THREE YEARS OPERATION OF A 270 MLD C-TECH SBR – LESSONS FOR NEW TECHNOLOGIES

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Abstract

The 270 MLD (ADWF) Jelutong Sewage Treatment Plant (JSTP), is designed to meet advanced treatment standards for biological nitrogen removal (BNR) with the option of operating for enhanced biological phosphorus removal (EBPR) in the future. It is one of the largest plants in the world and the largest plant in Asia to adopt cyclic activated sludge technology using the C-Tech Sequencing Batch Reactor (SBR) configuration and operating method for the water line treatment. This paper summarizes wastewater characteristics and treatment performance during an initial 'calibration' benchmark period and the third and fourth years of its operational maturity. An initial benchmark effluent quality was established, based on flow proportioned two hour influent and one hour effluent sampling of a four basin module (out of the total three modules and 12 basins) operating at as received nominal 90 MLD ADWF design hydraulic loading. Mean effluent values of 3.8 mg/L BOD, 9.4 mg/L TSS, 25 mg/L COD, 3.5 mg/L TKN, 1.7 mg/L NH3-N, 5 mg/L (NH3-N + NO3-N) and 2.5 mg/L TP were generated covering the operation over 1050 continuous nominal four hour basin cycles. The calibration procedure included operation after 166 continuous basin cycles of two of the four basins at a two order of magnitude step change organic loading to evaluate process sensitivity response to full scale load variation with two basins operated at their same initial loading functioning as a reference. Each basin is instrumented with DO and ORP sensors for process monitoring and OUR/ORP interactive control together with MLSS sensors for in basin determination of a settled sludge interface velocity (SSIV), biomass auditing and regulation of sludge wasting. Performance statistics in the third and fourth year demonstrated monthly mean values of less than 5 mg/L TN and enhanced biological phosphorus removal to 0.3 mg/L TP. The facility is currently required to meet an effluent quality of 10 mg/L mean and 20 mg/L maximum BOD, 20 mg/L mean and 50 mg/L maximum TSS, 50 mg/L maximum COD, 5 mg/L maximum NH3-N and 10 mg/L maximum (NH3-N + NO3-N) based on Malaysian guideline directives.

Keywords

Cyclic activated sludge technology (C-Tech), Sequencing batch reactor (SBR), Simultaneous nitrification denitrification (SND), Multi-cell bioselector, Enhanced biological phosphorus removal (EBPR), Oxidation reduction potential (ORP), Oxygen Uptake Rate (OUR), Wastewater characterisation, Equatorial tropical climate, carbon limitation.

Cyclic activated sludge technology

Cyclic activated sludge technology in the C-Tech SBR configuration typically focuses on variable volume fed batch reactor processing combined with a basin dedicated multi cell bioselector

Figure 1: C-Tech configured sequencing batch reactor - Jelutong

(Wilderer, Irvine, Goronszy, 2001) and lowering weir rotating drum decanters for deep basin and rapid effluent removal. Biomass is directed from the reactor basin for unaerated admixture with influent wastewater at near soluble substrate (organics) saturation in the selector. By comparison with conventional and modified activated sludge processes treating domestic sewage where internal recycle flows can be up to the order of 5 X ADWF or more (MLE, Bardenpho, VIP, UCT, A_2O), the C-Tech configured process operates with a minor flow of circa 0.2 X ADWF. Reaction conditions for C, N and P removal are provided for in a simplified complete mix and segregated solids liquid environment through, in simple terms, ORP/OUR/DO/MLSS/cycle time management. The process operates without formal anoxic or anaerobic mixing sequences.

The technology is a well proven and mature high removal efficiency single basin single activated sludge methodology since the seventies (Eckenfelder, Quirk, Goronszy; 1985). It was considered as an innovative and alternative technology in the USA during the early eighties under the Innovative and Alternative Technologies Grants Program administered by the EPA whereby savings in capital and or operating costs of 15% or more compared to conventional methods qualified eligible technologies for very favorable funding. Unfortunately that program saw fit to limit SBR type processing to less than 20 MLD. Other countries, and without the organised vested interests of the establishment, recognised the benefits that could be gained in large scale applications well in excess of 20 MLD (Australia, United Kingdom, Ireland, Asia, Saudi Arabia, India, Republic of Czech, Hungary, Poland; especially in design build and operate applications.

Cyclic operation of a single variable volume (fed batch) reactor using operational control logic that governs DO, OUR and ORP through time and sludge wasting is key to this simplification of the activated sludge method of treatment for BOD and nutrient removal. One of the major benefits is the removal of the secondary settling basin as a separate reactor unit operation from the activated sludge process. Another is the absence of specific anoxic and anaerobic reactors that are necessary in conventional water line dispersed growth processes for nitrogen and biological phosphorus removal.

C-Tech combines single basin single sludge biological processing for carbonaceous oxidation, nitrification, denitrification, phosphorus (enhanced biological and chemical) removal, alkalinity

recovery, solids liquid separation and effluent decanting with simple controlled air on and air off sequencing with true batch reactor interrupted inflow during the settle and decant sequences.
C-Tech methodology optimizes and minimizes the duration of process favorable cycles through single sludge co current nitrogen and enhanced biological phosphorus removal as opposed to sequential mechanisms that require longer cycles and hence more reactor volume (hydraulic retention), as in the generic SBR method ,to achieve a similar result. The methodology focuses on cyclic aeration and biomass inventory for the management of ORP/OUR set points.
Combined nitrogen removal and EBPR (Goronszy et al, 1992) derives from cyclic regulation of the micro and macro biomass ORP environments which enables process (batch) cycle times to be three to four hours duration (Goronszy and Rigel, 1991); contrasting to six and more hours inherently required by generic sequencing batch reactor methodology.
As exampled in this paper the technology has a high element of operational flexibility that can meet many expected and or unexpected changes to influent parameters for both long and short term (diurnal) after a plant has been constructed and without loss of efficacy.
The multi cell selector is statically mixed having a selectable operational volume and environment from oxic to anaerobic which serves to maximize the sequestration of readily degradable and enmeshment of colloidal organics (readily solubilised) for their conversion to intra cellular stored organics (PHB) resulting in a very successful and simple method for containing the proliferation of many filamentous bulking sludge species (the low F/M growers)**.**
The technology uses dissolved oxygen (DO) and oxygen utilization rate (OUR/ORP) set point logic that also enables operation for optimal biomass activity and power consumption.
Operation of the basins as fed batch reactors provides a high capacity to tolerate organic and hydraulic shock loads with an added ability to automatically detect and monitor toxic and or inhibitory input events.

