVE***	**SSD**	**N**	***AVE***	***SSD***	***N***	***AVE***	***SSD***	***N***
8	*56.4*	*4.5*	*4*	*30.9*	*5.7*	*4*	*225.2*	*48.2*	*4*	*22.2*	*1.1*	*4*	*18.1*	*0.6*	*4*
9	*46.1*	*7.0*	*4*	*31.2*	*6.5*	*4*	*n/a*			*n/a*			*13.9*	*1.5*	*4*
10	*61.0*	*2.8*	*4*	*41.3*	*2.5*	*4*	*250.3*	*84.0*	*4*	*17.5*	*2.7*	*4*	*13.8*	*2.7*	*4*
11	*48.4*	*1.1*	*5*	*33.7*	*1.7*		*n/a*			*n/a*			*7.6*	*1.3*	*5*
12	*54.3*	*1.8*	*5*	*34.7*	*0.9*	*5*	*233.8*	*27.2*	*5*	*17.1*	*6.2*	*5*	*12.0*	*1.2*	*5*
13	*50.0*	*1.0*	*5*	*33.9*	*1.5*	*5*	*n/a*			*n/a*			*13.2*	*6.3*	*5*
14	*52.9*	*3.1*	*5*	*34.4*	*1.8*	*5*	*247.5*	*21.0*	*5*	*21.5*	*4.3*	*5*	*13.3*	*2.9*	*5*
15	*73.3*	*1.7*	*4*	*47.8*	*4.4*	*4*	*233.9*	*21.5*	*4*	*50.2*	*3.4*	*4*	*37.9*	*0.4*	*4*
16	*57.4*	*2.7*	*3*	*28.9*	*4.3*	*3*	*236.7*	*11.9*	*3*	*10.6*	*1.6*	*3*	*8.4*	*0.6*	*3*

n/a refers to sewage batches for which daily filtered (0.45 µm membrane) effluent concentrations, settleable solids and DSVI only were measured while the UCT system was fully tested

Table C.3:JHB system average FSA concentrations for each sewage batch

BATCH No	FILTERED INFLUENT (FI)			FILTERED EFFLUENT (FE)		
	FSA	SSD	N	*FSA*	*SSD*	*N*
8	***27.4***	**4.2**	***4***	***16.3***	***2.6***	***4***
9	***23.9***	**4.1**	***4***	***14.5***	***1.5***	***4***
10	***32.0***	**2.8**	***4***	***9.7***	***1.9***	***4***
11	***18.2***	**6.7**	***5***	***3.9***	***0.8***	***5***
12	***25.9***	**3.5**	***5***	***7.8***	***1.1***	***5***
13	***26.5***	**0.6**	***5***	***3.9***	***0.2***	***5***
14	***26.7***	**1.7**	***5***	***9.3***	***2.4***	***5***
15	***42.1***	**0.9**	***4***	***32.4***	***1.4***	***4***
16	***21.4***	**0.0**	***3***	***5.4***	***0.0***	***3***

Table title row: **JHB SYSTEM VERAGE FSA (*mg* NH_3*-N/ℓ*)**

Table C.4:JHB system average nitrite concentrations for each sewage batch

JHB SYSTEM AVERAGE NITRITE (*mg* NO_2*-N/ℓ*)

BATCH No	INFLUENT (I)			AN REACTOR (AN)			ANOXIC REACTOR (AX)			AEROBIC REACTOR (AE)			FILTERED EFFLUENT (FE)		
	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N
8	*0.11*	*0.0*	*4*	*0.02*	*0.0*	*4*	*0.0*	*0.0*	*4*	*0.02*	*0.0*	*4*	*0.12*	*0.0*	*4*
9	*0.00*	*0.0*	*4*		*n/a*			*n/a*			*n/a*		*0.14*	*0.0*	*4*
10	*0.00*	*0.0*	*4*	*0.00*	*0.0*	*4*	*0.0*	*0.0*	*4*	*1.19*	*1.2*	*4*	*0.98*	*1.0*	*4*
11	*0.00*	*0.0*	*5*		*n/a*			*n/a*			*n/a*		*0.00*	*0.0*	*5*
12	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.1*	*5*
13	*0.00*	*0.0*	*5*		*n/a*			*n/a*			*n/a*		*0.11*	*0.1*	*5*
14	*0.14*	*0.1*	*5*	*0.03*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.33*	*0.3*	*5*	*0.07*	*0.2*	*5*
15	*0.02*	*0.0*	*4*	*0.00*	*0.0*	*4*	*0.00*	*0.0*	*4*	*0.06*	*0.2*	*4*	*0.11*	*0.0*	*4*
16	*0.00*	*0.0*	*3*	*0.00*	*0.0*	*3*	*0.00*	*0.0*	*3*	*0.43*	*0.3*	*3*	*0.37*	*0.1*	*3*

n/a refers to sewage batches for which daily filtered (0.45 µm membrane) effluent concentrations, settleable solids and DSVI only were measured while the UCT system was fully tested

Table C.5: JHB system average nitrate concentrations for each sewage batch

JHB SYSTEM AVERAGE NITRATE ($mg\ NO_3\text{-}N/\ell$)															
BATCH No	**INFLUENT (I)**			**AN REACTOR (AN)**			**ANOXIC REACTOR (AX)**			**AEROBIC REACTOR (AE)**			**FILTERED EFFLUENT (FE)**		
	AVE	***SSD***	***N***	***AVE***	***SSD***	***N***	***AVE***	***SSD***	***N***	***AVE***	***SSD***	***N***	***AVE***	***SSD***	***N***
8	*0.00*	*0.0*	*4*	*0.00*	*0.0*	*4*	*0.00*	*0.00*	*4*	*0.00*	*0.00*	*4*	*0.00*	*0.00*	*4*
9	*0.00*	*0.0*	*4*	*n/a*			*n/a*			*n/a*			*0.00*	*0.00*	*4*
10	*0.00*	*0.0*	*4*	*0.00*	*0.0*	*4*	*0.00*	*0.00*	*4*	*1.76*	*1.46*	*4*	*1.57*	*1.22*	*4*
11	*0.00*	*0.0*	*5*	*n/a*			*n/a*			*n/a*			*0.00*	*0.00*	*5*
12	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.00*	*5*	*0.00*	*0.00*	*5*	*0.03*	*0.03*	*5*
13	*0.00*	*0.0*	*5*	*n/a*			*n/a*			*n/a*			*0.22*	*0.30*	*5*
14	*0.00*	*0.0*	*5*	*0.00*	*0.0*	*5*	*0.00*	*0.00*	*5*	*0.06*	*0.09*	*5*	*0.00*	*0.02*	*5*
15	*0.02*	*0.0*	*4*	*0.03*	*0.0*	*4*	*0.03*	*0.01*	*4*	*0.20*	*0.04*	*4*	*0.21*	*0.10*	*4*
16	*0.00*	*0.0*	*3*	*0.00*	*0.0*	*3*	*0.00*	*0.00*	*3*	*0.08*	*0.11*	*3*	*0.01*	*0.02*	*3*

n/a refers to sewage batches for which daily filtered (0.45 µm membrane) effluent concentrations, settleable solids and DSVI only were measured while the UCT system was fully tested

Table C.6: JHB system average Total Phosphorus concentrations for each sewage batch

JHB SYSTEM AVERAGE PHOSPHORUS (mg PO_4-P/ℓ)

BATCH No	INFLUENT (I)			AN REACTOR (AN)			ANOXIC REACTOR (AX)			AEROBIC REACTOR (AE)			MIXED LIQUOR (ML)			FILTERED EFFLUENT (FE)		
	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N	AVE	SSD	N
8	22.4	0.3	4	10.4	0.5	4	6.6	0.2	4	6.8	0.6	4	81.4	7.5	4	7.3	0.8	4
9	10.2	0.2	4	n/a			n/a			n/a			n/a			19.7	1.0	4
10	21.2	1.1	4	18.5	3.7	4	10.9	8.6	4	11.0	8.3	4	90.0	14.3	4	9.0	6.1	4
11	14.7	3.1	5	n/a			n/a			n/a			n/a			2.4	1.4	5
12	21.5	1.5	5	21.8	3.3	5	5.1	4.6	5	3.4	0.6	5	70.7	8.5	5	3.5	0.6	5
13	23.1	5.3	5	n/a			n/a			n/a			n/a			1.3	1.0	5
14	23.1	1.8	5	23.7	2.6	5	14.2	10.1	5	10.0	9.3	5	80.1	11.7	5	11.8	10.2	5
15	19.4	6.5	4	9.5	7.7	4	8.4	4.6	4	8.4	5.1	4	56.2	5.7	4	10.7	6.0	4
16	19.7	0.9	3	12.9	0.3	3	4.5	1.6	3	2.8	0.0	3	74.7	8.2	3	2.8	0.0	3

n/a refers to sewage batches for which daily filtered (0.45 µm membrane) effluent concentrations, settleable solids and DSVI only were measured while the UCT system was fully tested

Table C.7: JHB system average aerobic VSS and TSS concentrations for each sewage batch

JHB SYSTEM AVERAGE AEROBIC VSS (*mg VSS/ℓ*) AND TSS (*mg TSS/ℓ*)

BATCH No	**AEVSS**			**AETSS**		
	AVE	**SSD**	**N**	**AVE**	**SSD**	**N**
8	*1673*	*89*	*4*	*1815*	*109.2*	*4*
9	*2392*	*346*	*4*	*2576*	*390.1*	*4*
10	*2317*	*221*	*4*	*2504*	*214.8*	*4*
11	*2061*	*195*	*5*	*2221*	*181.5*	*5*
12	*2179*	*184*	*5*	*2435*	*193.1*	*5*
13	*1811*	*168*	*5*	*2096*	*223.6*	*5*
14	*2714*	*535*	*5*	*2943*	*541.8*	*5*
15	*2813*	*481*	*4*	*3186*	*492.3*	*4*
16	*2852*	*366*	*3*	*2848*	*469.1*	*3*

Actual Flow Data

The procedure for measuring flows is as explained in **Chapter 3**,**Section 3.2.6** on experimental testing methods. The only flow measured was Q_8. The remaining flows were calculated as follow:

