Start-up and Initial Operation of Singapore's 800,000 m^3/day Changi Water Reclamation Plant

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Abstract: The new Changi Water Reclamation Plant (CWRP) in Singapore is designed for ultimate expansion to 2,400,000 m^3/day. Construction of the initial 800,000 m3/day phase began in 2001 and will be completed in mid 2008. Designed as a compact, underground facility, the plant incorporates stacked rectangular primary and secondary clarifiers along with the anoxic step feed process. Solids processing consists of centrifuge thickening, anaerobic digestion, centrifuge dewatering, and thermal drying. A 227,000 m^3/day "NEWater® Factory", or Reclaimed Water Production Plant, will be constructed under a Design Build Own and Operate (DBOO) concession on top of the liquid process modules to produce high grade water for indirect potable and non-potable uses. Phased start-up of the facility began in February, 2007 and has continued through 2008. Initial performance has generally met expectations, resulting in excellent performance when the plant is not hydraulically overloaded, partial nitrification and denitrification as intended with the anoxic step feed process used which provided stable treatment and avoided significant pH depression, and SVI values which averaged 105 mL/g and were consistently below 150 mL/g.

Keywords: Wastewater Treatment, Plant, Large, Design, Operation, Tropics

INTRODUCTION

The new 2,400,000 m^3/day Changi Water Reclamation Plant (CWRPP) is being implemented by the PUB, the national water agency of Singapore, in a series of phases. Consisting ultimately of six liquid process modules, the initial 800,000 m^3/day phase consists of two liquid process modules which will complete construction in mid 2008. The first liquid process module began operation in February, 2007 with the first half, a 200,000 m^3/day "train" which simulates the full-scale liquid treatment process. The second train (half) of the first module began operation in late May, 2007, giving a total capacity of 400,000 m^3/day. The first train of the second module began operation in February, 2008, and the plant is expected to be fully operational by the end of 2008. This plant is significant on a global scale for several reasons, including:

1. It is a grassroots facility, incorporating current design and operations concepts and building on the Singapore PUB's experience operating its existing six secondary wastewater treatment plants. Plant facilities are designed to minimize manpower requirements.
2. Located in a tropical climate, treatment challenges include a warm, septic, high-strength wastewater that had proven difficult to treat due to its tendency to produce a poor-setting, bulking activated sludge and a low alkalinity/TKN ratio that led to pH depression when nitrification occurs (which is frequent due to the higher wastewater temperature) (Von Sperling and de Lemon Chernicharo, 2005).
3. It is a large facility, easily expandable and designed to be a crucial component providing service to Singapore's current 4.7 million population and a conceptual 2100 population of approximately 7 million. Designed for easy, phased expansion.
4. Significant site constraints which necessitated placing most of the liquid treatment process underground and using compact process tankage configurations such as step feed activated sludge and two-level, stacked primary and secondary clarifiers. A 227,000 m^3/day

“NEWater® Factory”, or Reclaimed Water Production Plant is currently being designed to be constructed under a Design Build Own and Operate (DBOO) concession on top of the liquid process modules to produce high grade water for indirect potable and non-potable uses.
5. Stringent odour and noise criteria.
6. Influent conveyed through a newly constructed Deep Tunnel Sewerage System (DTSS).

This paper will describe the design solutions incorporated into the facility, start-up experience, and plant loading and performance results to date.

METHODS

Plant Design

To address the challenges listed above, a process train (Figure 1) consisting of coarse screening and influent pumping; preliminary treatment consisting of fine screening, vortex grit removal, and oil and grease removal; primary treatment; activated sludge using the anoxic step feed process with secondary clarification; primary sludge de-gritting; primary and waste activated sludge (WAS) thickening using centrifuges; anaerobic digestion in cylinder digesters; dewatering using centrifuges; and thermal drying was selected. Anoxic step feed was selected to minimize tank volume, control activated sludge settling characteristics, and recover alkalinity to minimize pH depression with nitrification (Grady, *et al.*, 1999). A compact configuration was selected using rectangular tankage with two-story stacked primary and secondary clarifiers designed based on computational fluid dynamics (CFD) modelling as described in Ducoste, *et al*., 1999.