The Jelutong sewage treatment plant

Background to process selection

Recognizing the need to replace an existing close shore raw sewage outfall into the Penang Straits initial planning for the establishment of centralized sewage treatment facilities for the Greater Georgetown Catchment at the Jelutong site began in 1997. The design, for an ultimate 1.2 million P.E. (2014), was envisaged as three modular stages of 400,000 P.E with a total average daily flow of 270 MLD. Sewage flows comprise 66% residential, 2% industrial and 32% commercial and institutional. Available land was limited to a 14.7 hectare unlined ex-landfill site; a key factor for the selection of a candidate technology. Further limitation, incurred by a near sea low water table imposed an in ground basin construction depth limit of 2 metres. To minimize civil requirements, the candidate process had to be as compact as possible, offer a simple configuration with minimal number of unit processes and process tanks. Water line process flexibility required a capability of taking one or more units off-line while still maintaining process performance requirements.
Three candidate processes included conventional activated sludge (primary and secondary clarifiers) in a Modified Ludzack Ettinger (MLE) configuration, extended aeration activated

sludge (secondary clarifiers) also in an MLE configuration and Sequencing Batch Reactor (SBR) (Kadir and Lim, 2010) configured to provide a deep decant depth and an overall continuous inflow-outflow waterline flow. Being driven by space efficiency and using the Malaysian Guidelines for Developers - Sewage Treatment Plants as a common design basis, the SBR in the C-Tech configuration was selected (fifty percent less area ; 110m^2 vs 227 m^2/1000 m^3.d).
The solids line anticipated two design stages of 600000 P.E. each consisting of dual mesophilic anaerobic digesters (17 days HRT at 6% solids) and membrane gas holders. The project was let as a negotiated design, build and operate contract to WWE Holdings Bhd (Malaysia); the lead consultant was Sepakat Setia Perunding Sdn. Bhd.(Malaysia);SFC Umwelttechnik GmbH (Austria) was the process technology provider for the solid and water lines. The plant was implemented under the 9th Malaysia Plan.

Plant description outline

The JSTP process water line was designed to accommodate flows and loads through to a 2014 design horizon, for a maximum received flow of 6.75 m^3/s and an average biological load of 67,500 kg/d and 81,000 kg TSS/d without primary settling. Table 1 summarizes the process design parameters for the plant (Malaysian Guidelines). Effluent quality compliance requirements include 10 mg/L mean and 20 mg/L maximum BOD, 20 mg/L mean and 50 mg/L maximum TSS, 50 mg/L maximum COD, 5 mg/L maximum NH_3-N and 10 mg/L maximum (NH_3-N + NO_3-N) based on Malaysian Standard EQA 1979 directives. Biosolids processing was designed to yield a minimum dry solids content of 25 % after mesophilic anaerobic digestion.

Table 1: Specified process design parameters

BODt, mg/L	CODt, mg/L	TSS, mg/L	TKN, mg/L	NH_3-N, mg/L	Alkalinity ($CaCO_3$) mg/L	TP, mg/L	SVI_{60}, mg/L	SRT days
250	500	300	20-65	12-55	100	18	130	10 at 26^{0}C

Plant unit operations feature,

- Main inlet receiving well, Primary screen and pump station (wet and dry well)
- Receiving station for road delivered septic tank wastes
- Preliminary treatment, Secondary screen, Aerated fats, oil, grease and grit (FOGG) removal
- Screenings management for offsite disposal
- FOGG handling equipment
- Single channel delivery and flow splitting using motorised weirs
- Biological treatment, C-Tech configured SBRs
- Waste sludge holding tank for primary thickening (2%)
- Waste sludge thickening, Gravity belt thickener (to 6%)
- Mesophilic anaerobic digestion (17 days HRT), gas mixed and heated, membrane gas holders
- Digested sludge dewatering, Centrifuge (25%)
- Dewatered sludge storage for 30 days and offsite disposal

- Odor treatment of inlet works and sludge dewatering foul air
- Provision for UV disinfection in the future
- Demonstration unit for power generation using biogas production

The C-Tech configured SBRs

The SBRs are configured as three modules, each sized for a specified dry weather total flow of 90,000 m^3/d and a peak three hour wet weather flow factor of 2.16. Basin decant volume is 5,630 m^3/basin/cycle and is gravity removed by synchronously driven dual rotating drum lowering weir decanters at a rate of 100 m^3/min. Top water level (TWL) is up to 6,300 mm; top basin level is 7,000 mm. Each Basin has a dry volume of 18,760 m^3. BOD volumetric loading referenced to TWL is 0.5 kg BOD/m^3.
The modules are operated with time controlled and phase displaced interactive cycles and sequences that allow repetition of all of the mechanistic biological processes for soluble substrate sequestration, aerated simultaneous nitrification denitrification (SND), and enhanced biological phosphorus removal (EBPR); all as a single sludge system. Operation is on 56 minute quads (using a 7 minute interval numeric format) that provide repetitive time cycles of 224 minutes for fill sequencing with and without aeration and true batch interrupted flow sequencing for the non aerated sequences that govern solids liquid separation and effluent decanting.
Each basin can be served by dual variable frequency driven 350 kW positive displacement blowers, four duty and one standby per module. Aeration and mixing in each basin is combined using 660 floor mounted polyurethane mini panel membrane diffusers for an air delivery of up to 26,900 Nm^3/h/basin; minimum aeration is 1.8 Nm^3 h/m^2 (floor area). Each basin is instrumented to monitor MLSS, settled sludge interface velocity (SSIV) and a related settled volume indication, dissolved oxygen, OUR (derived) ORP, Temperature, liquid depth and fill and empty rate (derived). Present installed and operating capacity is provided in two modules.
During the design stage, the wastewater was considered to be deficient in available carbon and alkalinity relative to established (conventional) ratios for COD:TKN and $CaCO_3$:TKN needed to meet nitrogen and pH limits. Provision was made in the design for the inclusion of equipment to augment the available COD and alkalinity through addition of molasses and lime.

Operating performance

As with the design of all waste water treatment facilities, the design serves to define boundary conditions and sizing by which to conduct the process kinetics of that design. Before the time of start up and conditioning, representative sampling procedures were adopted to determine the range of concentrations for characterization of the water line parameters. Using a single module, a process calibration program was designed keeping two of the basins at a nominal constant mean loading as a duplicate reference with operation of the other two basins at higher loadings to embrace the design aerated sludge age of 5 days. The value of taking fixed time samples at 0900 and 1000 to measure/monitor representative plant performance at a later time was also assessed. The results of flow averaged and flow proportional sampling were also compared, but are not included in this paper.