- $Q_w = V_{\text{JHB system}} / \text{SRT}$

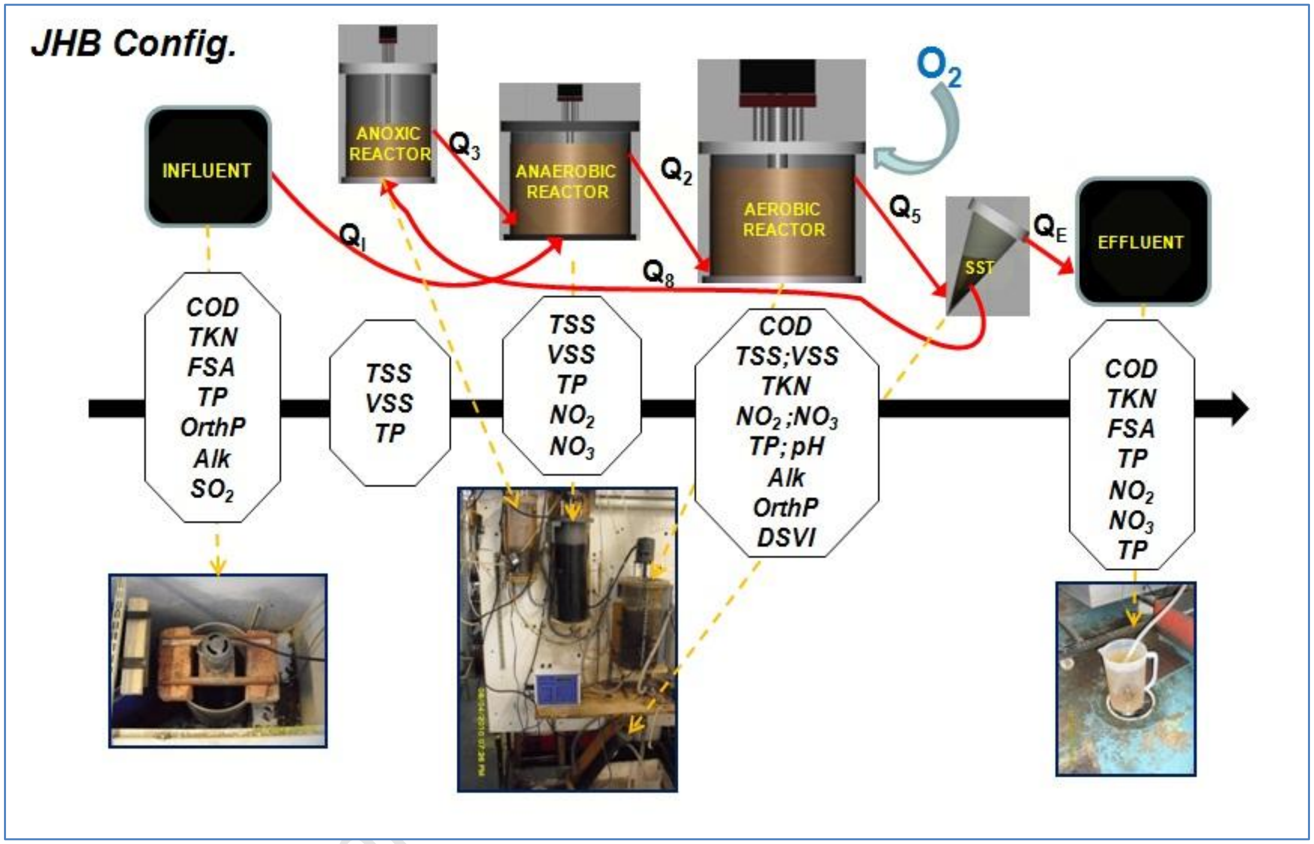
Where:

$V_{\text{JHB system}}$ = overall reactor volume $= (V_{\text{actual}} * V_{\text{equivalent of mass}})_{\text{anaerobic}} + (V_{\text{actual}} * V_{\text{equivalent of mass}})_{\text{anoxic}} + (V_{\text{actual}} * V_{\text{equivalent of mass}})_{\text{aerobic}}$

$= (4.4*1) + (1.1*2) + (8*1)$

$= 14.6$ l

SRT = sludge age = 5 days



- Q_e = $Q_i - Q_w$
- Q_3 = Q_8
- Q_2 = $Q_i + Q_3$
- Q_5 = $Q_2 - Q_w$

Table C.8: Actual average flow data for each sewage batch of the JHB system

BATCH No	Pump 0n/Off							
	Flow	Qi	Q2	Q3	Q5	Qeff	Q8	Qw
	Recycle		1+s	s			s	
	Flow/Qi	1.0	2.0	1.0	1.8	0.8	1.0	
	ℓ/s	0.0002	0.0003	0.0002	0.0003	0.0001	0.0002	0.00003
	ℓ/d	*15.0*	*30.0*	*15.0*	*27.1*	*12.1*	*15.0*	*2.9*
8	24 sec /60 sec							
	Flow/Qi	*1.0*	*2.3*	*1.3*	*2.1*	*0.8*	*1.3*	
	ℓ/s	0.0002	0.0004	0.0002	0.0004	0.0001	0.0002	0.00003
	ℓ/d	*15.0*	*34.9*	*20.0*	*32.0*	*12.0*	*20.0*	*2.9*
9	24 sec /60 sec							
	Flow/Qi	*1.0*	*2.3*	*1.3*	*2.1*	*0.8*	*1.3*	
	ℓ/s	0.0002	0.0004	0.0002	0.0004	0.0001	0.0002	0.00003
	ℓ/d	*15.0*	*34.9*	*20.0*	*32.0*	*12.0*	*20.0*	*2.9*
10	24 sec /60 sec							
	Flow/Qi	*1.0*	*2.3*	*1.3*	*2.1*	*0.8*	*1.3*	
	ℓ/s	0.0002	0.0004	0.0002	0.0004	0.0001	0.0002	0.00003
	ℓ/d	*15.0*	*34.9*	*20.0*	*32.0*	*12.0*	*20.0*	*2.9*
11	34 sec /60 sec							
	Flow/Qi	*1.0*	*2.5*	*1.5*	*2.3*	*0.8*	*1.5*	
	ℓ/s	0.0002	0.0004	0.0003	0.0004	0.0001	0.0003	0.00003
	ℓ/d	*15.0*	*37.7*	*22.9*	*34.8*	*12.0*	*22.9*	*2.9*
12	34 sec /60 sec							
	Flow/Qi	*1.0*	*2.5*	*1.5*	*2.3*	*0.8*	*1.5*	
	ℓ/s	0.0002	0.0004	0.0003	0.0004	0.0001	0.0003	0.00003
	ℓ/d	*15.0*	*37.7*	*22.9*	*34.8*	*12.0*	*22.9*	*2.9*
13	34 sec /60 sec							

	Flow/Qi	***1.0***	***2.5***	***1.5***	***2.3***	***0.8***	***1.5***	
	ℓ/s	0.0002	0.0004	0.0003	0.0004	0.0001	0.0003	0.00003
	ℓ/d	***15.0***	***37.7***	***22.9***	***34.8***	***12.0***	***22.9***	***2.9***
<u>14</u>	**34 sec /60 sec**							
	Flow/Qi	***1.0***	***2.5***	***1.5***	***2.3***	***0.8***	***1.5***	
	ℓ/s	0.0002	0.0004	0.0003	0.0004	0.0001	0.0003	0.00003
	ℓ/d	***15.0***	***37.7***	***22.9***	***34.8***	***12.0***	***22.9***	***2.9***
<u>15</u>	**34 sec /60 sec**							
	Flow/Qi	***1.1***	***2.6***	***1.5***	***2.4***	***0.9***	***1.5***	
	ℓ/s	0.0002	0.0005	0.0003	0.0004	0.0002	0.0003	0.00003
	ℓ/d	***16.8***	***39.7***	***22.9***	***36.7***	***13.9***	***22.9***	***2.9***
<u>16</u>	**34 sec /60 sec**							
	Flow/Qi	***1.0***	***2.5***	***1.5***	***2.3***	***0.8***	***1.5***	
	ℓ/s	0.0002	0.0004	0.0003	0.0004	0.0001	0.0003	0.00003
	ℓ/d	***15.0***	***37.7***	***22.9***	***34.8***	***12.0***	***22.9***	***2.9***

Table C.9: Influent WW COD characterization for the JHB system (5d SRT)

	B8	**B10**	**B12**	**B14**	**B15**	***Avg =***
S_{ti}	*997.0*	*1194.2*	*944.7*	*982.3*	*951.8*	***1014.0***
S_{si}	*172.0*	*566.7*	*301.8*	*280.1*	*226.9*	***309.5***
S_{pi}	*825.0*	*627.4*	*642.9*	*702.2*	*724.9*	***704.5***
S_{usi}	*102.0*	*139.7*	*121.5*	*98.7*	*163.7*	***125.1***
S_{bsi}	*70.0*	*427.1*	*180.3*	*181.4*	*63.3*	***184.4***
S_{upi}	*199.9*	*491.9*	*248.5*	*528.1*	*396.9*	***373.1***
S_{bpi}	*625.1*	*135.6*	*394.4*	*174.1*	*328.0*	***331.4***
S_{bi}	*695.1*	*562.6*	*574.7*	*355.5*	*391.3*	***515.8***
S_{ui}	*301.9*	*631.5*	*370.0*	*626.8*	*560.5*	***498.1***

*Note:*Table C.9 data ignore the biodegradable soluble COD (~ 70 % of measured 0.45µm membrane filtered effluent) exiting in the effluent of the JHB system.Refer to Appendix F for COD, N and P characterization procedures.

Table C.10: AN, AX and AE daily solids (TSS, VSS and ISS) variations for the JHB system (5d SRT).

Date	AN				AX				AE					
	TSS	ISS	VSS	VSS/TSS	TSS	ISS	VSS	VSS/TSS	TSS	ISS	VSS	VSS/TSS	SV_{30}	DSVI
				f_i				f_i				f_i		
–	mg/L	mg/L	mg/L	—	mg/L	mg/L	mg/L	—	mg/L	mg/L	mg/L	—	ml	ml/gTSS
25-Mar-10	2260	132	2128	0.94	5204	402	4802	0.92	2790	204	2586	**0.93**	150	108
26-Mar	1860	138	1722	0.93	3984	316	3668	0.92	2618	214	2404	**0.92**	160	122
27-Mar	1864	130	1734	0.93	4488	406	4082	0.91	2496	220	2276	**0.91**	160	128
29-Mar	2102	122	1980	0.94	3932	326	3606	0.92	2240	190	2050	**0.92**	130	116
31-Mar	2284	142	2142	0.94	3988	300	3688	0.92	2420	180	2240	**0.93**	130	107
1-Apr	2430	150	2280	0.94	4130	328	3802	0.92	2310	190	2120	**0.92**	130	113
2-Apr	2250	164	2086	0.93	4008	328	3680	0.92	2332	210	2122	**0.91**	115	99
3-Apr	2272	190	2082	0.92	3854	320	3534	0.92	2126	184	1942	**0.91**	110	103
4-Apr	2016	142	1874	0.93	3582	286	3296	0.92	2032	160	1872	**0.92**	99	97
6-Apr	1802	102	1700	0.94	3148	226	2922	0.93	1908	138	1770	**0.93**	80	84
7-Apr	1456	80	1376	0.95	2758	186	2572	0.93	1698	132	1566	**0.92**	70	82
9-Apr	1694	62	1632	0.96	3070	232	2838	0.92	1696	124	1572	**0.93**	60	71
10-Apr	1706	110	1596	0.94	3010	220	2790	0.93	1764	134	1630	**0.92**	45	51