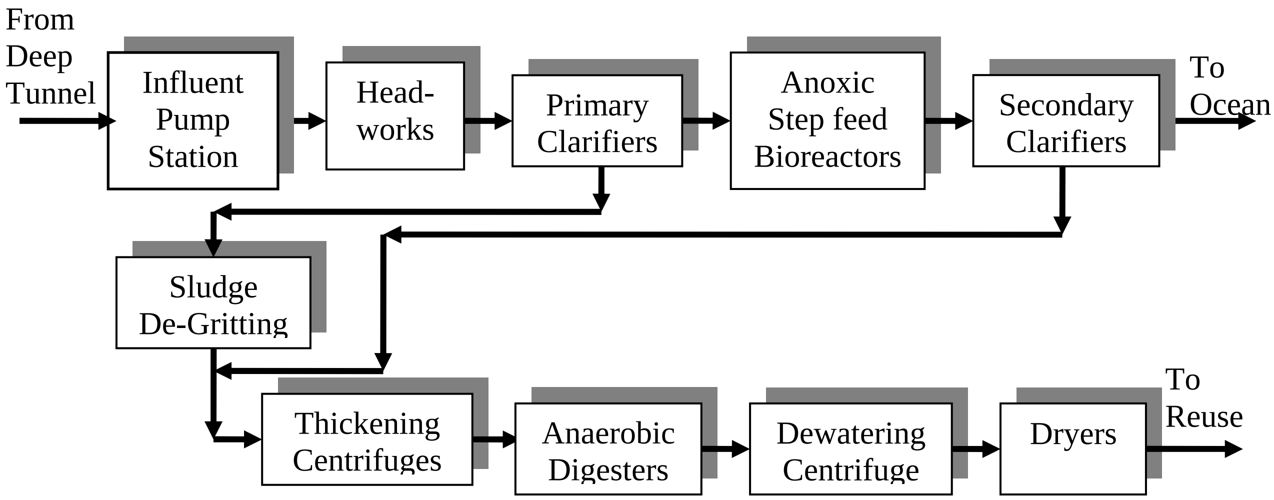

Figure 1. CWRP Process Flow Diagram.

As illustrated in Figure 2, the liquid treatment process is constructed largely underground and was designed to allow facilities to be constructed on top of the liquid treatment process. Odour control is by two-stage chemical scrubbing followed by activated carbon polishing. Table 1 summarizes plant design criteria. The construction of the 800,000 m^3/day phase is estimated to cost SGD$ 2 Billion. Four more parallel liquid modules and necessary solids handling units will be added as needed to reach its ultimate 2,400,000 m^3/day design capacity.

Anticipated Operating Conditions

Although designed for a strong wastewater, a relatively weak wastewater was initially received at the CWRP. This was because the tunnel system was being used to convey a mixture of wastewater and treated secondary effluent from some of PUB’s existing WWTP’s that will eventually be phased out as subsequent phases of the CWRP are completed. As plant capacity increased with the completion of plant construction during 2007 and early 2008, the proportion of wastewater in the CWRP influent wastewater increased and wastewater strength increased. Table 2 summarizes the anticipated influent wastewater flows and loads used to plan the various stages of plant start-up and compares them to the original plant design values. While the anticipated hydraulic loading initially exceeded the nominal capacity of one process train (200,000 m^3/day), it was expected to be below nominal design values for the other operational phases. Plant pollutant loadings were consistently below design values, especially during the first operating phase. The BOD_5/TKN ratio was expected to be consistently below the design value. The alkalinity-to-nitrogen ratios were expected to be more favourable for nitrification than the design values, even though it could be insufficient to achieve complete nitrification as indicated by an influent alkalinity/NH_3-N ratio less than the theoretical value of 7.2. It was considered that operation of the step feed process to achieve partial nitrification (a characteristic of this process, Gujer and Jenkins, 1975) and to achieve partial denitrification to recover alkalinity (Grady, *et al.*, 1999) would be necessary to avoid unacceptable pH depression.