Data for a four basin module operating at higher influent concentrations using a reduced frequency of sampling for years 3 and 4 (part) after calibration are also included for comparison**.**

Calibration testing

Calibration testing included rigorous characterisation of the wastewater based on two hour flow proportional composite samples taken from the common inlet distribution channel (flow distributor) that feeds the twelve SBR basins. Effluent quality from each basin was determined for each cycle comprising three equal samples over each decant. These data were used to define the influent loadings to each basin, the effluent quality from each basin and from the module under test in total. Process calibration took place over a total of 1050 basin cycles. Monitoring also included cycle volume, basin volume per day, inbasin temperature, MLSS at TWL, sludge settling as SSV_{30} and in basin SSIV (settled sludge interface velocity relative to a fixed in basin position 900 mm below designated BWL).

Wastewater characterisation

Process calibration provided the basis for the determination of the as received flow distribution, wastewater treatment parameters (Table 2) and the important derived parameter ratios (Table 3) and determination of benchmark treatment efficacy. Relevant data are shown as mean values ± 1 standard deviation (t represents total, f represents filtered sample 0.45 micron, ND represents not detected). For extrapolation purposes the mean value plus two standard deviations closely approximates a 95 percentile value. Figure 2 shows the total raw data (504 data points) over 1050 basin cycles for each two hours for the influent CODt:TKN ratio. Surprisingly and considering that the wastewater is essentially of domestic origin, 46% of the sample population exhibited a CODt:TKN ratio of less than 10 with 26% being less than 7.5(Table 3). Also surprisingly, the actual mean concentrations as analysed are about half the concentrations that were used for the design of the plant (Table 1); the hydraulic load on the calibration module was set to operate at as received design conditions. Process calibration operation accorded with 95 percentile influent values of 210 mg/L BOD, 460 mg/L COD, 49 mg/L TKN, 29 mg/L NH_3-N, 220 mg/L TSS and 7.8 mg/L TP (see Table 2).

Table 2: Summary of plant influent and effluent parameters (mean ± std. dev.) over the calibration period at 30^{0}C in basin temperature

Parameter	BODt mg/L	BODf mg/L	CODt mg/L	CODf mg/L	TSS, mg/L	NH_3N mg/L	TKN, mg/L	NO_3N mg/L	Alk., mg/L	O&G mg/L	Pt mg/L	pH
Influent	136 ± 39	38 ± 12	287 ± 87	88 ± 23	126 ± 47	18.4 ± 5.3	29.1 ± 10.1	0.7 ± 0.6	150 ± 26	3.6 ± 1.3	5.0 ± 1.4	6.2 - 7.6
Effluent	4.0 ± 1.9	2.1 ± 0.3	24 ± 7	7.2 ± 5.1	9.3 ± 2.9	1.6 ± 1.6	3.3 ± 2.0	3.2 ± 1.4	53 ± 18	N/D	2.6 ± 0.9	6.0 - 7.5