11-Apr	*1612*	*102*	*1510*	*0.94*	*3082*	*240*	*2842*	*0.92*	*1866*	*150*	*1716*	***0.92***	*50*	*54*
12-Apr	*1482*	*86*	*1396*	*0.94*	*2926*	*204*	*2722*	*0.93*	*1616*	*106*	*1510*	***0.93***	*60*	*74*
13-Apr	*1370*	*84*	*1286*	*0.94*	*3122*	*212*	*2910*	*0.93*	*1674*	*114*	*1560*	***0.93***	*55*	*66*
4-May	*1806*	*114*	*1692*	*0.94*	*4422*	*328*	*4094*	*0.93*	*1814*	*130*	*1684*	***0.93***	*80*	*88*
5-May	*1588*	*70*	*1518*	*0.96*	*4456*	*254*	*4202*	*0.94*	*1836*	*106*	*1730*	***0.94***	*80*	*87*
6-May	*1806*	*80*	*1726*	*0.96*	*5268*	*312*	*4956*	*0.94*	*2092*	*110*	*1982*	***0.95***	*100*	*96*
7-May	*2278*	*170*	*2108*	*0.93*	*3404*	*314*	*3090*	*0.91*	*3452*	*356*	*3096*	***0.90***	*100*	*58*
8-May	*2556*	*168*	*2388*	*0.93*	*5214*	*388*	*4826*	*0.93*	*2470*	*146*	*2324*	***0.94***	*105*	*85*
10-May	*2424*	*140*	*2284*	*0.94*	*4518*	*304*	*4214*	*0.93*	*2336*	*156*	*2180*	***0.93***	*100*	*86*
11-May	*2662*	*152*	*2510*	*0.94*	*4488*	*308*	*4180*	*0.93*	*4090*	*358*	*3732*	***0.91***	*180*	*88*
12-May	*2640*	*192*	*2448*	*0.93*	*3808*	*304*	*3504*	*0.92*	*2920*	*224*	*2696*	***0.92***	*210*	*144*
17-May	*2936*	*190*	*2746*	*0.94*	*5350*	*358*	*4992*	*0.93*	*3308*	*214*	*3094*	***0.94***	*210*	*127*
18-May	*2462*	*172*	*2290*	*0.93*	*4472*	*370*	*4102*	*0.92*	*2620*	*206*	*2414*	***0.92***	*120*	*92*
19-May	*2522*	*150*	*2372*	*0.94*	*4562*	*336*	*4226*	*0.93*	*2892*	*222*	*2670*	***0.92***	*130*	*90*
20-May	*2592*	*156*	*2436*	*0.94*	*5962*	*412*	*5550*	*0.93*	*2840*	*208*	*2632*	***0.93***	*120*	*85*
21-May	*2444*	*130*	*2314*	*0.95*	*4852*	*334*	*4518*	*0.93*	*2532*	*186*	*2346*	***0.93***	*90*	*71*
22-May	*2018*	*100*	*1918*	*0.95*	*4166*	*274*	*3892*	*0.93*	*2042*	*122*	*1920*	***0.94***	*85*	*83*

1-Jun	2402	242	2160	0.90	4978	526	4452	0.89	2562	296	2266	**0.88**	110	86
2-Jun	2270	132	2138	0.94	4386	432	3954	0.90	2662	208	2454	**0.92**	120	90
3-Jun	2202	142	2060	0.94	3700	336	3364	0.91	4036	396	3640	**0.90**	115	57
4-Jun	2188	178	2010	0.92	4166	438	3728	0.89	2586	226	2360	**0.91**	125	97
5-Jun	2310	152	2158	0.93	4088	450	3638	0.89	2542	242	2300	**0.90**	120	94
6-Jun	2194	142	2052	0.94	4024	264	3760	0.93	2422	148	2274	**0.94**	110	91
8-Jun	1982	126	1856	0.94	3384	366	3018	0.89	2110	234	1876	**0.89**	110	104
9-Jun	1988	150	1838	0.92	3478	310	3168	0.91	2284	198	2086	**0.91**	120	105
10-Jun	2150	144	2006	0.93	3892	340	3552	0.91	2272	184	2088	**0.92**	120	106
12-Jun	2292	134	2158	0.94	4056	362	3694	0.91	2512	194	2318	**0.92**	120	96
13-Jun	1844	96	1748	0.95	3298	238	3060	0.93	2052	152	1900	**0.93**	110	107
14-Jun	1978	108	1870	0.95	3486	254	3232	0.93	2100	134	1966	**0.94**	110	105
15-Jun	1960	152	1808	0.92	3390	280	3110	0.92	2082	194	1888	**0.91**	120	115
17-Jun	1920	172	1748	0.91	3428	348	3080	0.90	2188	224	1964	**0.90**	110	101
18-Jun	2282	144	2138	0.94	3812	274	3538	0.93	2534	180	2354	**0.93**	120	95
19-Jun	2002	146	1856	0.93	3650	326	3324	0.91	2704	240	2464	**0.91**	125	92
21-Jun	2188	148	2040	0.93	3582	260	3322	0.93	2382	194	2188	**0.92**	140	118

23-Jun	2462	258	2204	0.90	3750	350	3400	0.91	2264	184	2080	**0.92**	130	115
24-Jun	2380	200	2180	0.92	3800	460	3340	0.88	2462	266	2196	**0.89**	140	114
25-Jun	1926	134	1792	0.93	2874	240	2634	0.92	2038	194	1844	**0.90**	135	132
26-Jun	1710	38	1672	0.98	2450	158	2292	0.94	1584	76	1508	**0.95**	100	126
28-Jun	1788	122	1666	0.93	2774	212	2562	0.92	1844	132	1712	**0.93**	100	108
29-Jun	1470	22	1448	0.99	1852	90	1762	0.95	1420	38	1382	**0.97**	95	134
30-Jun	1774	150	1624	0.92	2692	250	2442	0.91	1872	162	1710	**0.91**	115	123
1-Jul	1688	122	1566	0.93	1400	26	1374	0.98	2130	252	1878	**0.88**	140	131
2-Jul	2128	186	1942	0.91	3368	376	2992	0.89	2318	236	2082	**0.90**	130	112
3-Jul	1910	130	1780	0.93	1862	186	1676	0.90	2630	280	2350	**0.89**	170	129
4-Jul	2212	144	2068	0.93	2356	250	2106	0.89	2356	250	2106	**0.89**	165	140
5-Jul	2000	174	1826	0.91	3454	416	3038	0.88	2194	260	1934	**0.88**	150	137
7-Jul	2252	212	2040	0.91	4006	528	3478	0.87	2756	324	2432	**0.88**	170	123
10-Jul	1988	192	1796	0.90	3260	428	2832	0.87	2478	306	2172	**0.88**	140	113
12-Jul	1802	150	1652	0.92	3298	384	2914	0.88	2072	252	1820	**0.88**	130	125
13-Jul	1720	146	1574	0.92	3040	396	2644	0.87	1922	228	1694	**0.88**	110	114
14-Jul	1736	344	1392	0.80	2946	356	2590	0.88	2270	276	1994	**0.88**	130	115

15-Jul	1824	142	1682	0.92	3266	412	2854	0.87	2308	340	1968	**0.85**	130	113
16-Jul	2140	214	1926	0.90	3784	614	3170	0.84	2348	348	2000	**0.85**	130	111
17-Jul	1914	180	1734	0.91	2458	330	2128	0.87	1892	256	1636	**0.86**	100	106
18-Jul	1682	138	1544	0.92	2838	340	2498	0.88	1876	210	1666	**0.89**	110	117
19-Jul	1746	160	1586	0.91	2748	348	2400	0.87	2056	272	1784	**0.87**	125	122
20-Jul	1840	92	1748	0.95	3060	114	2946	0.96	2138	138	2000	**0.94**	170	159
21-Jul	2124	188	1936	0.91	4296	530	3766	0.88	2956	314	2642	**0.89**	148	100
22-Jul	2252	176	2076	0.92	4162	404	3758	0.90	2398	222	2176	**0.91**	165	138
23-Jul	2094	156	1938	0.93	3732	390	3342	0.90	2358	280	2078	**0.88**	170	144
25-Jul	2856	228	2628	0.92	4026	464	3562	0.88	3296	414	2882	**0.87**	170	103
26-Jul	2548	238	2310	0.91	4138	500	3638	0.88	3542	444	3098	**0.87**	160	90
27-Jul	3396	382	3014	0.89	4752	572	4180	0.88	2182	406	1776	**0.81**	290	266
28-Jul	2928	228	2700	0.92	4122	330	3792	0.92	3186	230	2956	**0.93**	210	132
29-Jul	3014	196	2818	0.93	3910	296	3614	0.92	2700	228	2472	**0.92**	180	133
3-Aug	2494	206	2288	0.92	3888	296	3592	0.92	2630	222	2408	**0.92**	180	137
5-Aug	3108	272	2836	0.91	3876	320	3556	0.92	2700	228	2472	**0.92**	160	119
7-Aug	2672	200	2472	0.93	3306	264	3042	0.92	5362	308	5054	**0.94**	200	75

8-Aug	3080	402	2678	0.87	4892	456	4436	0.91	2672	238	2434	**0.91**	180	135
9-Aug	2676	88	2588	0.97	4628	484	4144	0.90	3236	366	2870	**0.89**	210	130
12-Aug	3092	256	2836	0.92	5976	626	5350	0.90	4276	498	3778	**0.88**	270	126
13-Aug	3966	316	3650	0.92	5460	542	4918	0.90	3316	314	3002	**0.91**	350	211
14-Aug	2436	178	2258	0.93	3990	52	3938	0.99	3246	320	2926	**0.90**	270	166
15-Aug	2990	72	2918	0.98	5130	200	4930	0.96	3082	390	2692	**0.87**	350	227
16-Aug	2782	228	2554	0.92	4556	404	4152	0.91	2716	232	2484	**0.91**	330	243
18-Aug	3564	274	3290	0.92	4386	294	4092	0.93	2620	186	2434	**0.93**	260	198
22-Aug	3738	380	3358	0.90	4190	520	3670	0.88	4212	586	3626	**0.86**	200	95
24-Aug	3210	304	2906	0.91	4940	622	4318	0.87	4000	520	3480	**0.87**	260	130
25-Aug	3538	326	3212	0.91	5198	450	4748	0.91	3486	320	3166	**0.91**	290	166
26-Aug	3240	290	2950	0.91	4462	354	4108	0.92	3832	352	3480	**0.91**	240	125
27-Aug	2170	192	1978	0.91	2792	256	2536	0.91	2886	258	2628	**0.91**	200	139
28-Aug	2778	232	2546	0.92	3866	280	3586	0.93	2704	206	2498	**0.92**	260	192
2-Sep	2918	270	2648	0.91	3742	400	3342	0.89	2756	296	2460	**0.89**	230	167
3-Sep	3134	350	2784	0.89	4444	530	3914	0.88	2866	340	2526	**0.88**	240	167
5-Sep	3716	402	3314	0.89	3776	364	3412	0.90	3310	342	2968	**0.90**	420	254