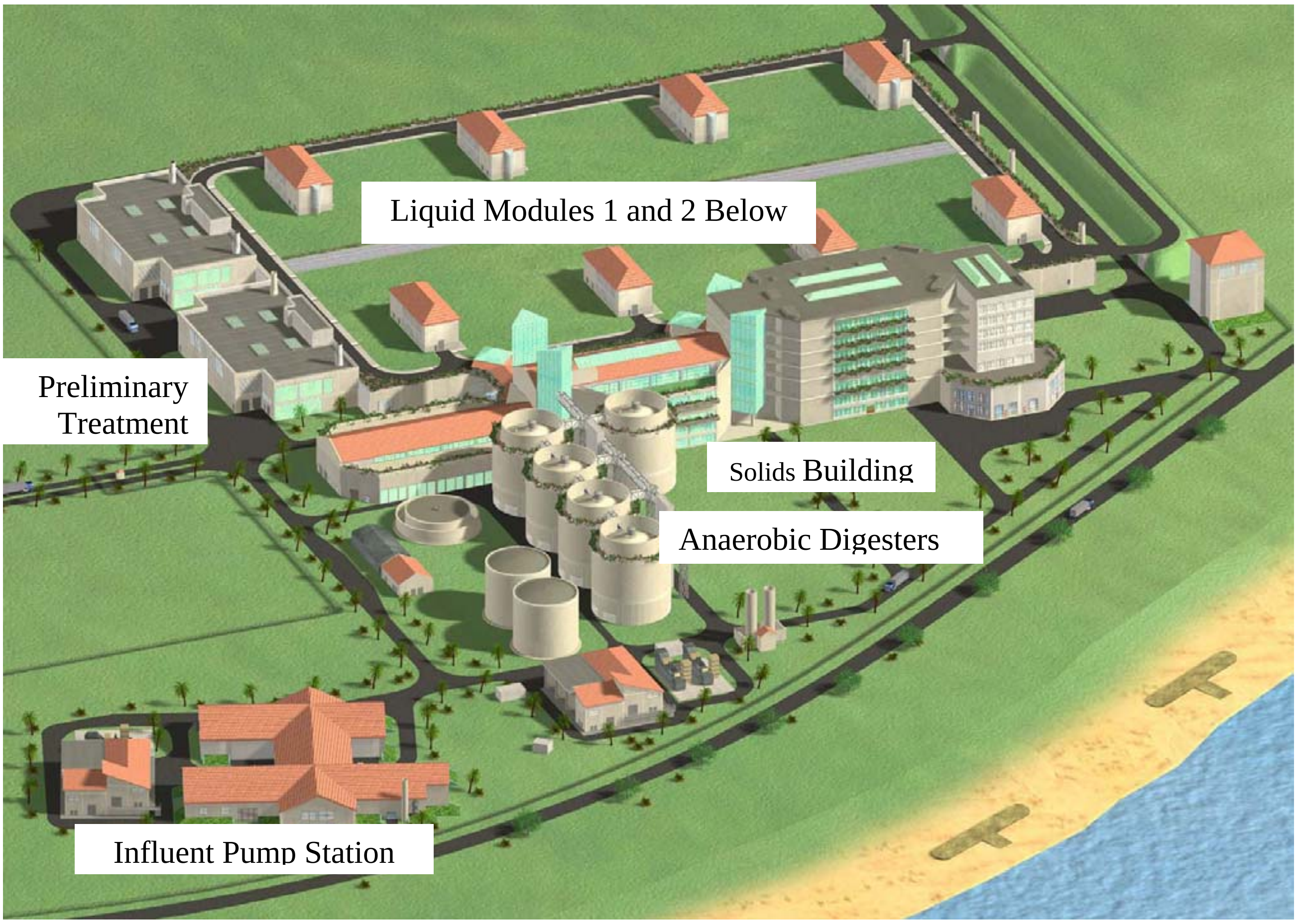

Figure 2. CWRP Layout.