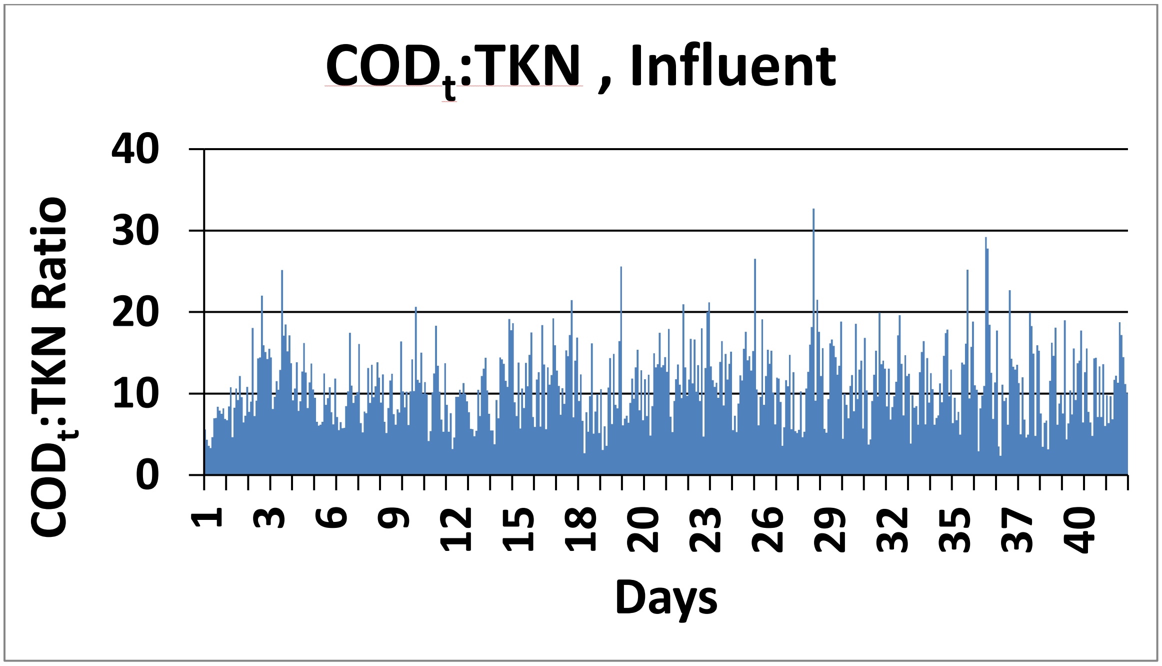

Figure 2: Variation of CODt:TKN ratio of the raw sewage 1050 basin cycles

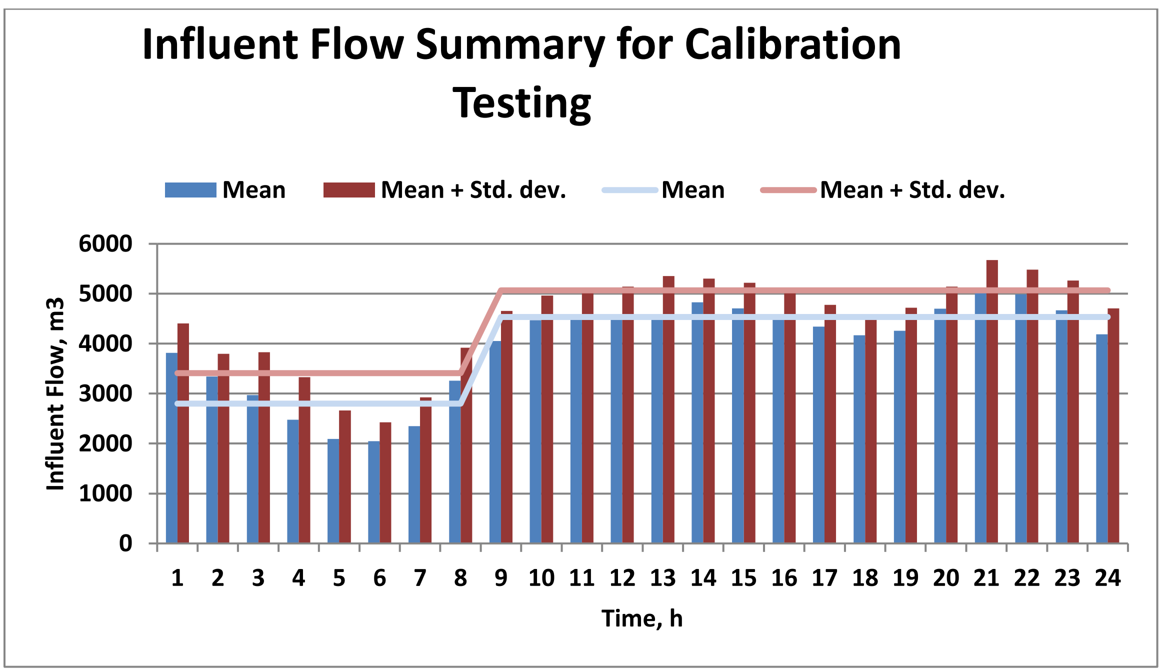

Figure 3: Single module influent diurnal flow summary 1050 basin cycles

Table 3: Summary of raw sewage characterisation – derived parameters (504 data points, 1050 basin cycles)

Ratio		Ratio	
CODf:CODt	0.33 ± 0.10	(BODt-BODf):TSS	0.85 ± 0.40
BODf:BODt	0.3 ± 0.10	NH_3-N:TKN	0.68 ± 0.2
BODf:CODt	0.14 ± 0.10	BODt:TKN	5.3 ± 2.4
CODt:BODt	2.05 ± 0.6	CODt:TKN	11.0 ± 4.6
CODf:BODf	2.51 ± 1.0	BODt:TP	29.3 ± 14.0
(CODt-CODf):TSS	1.7 ± 0.8	CODt:TP	61.6 ± 25.7
COD:TKN < 7.5	26%	COD:TKN < 10	46%
BOD:TKN < 3.5	26%	$CaCO_3$: TKN	5.2

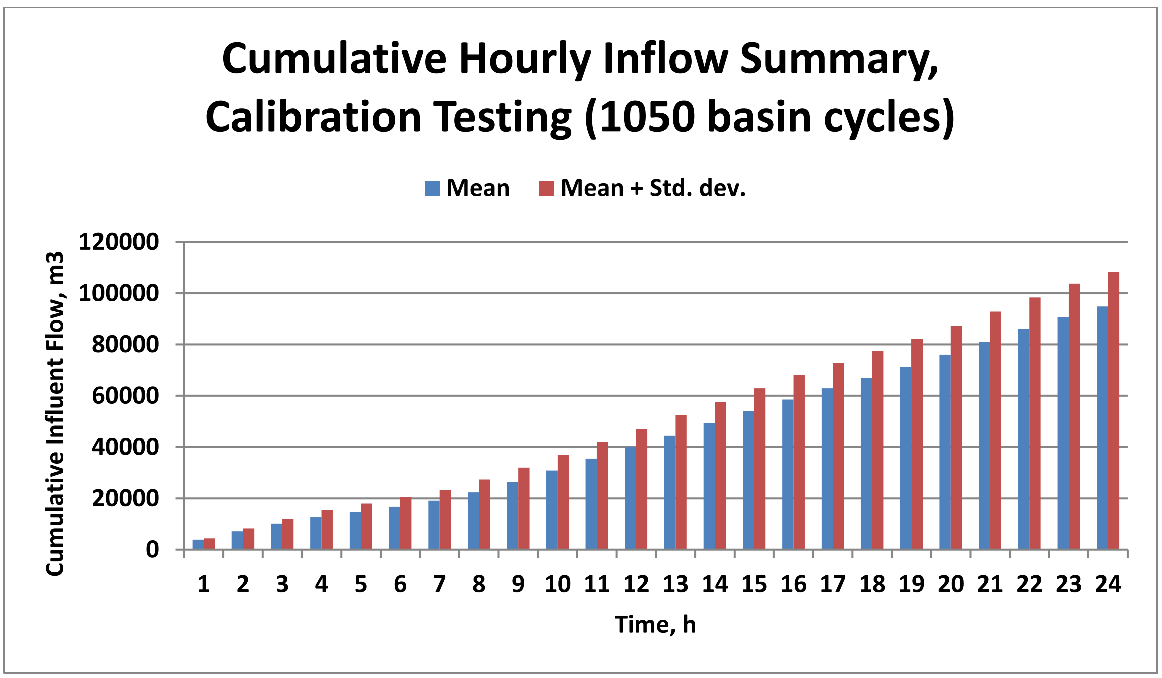

Figure 4: Single module hydraulic loading profile expressed as hourly accumulated flow

Hydraulic loading

The module 1 dry weather hydraulic loading profile is shown in Figure 3 as mean and standard deviation hourly values over the duration of the 1050 basin cycles of testing. Figure 4 expresses these data as diurnal hourly accumulated flow using the mean and mean plus one standard deviation values. Figure 3 also demonstrates the relative consistency of the hydraulic loading during the process calibration period; mean value of 93,850 m^3/d, a standard deviation of 5,500 m^3/d (within 4% of nominal modular design) and an overall range of 78,700 – 108,500 m3/d (80% >90,000 m^3/d). Dry weather daily peak flow factor was 1.4 ± 0.15. Basin daily flow distribution in module 1 was within 3 percent of the theoretical four way division as determined by daily decant volume summation.

Organic loading

Basins 1 and 4 were targeted to operate at 37,000±3,000 kg MLSS. Basins 3 and 4 after operating at the same biomass and aerated SRT were subject to an operational modification to adjust the aerated SRT which effectively provided a step jump in loading to simulate the effect of a random and significant increase in both carbonaceous and nitrogenous input. Basins 2 and 3 were effectively operated at 25,000±3,000 kg MLSS. MLSS concentration in Basins 1 and 4 was 2,960±370 and 3,460±1340 mg/L, respectively and 2,220±260 and 2,630±280 mg/L for Basins 2 and 3, respectively at TWL. The biomass volatile fraction was relatively constant in all four basins at 0.80-0.82±0.02-0.03. Aerated sludge age during the program covered the range of 2.5 days to 8 days (Basin 1;8 days; Basin 2;2.5 days; Basin 3;2.5 days; Basin 4;7 days). Equivalent organic loading is summarized in Table 4 and expressed as kg COD/kg MLSS/$d_{aerated}$.