6-Sep	3288	310	2978	0.91	4462	414	4048	0.91	2608	254	2354	**0.90**	270	207
7-Sep	3046	288	2758	0.91	3782	436	3346	0.88	2830	262	2568	**0.91**	250	177
8-Sep	3624	368	3256	0.90	4686	516	4170	0.89	2660	274	2386	**0.90**	245	184
9-Sep	4106	344	3762	0.92	4886	526	4360	0.89	2726	294	2432	**0.89**	270	198
10-Sep	2674	220	2454	0.92	3758	358	3400	0.90	3366	348	3018	**0.90**	230	137
11-Sep	2582	210	2372	0.92	4258	444	3814	0.90	2452	228	2224	**0.91**	200	163
12-Sep	3426	362	3064	0.89	4002	408	3594	0.90	3426	320	3106	**0.91**	240	140
15-Sep	3152	270	2882	0.91	6018	508	5510	0.92	6174	892	5282	**0.86**	200	65
17-Sep	2892	270	2622	0.91	3450	360	3090	0.90	2284	220	2064	**0.90**	215	188
18-Sep	2318	190	2128	0.92	2982	276	2706	0.91	1858	178	1680	**0.90**	175	188
20-Sep	2586	208	2378	0.92	2898	342	2556	0.88	1944	270	1674	**0.86**	125	129
21-Sep	2138	194	1944	0.91	3186	404	2782	0.87	5036	616	4420	**0.88**	170	68
23-Sep	2496	200	2296	0.92	3482	292	3190	0.92	4678	528	4150	**0.89**	150	64
25-Sep	2774	252	2522	0.91	3674	448	3226	0.88	2274	268	2006	**0.88**	160	141
4-Oct-10	2724	202	2522	0.93	3578	314	3264	0.91	5132	636	4496	**0.88**	161	63

APPENDIX D

CONVENTIONAL ACTIVATED SLUDGE UCT SYSTEM (CAS UCT)

TABLE D.1: Initial design and operating parameters of the Conventional AS UCT system (CAS UCT), Ramphao et al. (2004).

System parameter	CAS UCT
Sludge age (days)	*20*
$f_{m,anaerobic}$, Volume (ℓ)	*0.126* [1]*/ 5.6*
$f_{m,anoxic}$, Volume (ℓ)	*0.279* [1]*/ 6.2*
$f_{m,aerobic}$, Volume (ℓ)	*0.595* [1]*/ 13.2*
a-recycle (AE to AX)	*1:2*
r-recycle (AX to AN)	*1:1*
s-sludge recycle (SST to AX)	*1:1*
Hydraulic retention time (day)	*1.4*
MLVSS (AE) (mg/ℓ)	*3600*[2}
MLTSS (AE) (mg/ℓ)	*4950*[2}
Influent flow (ℓ/d)	*15*
Feed COD (mg/ℓ)	*1000*

[1] for the given a-, r- or s-recycle ratios; [2] predicted using processes and modeling of NDBEPR BNR (Wentzel et al., 1992).

TABLE D.2: Influent, effluent concentrations and removal efficiencies for the CAS UCT system, Ramphao et al. (2004).

PARAMETER		**Influent**	**Effluent**	**Efficiency**
COD	**mg COD/ℓ**	*987*	*73.2*[1] *(57*[2]*)*	*94%*
TKN	**mg N/ℓ**	*103*	*4.6*[1] *(3.2*[2]*)*	*95%*
FSA	**mg NH_3-N /ℓ**	*84*	*2.6*	*95%*
TP	**mgPO_4-P/ℓ**	*41*	*19*	*54%*
Ortho P	**mg PO_4-P/ℓ**	–	–	–
NO_3	**mg NO_3-N/ℓ**	*0.0*	*22*	–
SS	**mg TSS/ℓ**	–	*14.8*	–
pH	**n/a**	–	–	*n/a*

[1] Unfiltered sample; [2] 0.45 µm membrane filtered sample;

APPENDIX E

NATIONAL WATER ACT REGULATIONS

NATIONL WATER ACT

Sourced from Act 36 of 1998, Issue No 2 (2000), 3.37-3.39

vi. “**Industrial wastewater discharge**” means a wastewater discharge consisting of more than 10 % industrial wastewater, by volume, that is collected, treated and subsequently disposed of;

vii. “**Intake**” is water taken from a water resource and excludes water taken from any source that is not a water resource;

viii. “**Monitoring programme**” means a program for taking regular measurements of the quantity and/or quality of a water resource, waste or wastewater discharge at specified intervals and at specified locations to determine the chemical, physical and biological nature of the water resource, waste or wastewater discharge;

ix. “**Listed water resources**” are those water resources listed in Table 3.4 and include any tributary of a listed water resource and any water resource draining the catchment area of a listed water resource;

x. “**Wastewater**” means water containing waste or water that has been in contact with waste material;

xi. “**Wastewater limit value**” means the mass expressed in terms of concentration and/or level of a substance which may not be exceeded at any time. Wastewater Limit Values shall apply at the last point where the discharge of wastewater enters into a water resource, dilution being disregarded when determining compliance with the Wastewater Limit Values. Where discharge of wastewater does not directly enter a water resource, the Wastewater Limit Value shall apply at the last point where the wastewater leaves the premises of collection and treatment.

Discharging of domestic and industrial wastewater into water resources

3.7.(1) A person who-

- i. Owns or lawfully occupies property registered in the Deeds Office as at the date of this notice; or
- ii. Lawfully occupies or uses land that is not registered or surveyed,

Outside of the areas as excluded in paragraph 3.4 above, may on that property or land-

- a) Discharge up to 2000 cubic metres of wastewater on any given day into a water resource that is not listed water resource referred to in Table 3.4, provided-
  - i. The discharge complies with General Limit Values set out in Table 3.2;
  - ii. The discharge does not alter the natural ambient water temperature of the receiving water resource by more than 3 degrees Celsius; and
  - iii. The discharge is not a Complex Industrial Wastewater.

- b) Discharge up to 2 000 cubic metres of wastewater on any given day into a listed water resource referred to in Table 3.4, provided-
  - i. The discharge complies with the Special Limited Values set out in Table 3.2;
  - ii. The discharge does not alter the natural ambient water temperature of the receiving water resource by more than 2 degrees Celsius; and
  - iii. The discharge is not a Complex Industrial Wastewater.

(2)A person may discharge stormwater runoff from any premises, not containingwaste orwastewater emanating from industrial activities and premises, into a water resource.

Table 3.2: Wastewater Limit Values applicable to discharge of wastewater into a water resource.

SUBSTANCE/PARAMETER	GENERAL LIMIT	SPECIAL LIMIT
Faecal Coliforms (per 100 mℓ)	*1000*	*0*
Chemical Oxygen Demand (mg/ℓ)	*75**	*30**
pH	*5.5 – 9.5*	*5.5 – 7.5*
Ammonia (ionised and un-ionised) as Nitroen (mg/ℓ)	*3*	*2*
Nitrate/Nitrite as Nitrogen (mg/ℓ)	*15*	*1.5*
Chlorine as Free Chlorine (mg/ℓ)	*0.25*	*0*
Suspended Solids (mg/ℓ)	*25*	*10*
Electrical Conductivity (mS/m)	*70 mS/m above intake to a maximum of 150 mS/m*	*50 mS/m above background receiving water, to a maximum of 100 mS/m*
Ortho Phosphate as phosphorous (mg/ℓ)	*10*	*1 (median) and 2.5 (maximum)*

SUBSTANCE/PARAMETER	GENERAL LIMIT	SPECILA LIMIT
Fluoride (mg/ℓ)	*1*	*1*
Soap, Oil or Grease (mg/ℓ)	*2.5*	*0*
Dissolved Arsenic (mg/ℓ)	*0.02*	*0.01*
Dissolved Cadmium (mg/ℓ)	*0.005*	*0.001*
Dissolved Chromium (mg/ℓ)	*0.05*	*0.02*
Dissolved Copper (mg/ℓ)	*0.01*	*0.002*
Dissolved Cyanide (mg/ℓ)	*0.02*	*0.01*
Dissolved Iron (mg/ℓ)	*0.3*	*0.3*
Dissolved Lead (mg/ℓ)	*0.01*	*0.006*
Dissolved Manganese (mg/ℓ)	*0.1*	*0.1*
Mercury and its compounds (mg/ℓ)	*0.005*	*0.001*
Dissolved Selenium (mg/ℓ)	*0.02*	*0.02*
Dissolved Zinc (mg/ℓ)	*0.1*	*0.04*
Borron (mg/ℓ)	*1*	*0.5*

***After removal of algae**

Registration of discharge into water resources

3.8.(1) A person who discharges wastewater into a water resource in terms of this authorisation must submit a registration form obtained from the Department for registration of the water use before commencement of the discharge.

(2) On written acknowledgement of receipt of the application form by the Department, the person will be regarded as a registered water user.

APPENDIX F

INFLUENT CHARACTERIZATION AND $f_{S'up}$ CALCULATION

Waste water comprises both organic and inorganic materials, which are removed in AS by biological oxidation, phase transformations (liquid to solid or liuid to gas) and solid liquid separation. Non settleable (colloidal) and dissolved waste water constituents can be transformed to settleable solids (biomass, if biodegradable and enmeshed if unbiodegradable) and settled in SST.

Biological reactions in the AS reactors transform biodegradable organics to settleable biomass and enmeshing and entrapping biodegradable and unbiodegrdable organics into the sludge mass. Therefore all particulates become part of the sludge mass in the reactor. Some of this sludge mass is harvested from the reactor daily to control mass in the reactor.

The growth process transforms biodegradable organics into biomass. Y_{COD} of the electrons in the influent biodegradable organics of biomass (anabolism-2/3) and the rest of the electrons in the influent biodegradable organics are passed to oxygen (catabolism- 1/3). The electrons passed to oxygen represent electrons lost as heat. The growth process is rapid resulting virtually complete utilization of biodegradable organics. Therefore only unbiodegradable soluble organics form the effluent.

The PAOs in the BEPR systems require rapidly biodegradable organics given as S_{bsi} (RBCOD ready for conversion to SCFA) which for denitrification and excess phosphorus removal.

$$S_{bsi} = (S_{si} - S_{use}) - (r*8.6*NO_{3anaerobic})$$

S_{bsi} = (0.45µm membrane filtered influent from UCT or JHB – 0.45µm membrane filtered effluent from UCT or JHB) – (r-recycle *8.6* nitrates concentration in anaerobic (AN) reactor of the UCT or JHB).

Where r-recycle is from anoxic (AX) to anaerobic (AN) reactor and 8.6 is a factor for observed mgCOD removed/mgNO_3 concentration in anaerobic.

Table F.1: Influent WW COD, TKN and TP characterization.