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Table 4: Summary of effluent quality including step change operation during calibration period for Module 1

Parameter		F/Ma	BODt	BODf	Alk.	CODt	CODf	TKN	NH3-N	NO3-N	TSS	P	NH3 + NO3	pH
Basin	Period	kg/kg.d	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	mg/ L	Range
Basin 1	41 days	0.38± 0.10	3.1± 1.6	2.1± 0.4	53± 12	22± 6	6.6± 4.1	3.2± 2.2	1.5± 1.7	2.2± 1.2	9.3± 3.1	2.4± 1.0	3.7± 1.7	6.2-7.3
Basin 2	13 days	0.46± 0.12	3.5± 1.6	2.1± 0.3	44± 9	24± 8	7.4± 4.7	2.7± 1.6	1.7± 1.3	3.3± 1.1	10.0±4.0	2.6± 0.8	5.0± 1.8	6.0-7.1
	28 days	1.00± 0.84	5.2± 2.0	NA	79± 23	28± 6	NA	3.6± 2.5	1.6± 2.2	3.8± 1.5	9.1±2.0	2.4± 1.0	5.4± 1.8	6.5-7.5
Basin 3	19 days	0.53± 0.10	3.7± 1.6	2.1± 0.3	36± 8	25± 8	7.5± 5.4	3.5± 1.9	1.7± 1.4	3.6± 1.3	9.5± 3.3	2.9± 0.9	5.2± 1.9	6.0-7.0
	21 days	0.99± 0.25	5.7± 1.9	NA	50± 9	28± 6	NA	3.5± 1.9	1.6± 1.2	4.0± 1.1	9.3± 2.3	2.5± 1.0	5.6± 1.6	6.3-7.2
Basin 4	41 days	0.37± 0.08	3.6± 1.6	2.1± 0.3	46± 8	23± 6	7.3± 6.0	3.4± 1.7	1.5± 1.4	3.3± 1.3	9.2± 3.0	2.8± 0.9	4.8± 1.7	6.2-7.0

Process performance for calibration period

Table 4 summarizes the effluent quality of the four basins over the calibration period; Table 2 summarizes the effluent quality of Module 1. In basin temperature was sensibly constant at 30^{0}C (within ± 1^{0}C) over this period which covered a total of 1050 basin cycles. Figure 5 shows the distribution of BOD in Basin 2 and Basin 3 before and after the loading modification to effect an approximate two order of magnitude loading change. Mean value of effluent BOD increased by about 2 mg/L while the mean values and variance of the nitrogen components remained sensibly the same.

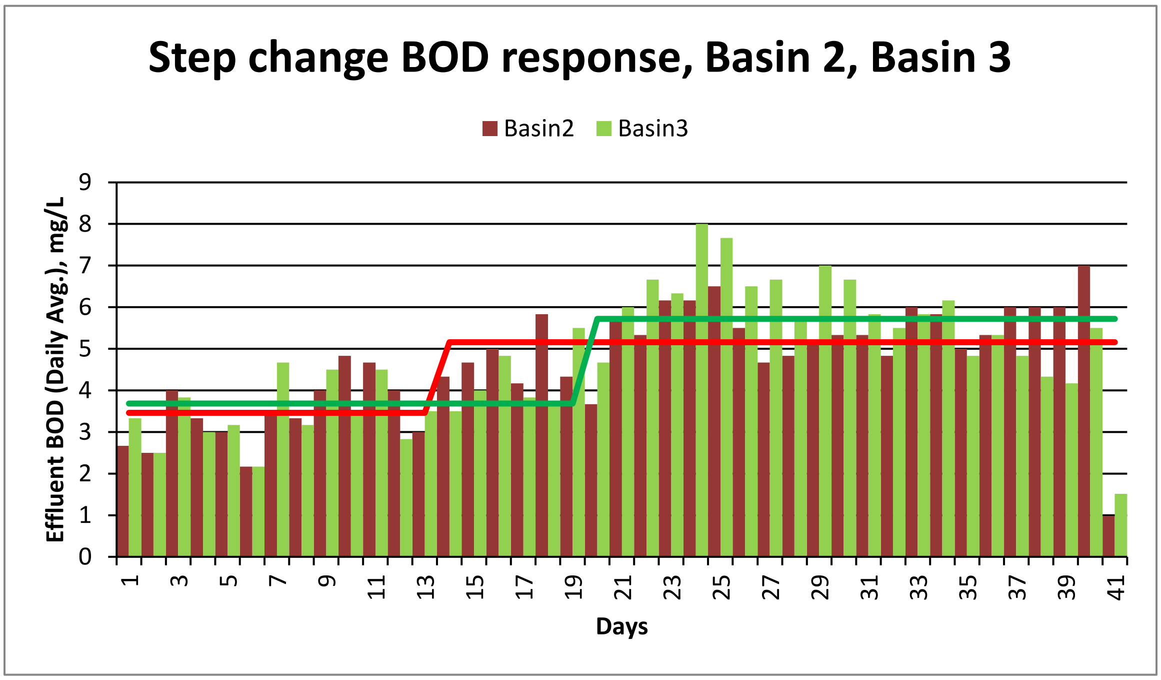

Figure 5: BOD response to step change loading in Basin 2 and Basin 3

In basin settling

In basin settling was evaluated using a 3,100 mm positioning (BWL 4,000 mm)of the MLSS sensors as a relative set point position for the determination of a Settled Sludge Interface Velocity (SSIV) from top water level (Figure 6) in order to simplify the plant operation relative to sludge wasting and aeration sequencing; an operational alarm condition for SSIV was set at 1.5 m/h. Conventional settleometer measurements (wide diameter 1,400 mL volume) were also taken for Settled Sludge Volume (SSV_{60}) and calculation of a Sludge Volume Index (SVI_{60}). SVI_{60} values over 250 basin cycles were 86±13, 68±10, 77±17 and 88±15 mL/g, respectively for Basin 1, Basin 2, Basin 3 and Basin 4.

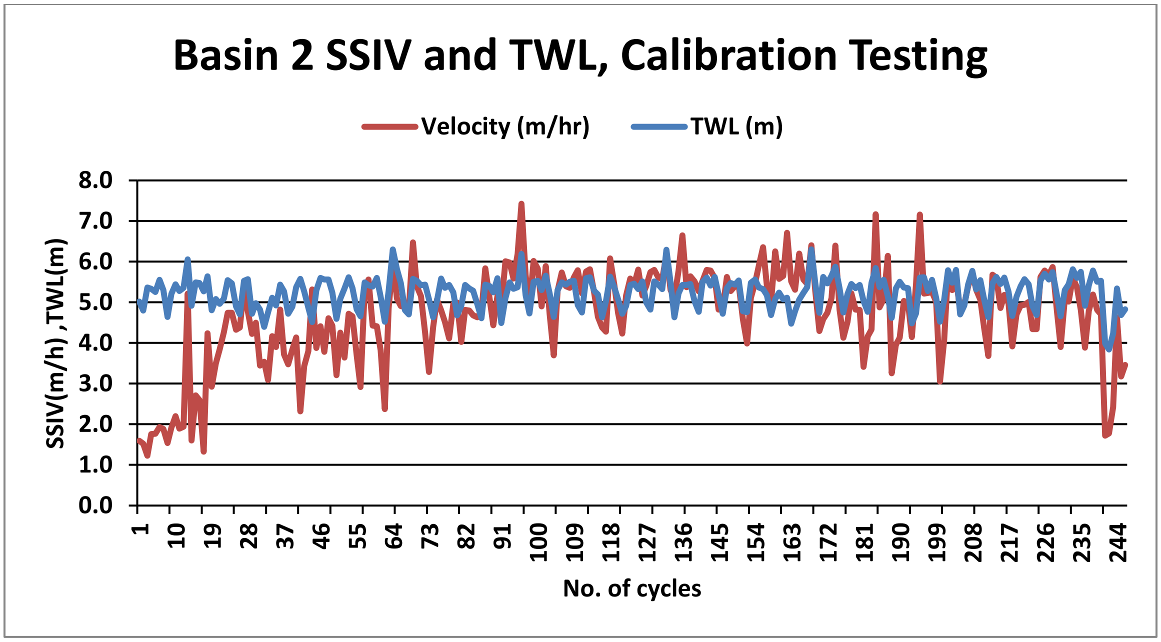

Figure 6: Basin 2 SSIV relative to TWL position over 250 cycles

OUR-Oxygen utilization rate

An operational in basin biomass oxygen utilization rate set point of circa 20-25 mg O_2/ L/ h (POUR factor circa 2) balanced the biological mechanisms with oxygen delivery that was necessary to meet all anticipated effluent quality parameters at operational in basin temperatures of 30-31°C. The potential oxygen utilization rate ratio (POUR) with SOUR provides a measure of the effectiveness of operation of the selector for the containment of filamentous sludge bulking. POUR was determined as the OUR measured under substrate saturation using influent screened sewage.

OUR/ORP is the major link in the determining dynamics of the simultaneous processes in the C-Tech processing. OUR as it is currently applied is a bulk parameter that incorporates the metabolic activity of the active fraction of biomass which is also a measure of stored organics (e.g. PHB) and is preferred to the use of SOUR (the specific oxygen utilization rate referenced to either MLSS or MLVSS). Figure 7 shows the derived in basin OUR taken from SCADA shown as a two cycle moving average over the calibration period for the four basins as an example of the method for maintaining dynamic stability. The DO and ORP sensors are located at the same relative reference positions in each basin.

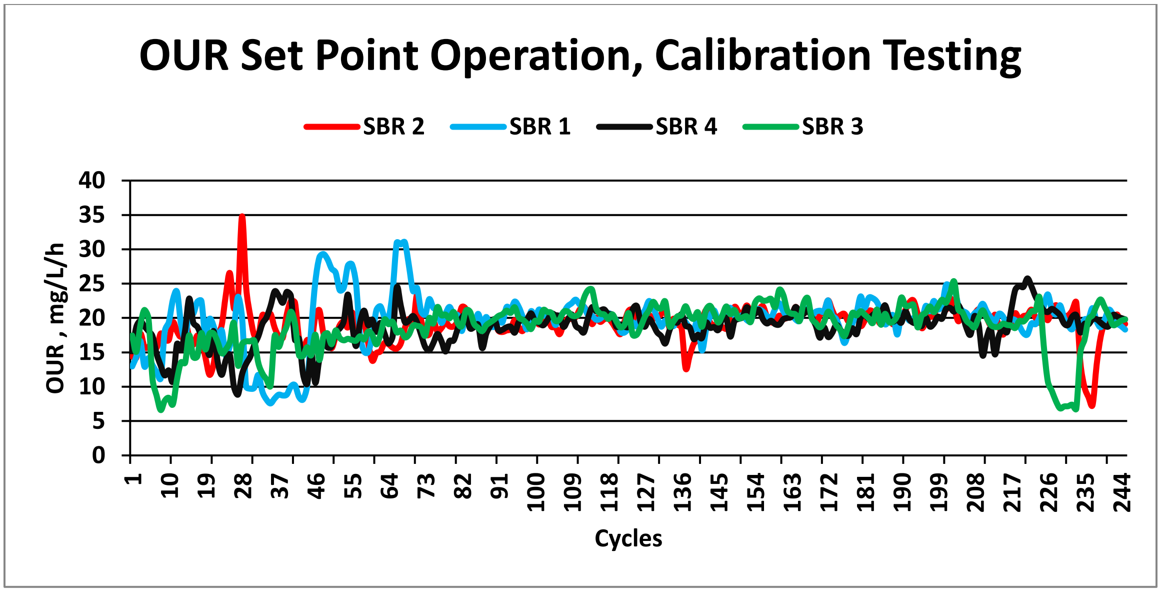

Figure 7: Module 1 OUR set point operation over the calibration period

Toxicity, inhibition monitoring

OUR is determined in basin for each cycle which provides an archive record of events that can affect the rate e.g major change in effective SRT, spike loads, toxics, etc. It is evident that a significant event occurred around the 226 cycle time in Basins 2 and 3 in that the OUR dropped 75% (Figure 7); typically a rapid reduction of more than 25% can be regarded as potentially significant. The most sensitive of the oxidative mechanisms is nitrification as reflected in Figure 8 showing the overall results of the step change loading response to effluent [NH3-N + NO3-N] concentration. The graph demonstrates the marked and rapid response for Basin 2 at the same time as the rapid reduction in OUR raising the total concentration form around 5.5 mg/L to around 9 mg/L. Basin 3 was not impacted as much.