COD characterization S_{ti} = Total Influent COD S_{si} = 0.45 µm membrane filtered influent COD $S_{pi} = S_{ti} - S_{si}$ (particulate COD in the influent) $S_{usi} = S_{use}$ = 0.45 µm membrane filtered effluent COD (unbiodegradable soluble COD in the influent) $S_{bsi} = S_{si} - S_{usi}$ (biodegradable soluble COD in the influent) $S_{upi} = f_{S'up} * S_{ti}$(unbiodegradable particulate COD in the influent) $S_{bpi} = S_{pi} - S_{upi}$ (biodegradable particulate COD in the influent) $S_{bi} = S_{bsi} + S_{bpi}$ (biodegradable COD in the influent) $S_{ui} = S_{usi} + S_{upi}$ (unbiodegrradable COD in the influent)	Where $f_{S'up}$ is calculated as shown in **Eq. F.5**below
TKN characterization N_{ti} = Total influent nitrogen (Total Kjeldahl Nitrogen = TKN) N_{ai} = Total influent ammonia $N_{oi} = N_{ti} - N_{ai}$ (organic nitrogen in the influent) N_{si} = 0.45 µm membrane filtered influent nitrogen (soluble nitrogen in the influent) $N_{pi} = N_{ti} - N_{si}$(particulate nitrogen in the influent)	

N_{ousi} = N_{ouse} = 0.45 µm membrane filtered effluent nitrogen (organic nitrogen unbiodegradable soluble in the influent) N_{obsi} = N_{si} - N_{ai} - N_{ousi} (organic nitrogen biodegradable soluble in the influent) N_{oupi} = (f_n/f_{CV})* S_{upi} (organic nitrogen unbiodegradable particulate in the influent) N_{obpi} = N_{pi} - N_{oupi}(organic nitrogen biodegradable particulate in the influent) N_{oui} = N_{oupi} - N_{ousi}(organic nitrogen unbiodegradable in the influent) N_{obi} = N_{obpi} - N_{obsi} (organic nitrogen biodegradable in the influent)	Where f_n*(mg N/mgVSS)* = (N_{AEML} –$N_{FILT.EFFL}$) / AEMLVSS f_{CV} *(mg COD/mgVSS)* = (S_{AEML} – $S_{FILT.EFFL}$) / AEMLVSS
TP characterization P_{ti} = Total influent phosphorus (phosphate) OrthoP$_i$ = Total influent orthophosphate P_{oi} = P_{ti} - OrthoP$_i$ (organic phosphorus in the influent) P_{si} = 0.45 µm membrane filtered influent phosphorus (soluble phosphorus in the influent) P_{pi} = P_{ti} - P_{si} (particulate phosphorus in the influent) P_{ousi} = P_{ouse} = 0.45 µm membrane filtered effluentphosphorus (organic phosphorus unbiodegradable soluble in the influent) P_{obsi} = P_{si} - P_{ai} - P_{ousi}(organic phosphorus biodegradable soluble in the	

influent) $P_{oupi} = (f_p/f_{CV})^* S_{upi}$ (organic phosphorus unbiodegradable particulate in the influent) $P_{obpi} = P_{pi} - P_{oupi}$ (organic phosphorus biodegradable particulate in the influent) $P_{oui} = P_{oupi} - P_{ousi}$ (organic phosphorus unbiodegradable in the influent) $P_{obi} = P_{obpi} - P_{obsi}$ (organic phosphorus biodegradable in the influent)	Where f_p *(mg P/mgVSS)* $= (P_{AEML} - P_{FILT.EFFL})$ / AEMLVSS f_{CV} *(mg COD/mgVSS)* $= (S_{AEML} - S_{FILT.EFFL})$ / AEMLVSS

$f_{S'up}$ CALCULATIONS FOR THE NDBEPR AS SYSTEM (See Ekama and Wentzel, 1999)

Below are the calculations of the unbiodegradable fraction, for the influent to the NDBEPR AS system, using the volatile organic solids and oxygen utilisation prediction formulae. Also given, is a formula for the calculation of the waste flow (Q_w).

USING MX_v PREDICTION CALCULATIONS

$$MX_V = MS_{ti}\left\{\left[\left(1 - f_{up} - f_{us} - {}^{S_{bsi}}/_{S_{ti}}\right)\left(\frac{(1 + f_{ep,H}b_H R_s)Y_H R_s}{(1 + b_H R_s)}\right)\right] + \left[\left(\frac{S_{bsi}}{S_{ti}}\right)\left(\frac{(1 + f_{ep,G}b_G R_s)Y_G R_s}{(1 + b_G R_s)}\right)\right] + \left[\frac{f_{up}R_s}{f_{cv}}\right]\right\} \quad \textbf{[Eq. F.1]}$$

Let

$$H = \left[\frac{(1+f_{ep,H}b_H R_s)Y_H R_s}{(1+b_H R_s)}\right] \quad \textbf{[Eq. F.2]}$$

$$G = \left[\frac{(1+f_{ep,G}b_G R_s)Y_G R_s}{(1+b_G R_s)}\right] \quad \textbf{[Eq. F.3]}$$

$$\frac{MX_V}{MS_{ti}} = \left[\left(1 - f_{us} - {}^{S_{bsi}}/_{S_{ti}}\right)H\right] + \left[\left(\frac{S_{bsi}}{S_{ti}}\right)G\right] - \left[f_{up}\left(\frac{R_s}{f_{cv}} - H\right)\right] \qquad \text{[Eq. F.4]}$$

$$f_{up} = \frac{\left({}^{MX_v}/_{MS_{ti}}\right) - \left[\left(1 - f_{us} - {}^{S_{bsi}}/_{S_{ti}}\right)H\right] - \left[\left({}^{S_{bsi}}/_{S_{ti}}\right)G\right]}{\left({}^{R_s}/_{f_{cv}} - H\right)} \qquad \text{[Eq. F.5]}$$

<u>Where :</u> $b_H = 0.24$

$b_G = 0.04$

$Y_H = Y_G = 0.45$

$f_{epH} = 0.2$

$f_{epG} = 0.25$

<u>Note:</u>

$$VSS\ (mgVSS/\ell) = \left[\frac{avg\ MX_V}{Reactor\ Volume}\right]$$

$$SRT\ (Sludge\ Age) = \left[\frac{Mass\ of\ sludge\ in\ reactor(s)}{Mass\ of\ sludge\ wasted\ from\ reactor(s)}\right]$$

<u>If waste from AE reactor:</u>

$$SRT\ (day) = \left[\frac{(TSS_{AN} * Vol_{AN}) + (TSS_{AX} * Vol_{AX}) + (TSS_{AE} * Vol_{AE})}{(TSS_{AE} * Q_w)}\right]$$

<u>Or</u>

$$Q_w(l/d) = \left[\frac{(Vol_{AN}) + (Vol_{AX}) + (Vol_{AE})}{SRT}\right] \quad \textbf{[Eq. F.6]}$$

<u>Where:</u> Vol_{AN}= 3.5 ℓ is the volume of the anaerobic (AN) reactor which has been diluted twice i.e. by the influent flow $Q_i$and the *s-recycle* in the case of the ***NDEBPR UCT system*** in this investigation.

Vol_{AX} = 2.2 ℓ is the volume of the anoxic (AX) which is multiplied by *two* because the TSS of the AX reactor is twice the strength of the TSS of the AN and AE reactors in the case of the ***EBPR JHB system*** in this investigation.

APPENDIX G

RESULTS OF NITRIFICATION BATCH TESTS DONE ON THE AEROBIC MIXED LIQUOR OF THE UCT SYSTEM

The OUR, FSA and NO_3 results of all the batch tests done on the aerobic mixed liquor from the UCT system are shown in **Figures G.1 – G.6**. Unlike batch tests 1 and 2, batch tests 3, 4, 5 and 6 were run over a much longer period i.e. 24 hours after the addition of ammonium chloride to the batch test reactor. The objective was to give the nitrifiers ample time to produce nitrate from the oxydation of the ammonia added. Batch test 5 was carried on the aerobic mixed liquor from the membrane system which is a fully nitrifying system to which normal (real) WW from Mitchell’s Plain WWTP was fed. The membrane system had the same UCT configuration and had VSS (TSS) between 5000 – 6500 mgSS/ℓ. The objective of batch test 5 was to provide results purely as a basis for comparison with the results obtained from the batch tests done on sludge harvested from the UCT system. In batch test 1, note that although the concentration of ammonia (NH_3) decreases from 24 to 15 mgN/ℓ over 7h, the nitrate production is negligible, i.e. only 1/20th of the ammonia decrease. Also the OU is only 15% of that expected from the ammonia decrease.The discrepancy between the decrease in ammonia and the nitrate production is also visible for batch tests 2, 3, 4 and 6. Results of batch tests 1, 2, 3, 4 and 6 supported the argument of no nitrification in the UCT system. For detailed discussion on the comparison of the results with batch test 5, see **section 4.1.2.8**.

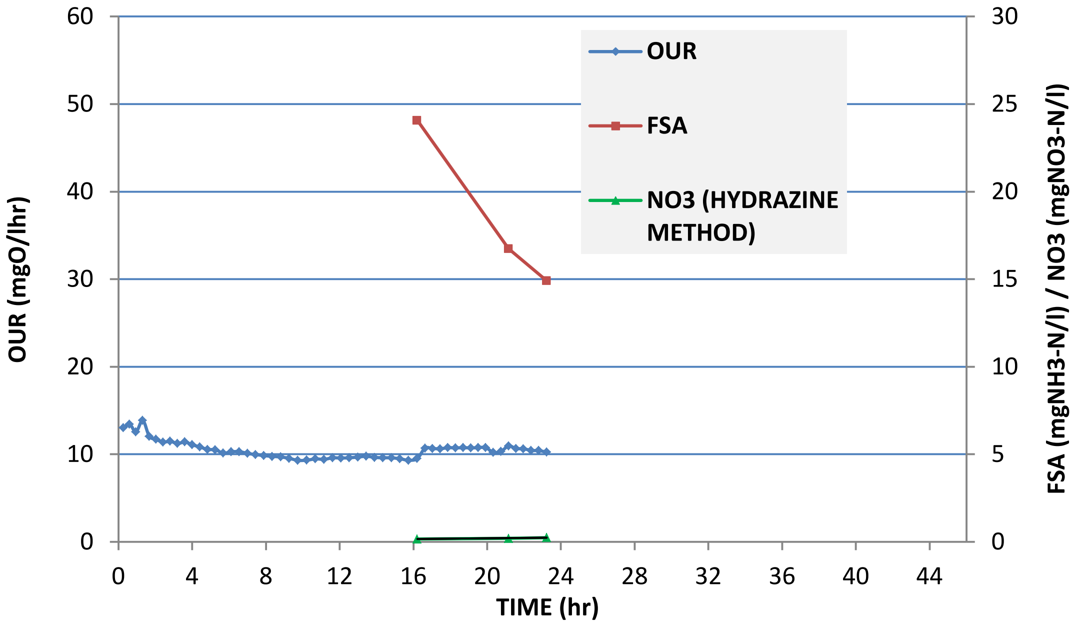


Figure G.1: OUR, FSA and NO3 results from batch test 1 (October 4, 2009). 50 ml of ammonium chloride solution (1 gNH4Cℓ/ℓ) were added 16 hours following the start of the batch test and nitrification was monitored over a period of 7 hours thereof. Sampling was done every 3 hours.