Operation of Jelutong Sewage Treatment Plant

Regular operational monitoring

Regular operational monitoring for regulatory compliance purposes involves daily sampling comprising four grab samples per day for influent and effluent pH, CODt, TSS taken at 0300, 0900, 1500 and 2100 hours (1460 data points per year each); the 0900 sample is also used for BODt, O&G, NO_3-N, NH_3-N, and Pt (365 data points per year each).
Tables 5 and 6 summarize the influent and effluent data for a module of 4 basins as mean ±1 standard deviation values for each month three years after calibration testing.

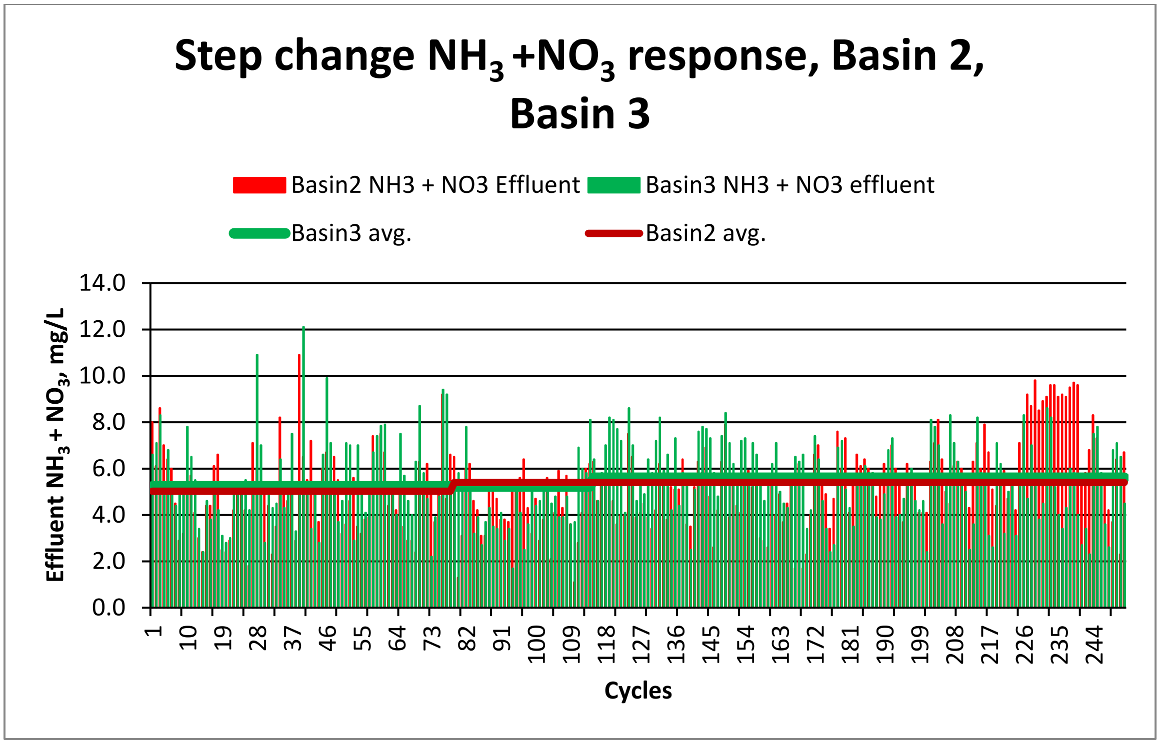

Figure 8: Toxic event relative to in basin OUR response

Table 5: Summary of routine influent monitoring third year of operation, 4 basin module

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BODt, mg/L	255 ± 76	265 ± 95	265 ± 74	230 ± 65	175 ± 50	170 ± 45	180 ± 63	205 ± 49	195 ± 58	180 ± 48	145 ± 48	145 ± 50
CODt, mg/L	390 ± 126	405 ± 134	420 ± 119	390 ± 111	345 ± 93	335 ± 124	340 ± 113	360 ± 113	315 ± 81	320 ± 84	290 ± 101	275 ± 91
TSS, mg/L	200 ± 87	240 ±114	245 ± 98	225 ± 86	190 ± 65	180 ± 88	180 ± 82	195 ± 88	155 ± 45	165 ± 66	155 ± 64	140 ± 61
NH_3-N, mg/L	23.4 ±3.7	24.6 ±3.5	24.9 ±3.5	23.3 ±2.1	22.3 ±3.6	20.8 ±2.4	22.4 ±2.0	23.2 ±1.5	21.4 ±2.6	23.1 ±2.2	22.4 ±3.5	22.1 ±3.2
NO_3-N, mg/L	2.6 ±0.5	2.5 ± 0.4	2.7 ±0.3	2.9 ±0.4	2.8 ±0.5	2.7 ±0.4	2.5 ±0.5	3.1 ±0.5	2.8 ±0.5	2.9 ±0.4	2.5 ±0.4	2.6 ±0.4
Oil and Grease, mg/L	5.9 ±1.3	6.4 ± 1.1	7.1 ±1.4	8.4 ±0.8	8.1 ±0.9	7.8 ±0.9	8.4 ±0.8	8.6 ±1.0	8.2 ±1.0	8.5 ±0.8	9.0 ±0.4	8.0 ±1.2
TP, mg/L	5.0 ±2.0	6.4 ± 4.6	5.1 ±2.0	7.3 ±3.3	5.5 ±2.3	5.7 ±2.7	6.7 ±2.7	9.8 ±3.8	8.1 ±2.8	7.7 ±3.2	7.6 ±3.1	6.8 ±1.8
pH	6.5 -7.2	6.5 - 7.3	6.5 -7.2	6.5 -7.3	6.5 -7.4	6.5 -7.0	6.3 -7.0	6.2 -7.2	6.5 -7.2	6.5 -7.4	6.5 -7.2	6.5 -7.2

TABLE 6: Summary of effluent routine monitoring third year of operation, 4 basin module

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BOD, mg/L	5.3 ±1.9	5.8 ±3.0	7.4 ±4.0	5.1 ±1.8	6.3 ±2.6	4.8 ±2.7	5.1 ±2.9	4.4 ±2.4	5.3 ±2.3	6.0 ±3.2	6.6 ±3.2	4.7 ±1.7
COD, mg/L	16 ± 9	19 ± 9	26 ±11	14 ± 9	12 ± 8	12 ± 7	16 ± 11	16 ± 12	14 ± 8	19 ± 10	18 ± 9	17 ± 9
TSS, mg/L	6.3 ±5.6	8.4 ±6.7	11.1 ±7.9	5.9 ±5.6	5.0 ±5.8	4.4 ±4.0	8.0 ±9.0	5.6 ±7.4	4.4 ±4.7	5.7 ±6.6	5.3 ±7.2	5.4 ±7.5
NH_3-N, mg/L	0.8 ±1.1	1.0 ±1.0	1.9 ±1.9	0.9 ±1.1	1.3 ±1.3	0.6 ±0.9	0.7 ±1.0	1.4 ±1.4	1.2 ±0.9	1.1 ±1.2	1.4 ±1.4	1.0 ±1.0
NO_3-N, mg/L	2.4 ±1.1	2.3 ±1.1	2.3 ±1.0	2.8 ±0.8	2.4 ±0.7	2.8 ±0.9	2.5 ±0.7	2.2 ±1.2	1.9 ±1.1	2.1 ±1.1	3.2 ±1.4	3.3 ±1.0
TP, mg/L	0.4 ±0.2	0.5 ±0.3	0.5 ±0.7	0.2 ±0.2	0.3 ±0.4	0.2 ±0.4	0.3 ±0.6	0.2 ±0.2	0.2 ±0.3	0.3 ±0.7	0.4 ±0.7	0.3 ±0.5
Oil and Grease, mg/L	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
pH	6.5 - 7.2	6.4 - 7.1	6.5 - 7.1	6.2 - 7.4	6.5 - 7.3	6.3 - 7.1	6.3 - 7.0	6.4 - 7.2	6.5 - 7.2	6.3 - 7.5	6.4 - 7.3	6.5 - 7.3

Table 7: Summary of influent effluent routine monitoring fourth year of operation, 4 basin module

INFLUENT QUALITY SUMMARY - 4th YEAR							EFFLUENT QUALITY SUMMARY - 4th YEAR						
Parameter	FEB	MAR	APR	MAY	JUN	JUL	Parameter	FEB	MAR	APR	MAY	JUN	JUL
BODt, mg/L	162 ± 44	193 ± 89	269 ± 86	238 ± 67	222 ± 75	173 ± 41	BODt, mg/L	5.3 ± 3.2	3.9 ± 2.0	4.6 ± 3.2	4.3 ± 2.6	6.0 ± 3.5	6.5 ± 4.2
CODt, mg/L	330 ± 89	359 ± 160	431 ± 168	406 ± 130	437 ± 149	325 ± 89	CODt, mg/L	21 ± 11	18 ± 9	17 ± 8	20 ± 10	21 ± 10	21 ± 10
TSS, mg/L	177 ± 69	207 ± 114	277 ± 133	259 ± 98	260 ± 107	155 ± 60	TSS, mg/L	8.0 ± 7.9	4.8 ± 6.2	5.5 ± 6.3	7.4 ± 9.2	8.0 ± 8.5	6.7 ± 8.6
NH_3-N, mg/L	26.8 ± 2.3	25.0 ± 2.7	24.5 ± 2.4	22.1 ± 2.7	25.6 ± 3.4	27.1 ± 3.8	NH_3-N, mg/L	1.4 ± 1.5	0.6 ± 0.8	0.6 ± 0.5	0.9 ± 1	0.7 ± 0.9	1.3 ± 1.4
NO_3-N, mg/L	3.1 ± 0.6	2.9 ± 0.6	3.2 ± 0.6	2.5 ± 0.7	2.5 ± 0.4	2.7 ± 0.5	NO_3-N, mg/L	2.2 ± 1.3	2.7 ± 1.2	2.4 ± 1.2	2.2 ± 1.2	2.6 ± 1.4	3.1 ± 1.4
Oil and Grease, mg/L	8.6 ± 0.7	8.5 ± 0.6	8.9 ± 1.4	10.1 ± 2.5	9.7 ± 2.3	10.9 ± 2.9	Oil and Grease, mg/L	N/D	N/D	N/D	N/D	N/D	N/D
TP, mg/L	6.7 ± 3.3	5.1 ± 1.9	9.3 ± 7.2	5.9 ± 1.8	6.2 ± 2.3	5.6 ± 2.4	TP, mg/L	0.2 ± 0.2	0.3 ± 0.5	0.3 ± 0.6	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.5
pH	6.6 - 6.7	6.6 - 6.8	6.6 - 6.8	6.6 - 6.8	6.5 - 7.2	6.5 - 7.1	pH	6.6 - 6.7	6.6 - 6.6	6.5 - 6.6	6.5 - 6.7	6.4 - 7.3	6.4 - 7.7
Flow m3/d	98850 ± 4340	111580 ± 13550	110310 ± 7360	97750 ± 7240	114580 ±7490	104650 ±11070	N/D			Not Detected			

Conclusions

- Data shown in the table summaries in this paper are presented as mean values ± 1 standard deviation, unless otherwise indicated; 95% values can be extrapolated and obtained from the sum of the mean and 2 standard deviation statistics.
- Initial benchmark performance was obtained from a continuous comprehensive operating program at as received modular design hydraulic loading and equivalent design aerated organic loading through adjustment of aeration sequencing.
- Operating conditions were established for full term plant operation which met mean and not to exceed performance limits.
- Effluent quality compliance was obtained up to a 95 percentile level in all basins for aerated sludge age values from 8 to 2.5 days which also provided the benchmark criteria for operation at the design SRT of 5 aerated days at a substantially constant in basin temperature of 30^{0}C.

- Modular plant performance data are summarized for operation in years 3 and 4 after commissioning during which influent concentrations are in keeping with design parameters for which effluent quality limits have been met.
- Mean monthly statistics of <5 mg/L BOD, < 10 mg/L TSS, <10 mg/L[NH3-N+NO3-N] and <1 mg/L TP are consistently demonstrated over 14,000 basin cycles.
- These data demonstrate the efficacy of process operation based on cyclic repetition of an ORP profile through the management of biomass oxygen utilization rate over fifty percent of design and at design loadings using the C-Tech SBR configuration and operating method.
- The effectiveness of in basin on line event monitoring against nitrification/denitrification toxicity based on biomass OUR was shown.
- The effectiveness of operating for process stability using OUR/ORP set point conditions in large reactor basins was demonstrated.
- The practicality of obtaining a settled sludge interface velocity (SSIV) and in basin MLSS concentration to automatically manage sludge wasting for SRT control was demonstrated.
- Effective SND and EBPR using C-Tech processing was demonstrated.
- Efficient nitrogen removal from an apparent carbon limited wastewater without chemical addition was demonstrated.

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