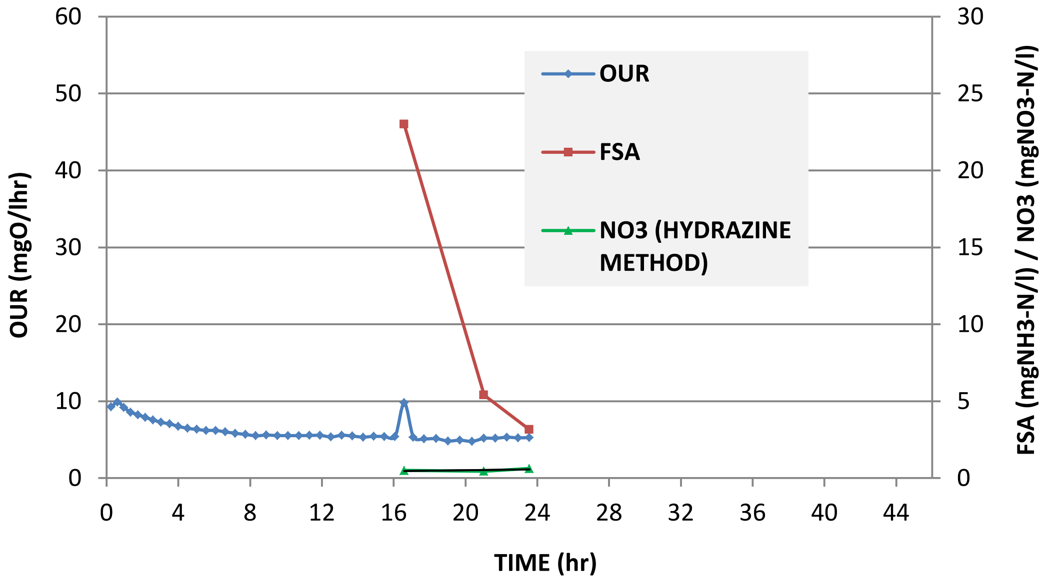


Figure G.2: OUR, FSA and NO3 results from batch test 2 (November 2, 2009).

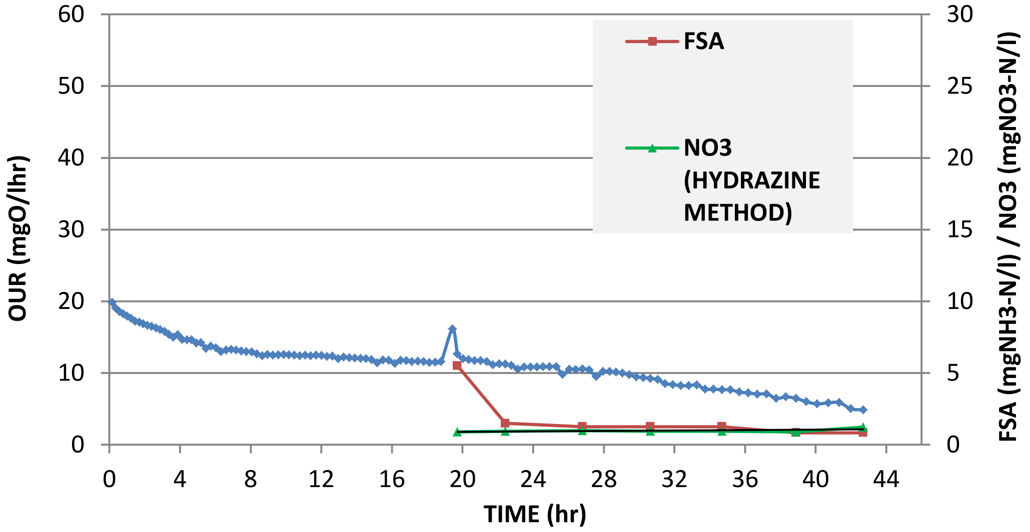


Figure G.3: OUR, FSA and NO_3 results from batch test 3 (January 18, 2010). A volume of 50 ml of ammonium chloride solution - standard at 0.020g NH4Cℓ/ℓ - was dosed 20 hours following the start of the batch test and nitrification monitored for 24 hours thereof. Sampling was done every 4 hours.

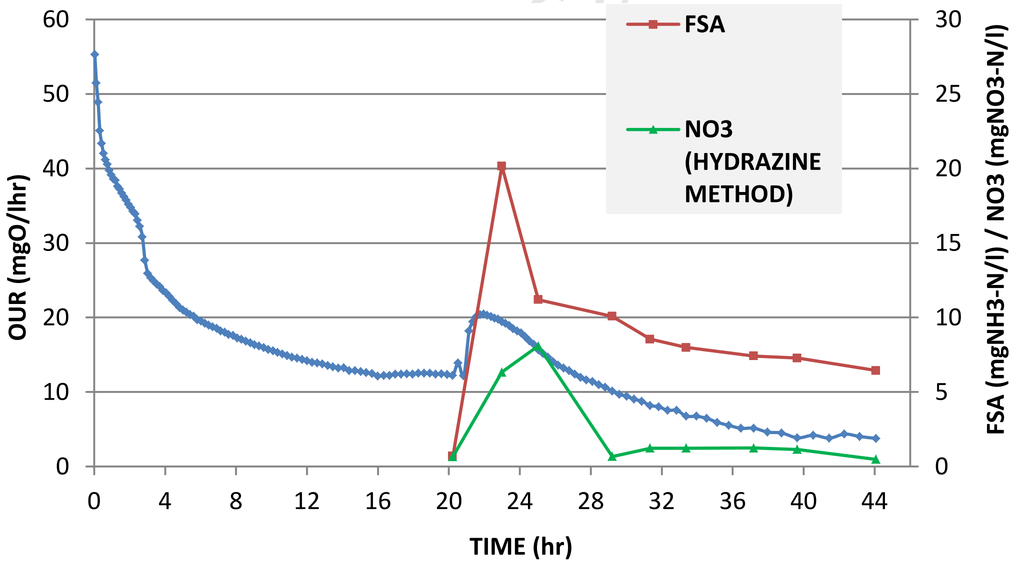


Figure G.4: OUR, FSA and NO_3 results from batch test 4 (February 2, 2010). A volume of 50 ml of ammonium chloride solution - standard at 1g $NH_4C\ell/\ell$ - was dosed 20 hours following the start of the batch test and nitrification monitored for 24 hours thereof. The increase in FSA indicates the concentration of ammonia in the batch test reactor prior to dosage of ammonium chloride. Samples were taken nearly every 4 hours.

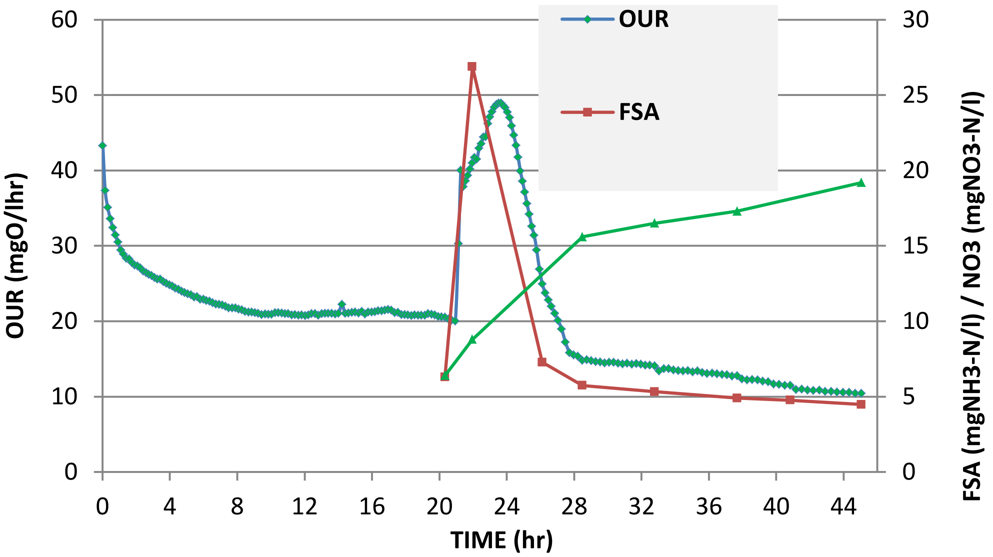


Figure G.5:OUR, FSA and NO$_3$ results from batch test 5 (February 24, 2010) done on sludge harvested from the membrane unit which, is a fully nitrifying system with the UCT configuration but twice the VSS (TSS) concentration than the UCT system and receiving normal (real) WW.

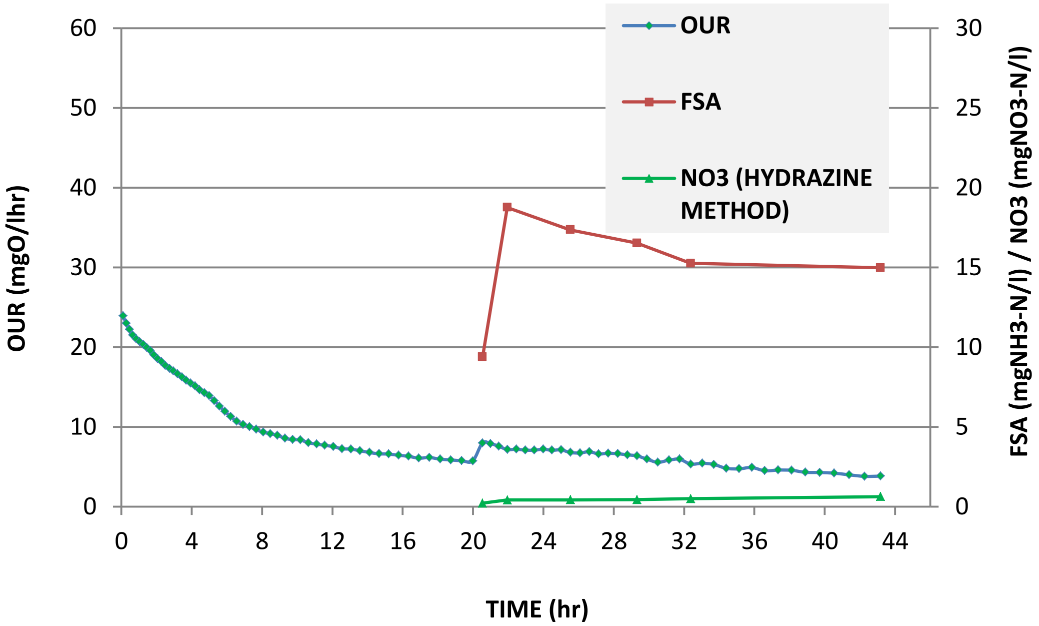
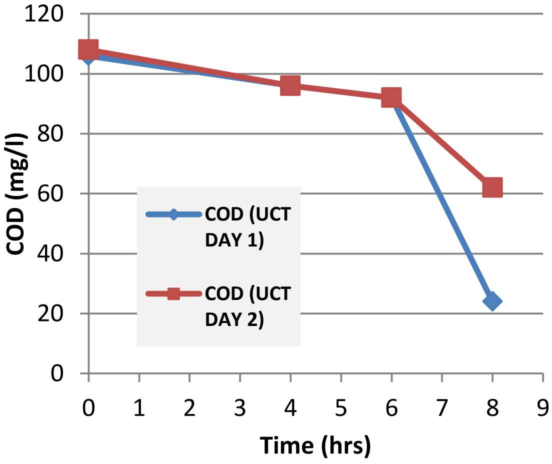


Figure G.6: OUR, FSA and NO$_3$ results from batch test 6 (March 26, 2010). Note the discrepancy between the OU and the ammonia decrease. The OU represents less than 30 % that expected from the ammonia decrease.

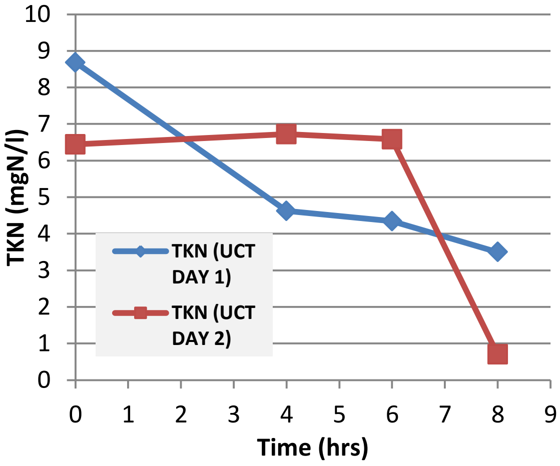
APPENDIX H

RESULTS OF AEROBIC BATCH TESTS DONE ON THE EFFLUENT OF THE UCT AND JHB SYSTEMS

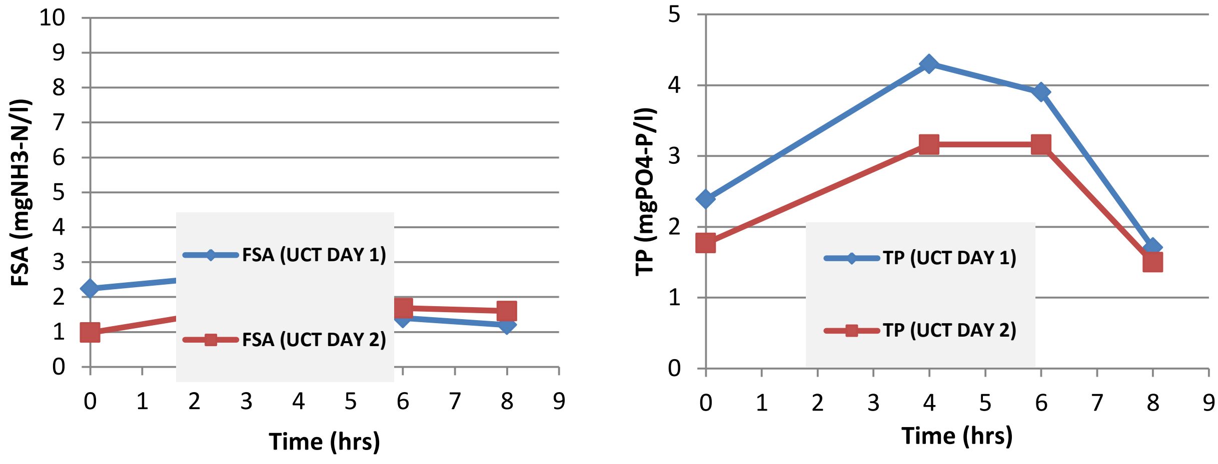
The aerobic batch tests were done to measure the residual biodegradable soluble concentrations (COD, TKN and TP) not utilized inside the system and exited with the effluent from the UCT (and JHB) system. These batch tests were conducted on the effluent collected separately from the BNR systems and to which a known volume of aerobic mixed liquor from a different NDEBPR system fed real WW was added. This system was a fully nitrifying BNR membrane AS system to which normal (real) WW from Mitchell's Plain WWTP was fed.**Figures H.1** and **H.2** gives the results of COD, TKN, TP and OrthoP concentrations of grab samples taken every 3 - 4 hours over the batch test periods. Two batch tests (identified as day 1 and day 2) were conducted on the effluent of each of the UCT and JHB sytems. The concentrations measured and recorded at time *zero (0) hour*(see **Figures H.1** and **H.2)** are the initial concentrations in the fresh effluent i.e. before it wastransferred into the batch reactor and mixed with the aerobic sludge of the membrane system.



a.COD

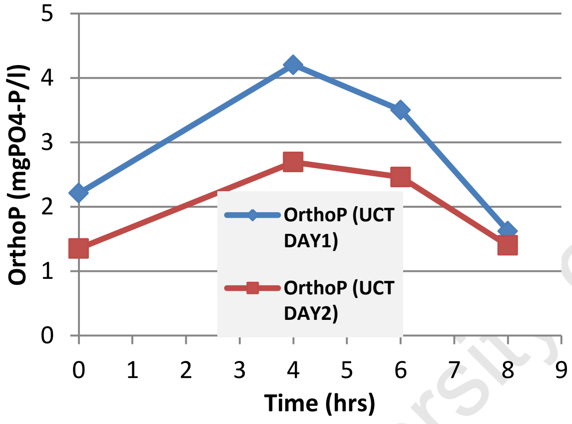


b. TKN



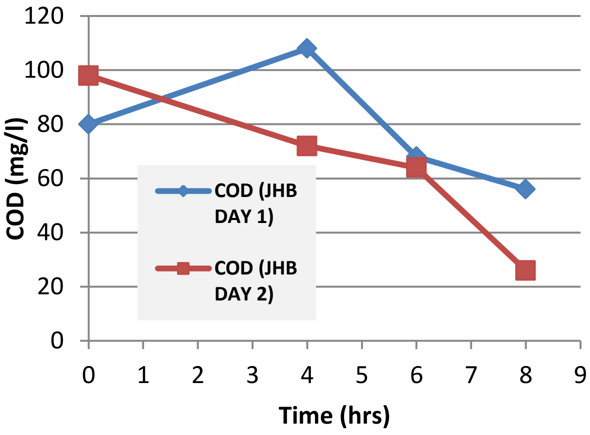
c. FSA

d. TP

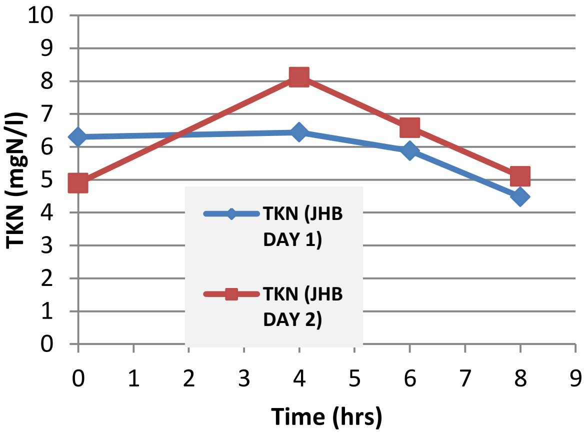


e. OrthoP

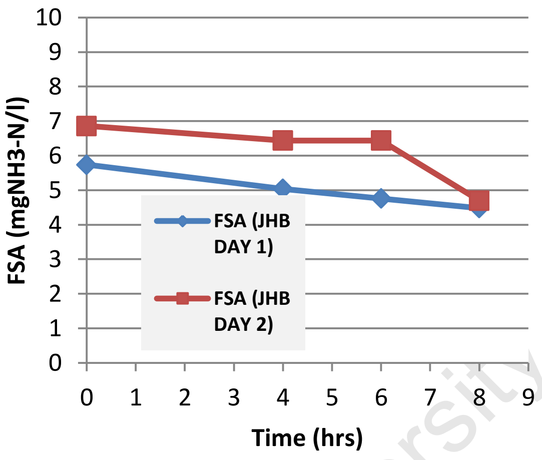
Figure H.1: Results of aerobic batch tests done on the effluent of the UCT system.



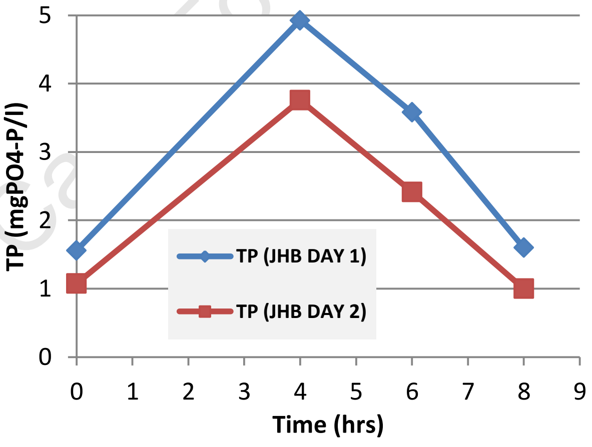
a. COD



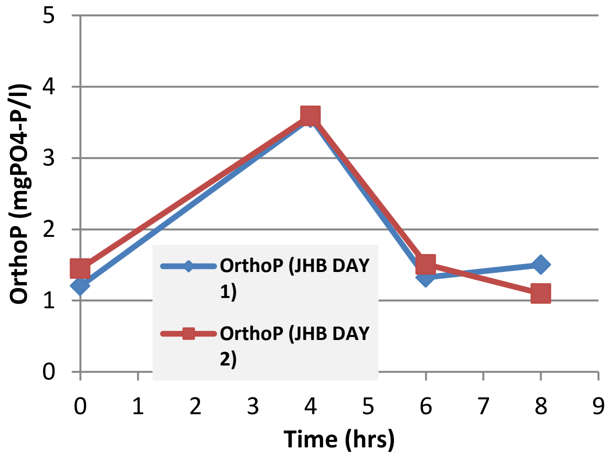
b. TKN



c. FSA



d. TP



e. OrthoP

Figure H.2: Results of aerobic batch tests done on the effluent of the JHB system.

APPENDIX I

NITROGEN, COD AND P MASS BALANCES

Three mass balances are generally applied to experimental data namely nitrogen (N), organics (COD) and phosphorus (P) mass balances. They are used as a check to validate the reliability of data. They are also used to investigate process behaviours in order to gain a better understanding of the mechanisms of these. Mass balance check can be applied to full-scale plants, pilot plants and laboratory-scale experimental systems (Ramphao et al., 2004).

I.1 DATA REQUIRED FOR N AND COD MASS BALANCES

N and COD mass balances require comprehensive data. These include information on both operating parameters and measured concentrations. The operating parameters involved are e.g. flows, recycle flows, sludge age (SRT) or sludge wastage. The measured concentrations are the influent and effluent TKN and COD, nitrite and nitrate; nitrite and nitrate in each reactor; oxygen utilization rate (OUR); volatile settleable solids (VSS) of the waste sludge; COD/VSS (f_{CV}) and TKN/VSS (f_n) ratios of the waste sludge.

I.1.1 N MASS BALANCE

The N mass balance compares the exiting N via the effluent, waste sludge stream and nitrate denitrified (from a nitrate balance over the AX and AN reactors) with the N entering the systems via the influent TKN.

The daily flux of nitrogen that enters the system in the form of influent TKN (FNt_i) exits it as flux of N denitrified (FNO_{xd}, mgN/d); flux of N in the waste sludge (FN_{tws}) and flux of N in the effluent, i.e. TKN (FN_{teffl}) plus nitrite and nitrate (FNO_{xeffl})

$$\%NITROGEN\_Balance = \frac{100*(FNO_{xd} + FN_{tWS} + FN_{teffl})}{FN_{ti}} \qquad \textbf{[Eq I.1]}$$

i. Flux of N denitrified (FNO_{xd}, mgN/d)

$FNO_{2d} = (a+s)*Qi*NO_{2,aerobic} + (1+r)*Qi*NO_{2,anaerobic} - (1+a+s)*Qi*NO_{2,anoxic} - r*Qi*NO_{2,anoxic}$

$FNO_{3d} = (a+s)*Qi*NO_{3,aerobic} + (1+a+s)*Qi*NO_{3,anoxic} + r*Qi*NO_{3,anoxic} – (1+r)*Qi*NO_{3,anaerobic}$

Where:

FNO_{2d}	Flux of nitrite denitrified (mg NO_2-N/d)
FNO_{3d}	Flux of nitrate denitrified (mg NO_3-N/d)
$NO_{2,aerobic}$	nitrite concentration in the aerobic reactor (mg NO_2-N/ℓ)
$NO_{3,aerobic}$	nitrate concentration in the aerobic reactor(mg NO_3-N/ℓ)
Q_i	Daily Influent flow (ℓ/d)
a, r & s	recycle ratios

Substituting the respective values from ***sewage Batch 2 (B2)*** into the above equation produce:

i. Flux of nitrite and nitrate denitrified

FNO_{2d} = (3.82+2.18)*15*0.20 + (1+1.50)*15*0 - (1+3.82+2.18)*15*0.14 - 1.50*15*0.14

= 0.15 mg NO_2-N/d

FNO_{3d} = (3.82+2.18)*15*0.17 + (1+1.50)*15*0 - (1+3.82+2.18)*15*0 - 1.50*15*0

= 15.3 mg NO_3-N/d

ii. flux of N in the waste sludge (FN_{tws})

FN_{tws} = $Q_w*(f_n*X_v+NO_{2,effl}+NO_{3,effl}+N_{teffl})$

= 1.425*(0.0899*3702+0.18+0.19+2.3)

= 478.1 mg N/d

iii. flux of N in the effluent (FN_{effl})

FN_{effl} = $(Q_i – Q_w)*(N_{te} + NO_{2,effl} + NO_{3,effl})$

= (15 – 1.425)*(2.3 + 0.18 + 0.19)

= 36.2 mg N/d

iv. Flux of N in the influent

FN_{ti}= $Q_i * N_{ti}$

= 15 * 50.4

= 756 mg N/d

% N mass balance = 100 *(0.15 + 15.3 +478.1 + 36.2)/756

= 70.1 %

Note: The method for calculating the N balance also applies to the JHB system.

I.1.2 COD MASS BALANCE

The COD balance was calculated by comparing the exiting COD via the effluent, waste sludge stream and oxygen utilized in the aerobic reactor (corrected for nitrification) with the COD entering the systems via the influent COD. For 100% COD balance, the flux of COD entering the system should be accounted by the flux of oxygen demand required per day for degradation of carbonaceous material in the aerobic reactor (FO_c, mgO/d); flux of oxygen recovered by denitrification of nitrate and nitrite (FO_d, gO/d); flux of COD in the waste sludge (FSt_{ws}, gCOD/d) and flux of COD in the effluent (FSt_{effl}, gCOD/d).

FO_c is obtained by subtracting the nitrification oxygen demand (FO_n, gO/d) from the measured oxygen demand, i.e. $FO_m = OUR_m * V_{aerobic} * 24$ and adding the oxygen recovered by denitrification (FO_d). FO_n is the sum of the oxygen required for nitrification of ammonia to nitrite (3.43 mgO/mgN) and nitrate (4.57 mgO/mgN) times the flux of nitrite and nitrate generated respectively. The nitrite/nitrate generated is obtained by doing a nitrite/nitrate mass balance over the aerobic reactor. Alternatively, for simplification, $FO_n = 4.57*(FNO_{xd} + FNO_{effl})$ where 4.57 represents the oxygen requirement for the nitrification of ammonia to nitrate. FO_d is 2.86 times the flux of nitrate denitrified, i.e. $FO_d = 2.86*FNO_{xd}$ where 2.86 is oxygen equivalent of nitrate when denitrifying one mgN of nitrate to nitrogen gas. The measured FO_c is then added to the flux of COD exiting the system via the effluent and waste flows to obtain the total COD exiting the system as follows:

[Eq I.2]

$$\%COD\_Balance = \frac{100*(FO_C + FO_d + FS_{tWS} + FS_{teffl})}{FS_{ti}}$$

For the same example of ***sewage batch 2 (B2)***, the respective calculations are:

i. Flux of nitrite and nitrate generated ($FNO_{2,generated}$, $FNO_{3,generated}$)

$FNO_{2,generated}$ = $(1+a+s+Q_w/Q_i)*Q_i*NO_{2,aerobic} – (1+a+s)*Q_i* NO_{2,anoxic}$
= $(1+3.82+2.18+1.425/15)*15*0.2 – (1+3.82+2.18)*15*0.14$
= 6.6 mg N/d

$FNO_{3,generated}$ = $(1+a+s+Q_w/Q_i)*Q_i*NO_{3,aerobic} – (1+a+s)*Q_i* NO_{3,anoxic}$
= $(1+3.82+2.18+1.425/15)*15*0.17 – (1+3.82+2.18)*15*0$
= 18.1 mg N/d

ii. Flux of nitrification oxygen demand (FO_n)

FO_n= $3.43*NO_{2,generated} + 4.57*NO_{3,generated}$
= 3.43*(6.6) + 4.57*(18.1)
= 105.4 mg O/d

iii. Flux of carbonaceous oxygen demand (FO_c)

FO_c= $(OUR*24*V_{reactor}) – FO_n$
= 23.9*24*15 – 105.4
= 8498.6 mg O/d

Where:

OUR is the Oxygen Utilization Rate in the aerobic reactor (mO/ℓhr)
$V_{aerobic}$ is the volume of the aerobic reactor

iv. Flux of denitrification oxygen demand (FO_c)

FO_d= 2.86 * FNO_{xd}
= 2.86 * (0.15 + 15.3)
= 44.2 mg O/d

Where:

FNO_{xd} is the sum of nitrite and nitrate denitrified

v. Flux of COD in waste sludge (FS_{tws})

FS_{tws} = Q_w*(f_{cv}*X_v + S_{te})
= 1.425*(1.267*3702+69.4)
= 6817 mg COD/d

vi. Flux of COD in effluent (FS_{teffl})

FS_{tefll} = (Q_i – Q_w)*S_{te}
= (15 – 1.425)*69.4
= 942.1 mg COD/d

vii. Flux of COD in influent (FS_{ti})

FS_{til} = Q_i *S_{ti}
= 15*1018.6
= 15279 mg COD/d

% COD balance = 100*(8498.6 + 44.2 + 6817 + 942.1)/15279
= 106.7 %

Note: the method for calculating the COD balance also applies to the JHB system.

I.2 DATA REQUIRED FOR P MASS BALANCE

P mass balance requires information on both operating parameters and measured concentrations. The operating parameters involved are e.g. measured flows, measured recycle flows, sludge age or sludge wastage. The measured concentrations are the influent and effluent TP as well as theTP, volatile settleable solids (VSS), VSS/TSS ratio (f_i) and TP/VSS (f_p) ratio of the waste sludge.

The P mass balance compares the exiting P flux via the effluent and waste flow with the system influent P flux. The P unaccounted for (“Uncc”) is the P deficit to close the P balance at 100%.

$$\%P\_Balance = \frac{100*(FP_{tWS} + FP_{teffl})}{FP_{ti}} \qquad \textbf{[Eq I.3]}$$

For the same example of ***sewage batch 2 (B2)***, the respective calculations are:

i. flux of P in the waste sludge (FP_{tws})

$$\begin{aligned}
FP_{tws} &= Q_w*(f_p*X_v+P_{teffl}) \\
&= Q_w*(f_p*X_v+P_{seffl} + P_{peffl}) \\
&= Q_w*(f_p*X_v+P_{seffl} + P_{peffl}) \\
&= Q_w*[f_p*X_v+P_{seffl} + (f_p*X_v*TSS_{effl})] \\
&= Q_w*\{f_p*X_v+P_{seffl} + [f_p*(AEVSS/AETSS)*(S_{teffl} - S_{seffl})/(f_{CV}*(AEVSS/AETSS))]\} \\
&= Q_w*\{f_p*X_v+P_{seffl} + [f_p*(S_{teffl} - S_{seffl})/(f_{CV})]\} \\
&= 1.425*\{0.035*3702+0.6+[0.035*(93.4-69.4)/(1.27)]\} \\
&= 186.4 \text{ mg P/d}
\end{aligned}$$

ii. flux of P in the effluent (FP_{effl})

$$\begin{aligned}
FN_{effl} &= (Q_i - Q_w)*(P_{teffl}) \\
&= (Q_i - Q_w)*(P_{seffl} + P_{peffl}) \\
&= (Q_i - Q_w)*\{P_{seffl} + [f_p*(S_{teffl} - S_{seffl})/(f_{CV})]\} \\
&= (15 - 1.425)*\{0.6 + [0.035*(93.4 - 69.4)/(1.27)]\} \\
&= 17.1 \text{ mg P/d}
\end{aligned}$$

iii. Flux of N in the influent

$FN_{ti}= Q_i * P_{ti}$

$= 15 * 19.5$

$= 292.5$ mg P/d

% N mass balance = 100 *(186.4 + 17.1)/292.5

= 69.6 %

Note: the method for calculating the P balance also applies to the JHB system.

APPENDIX J

Andre M.K. Mbaya (WRL UCT, 2009)