RESULTS AND DISCUSSION

Plant Flows and Loadings

Figure 3 summarizes actual daily influent plant flows from start-up through March, 2008, compared to the nominal design capacity of the facility trains in service. The results show the progressive increase in plant flow over this initial year of operation as additional service area was connected to the plant. Influent plant flows initially exceeded the capacity of the single train in service, as expected, but again exceeded capacity during late 2007 and early 2008 before the third train (second module) was placed in service.

Table 1. CWRP Plant Design Criteria.

Unit Process	Item	Value
Influent Pumping[2]	Type	Vertical Centrifugal, Variable Speed
	Number	10 (6 service, 4 Standby)
	Capacity, Each	400,000 m^3/day, 3,500 kW
Preliminary Treatment[1]	Fine Screens	4 Continuous Plate Units with 5 mm diameter perforated openings, 300,000 m^3/day each
	Grit Removal	4 Vortex Units, 10 m Diameter, 300,000 m^3/day each
	Oil and Grease Removal	4 Aerated Units
Primary Clarification[1]	Type	Double-Deck, Rectangular
	Number	8
	Dimensions	50m x 12 m x 8 m
Bioreactors[1]	Type	Anoxic Step Feed
	Number Trains	2
	Number Basins per Train	6
	Number Passes per Basin	2
	Dimensions	50m x 24 m x 8m
Secondary Clarification[1]	Type	Double-Deck, Rectangular
	Number	16
	Dimensions	50m x 12 m x 8 m
Thickening Centrigures[2]	Number	17 + 3 recuperative thickeners
	Capacity Each	4,906 m^3/day
Anaerobic Digesters[2]	Type	Silo-Shaped
	Number	5
	Volume Each	16,654 m^3
Dewatering Centrifuges[2]	Number	10
	Capacity Each	4 Dry Metric Tons/hr
Dryers[2]	Number	5 (2 or 3 in Stand-by)
	Type	Rotary
	Capacity Each	90.7 Dry Metric Tons/day

[1] Number per 400,000 m^3/day Liquid Module. Two Liquid Modules constructed for 800,000 m^3/day plant.
[2] Total for 800,000 m^3/day plant.

Figure 4 summarizes plant BOD_5 and TSS loadings, showing the progressive increase over the initial year of operation. As expected, influent loadings have been consistently less than the design values. Projected loadings were generally consistent with expectations presented in Table 2 at the beginning of each operational phase but increased consistently through each phase as additional wastewater was diverted to the facility. The TSS loading consistently exceeded the BOD_5 loading. The highly variable nature of plant influent loadings is also indicated in Figure 4.

Table 2. CWRP Plant Design Flows and Loads Compared to Anticipated Values for Each Stage of Plant Start-up.

Item	Original Design[2]	Module 1		Module 2
		Train 1[3]	Train 2[4]	Train 1[5]
Design Flow (m^3/day)	800,000	270,000	326,800	481400
BOD_5 (mg/L)	218,400	23,700	31,000	54,200
TSS (mg/L)	238,400	19,900	44,700	45,100
VSS (%)	75.2	90.6	87.5	94.1
TKN (mg/L as N)	41,600	6800	12,500	22,700
NH_3-N (mg/L as N)	31,200	7,400	7,500	10,200
Alkalinity (mg/L as $CaCO_3$)	156,800	38,800	52,800	87,700
BOD_5/TKN Ratio	5.3	3.5	2.6	2.4
Alkalinity/TKN Ratio	3.8	5.7	4.4	3.9
Alkalinity/NH_3-N Ratio	5.0	5.2	7.2	8.6

[1] Hydraulic Capacity Based on 3.0 Peaking Factor, Giving 2,400,000 m^3/day.
[2] Two Liquid Process Modules.
[3] February, 2007.
[4] Trains 1 and 2, May 2007.
[5] Liquid Module 1 and Liquid Module 2, Train 1, February, 2008.

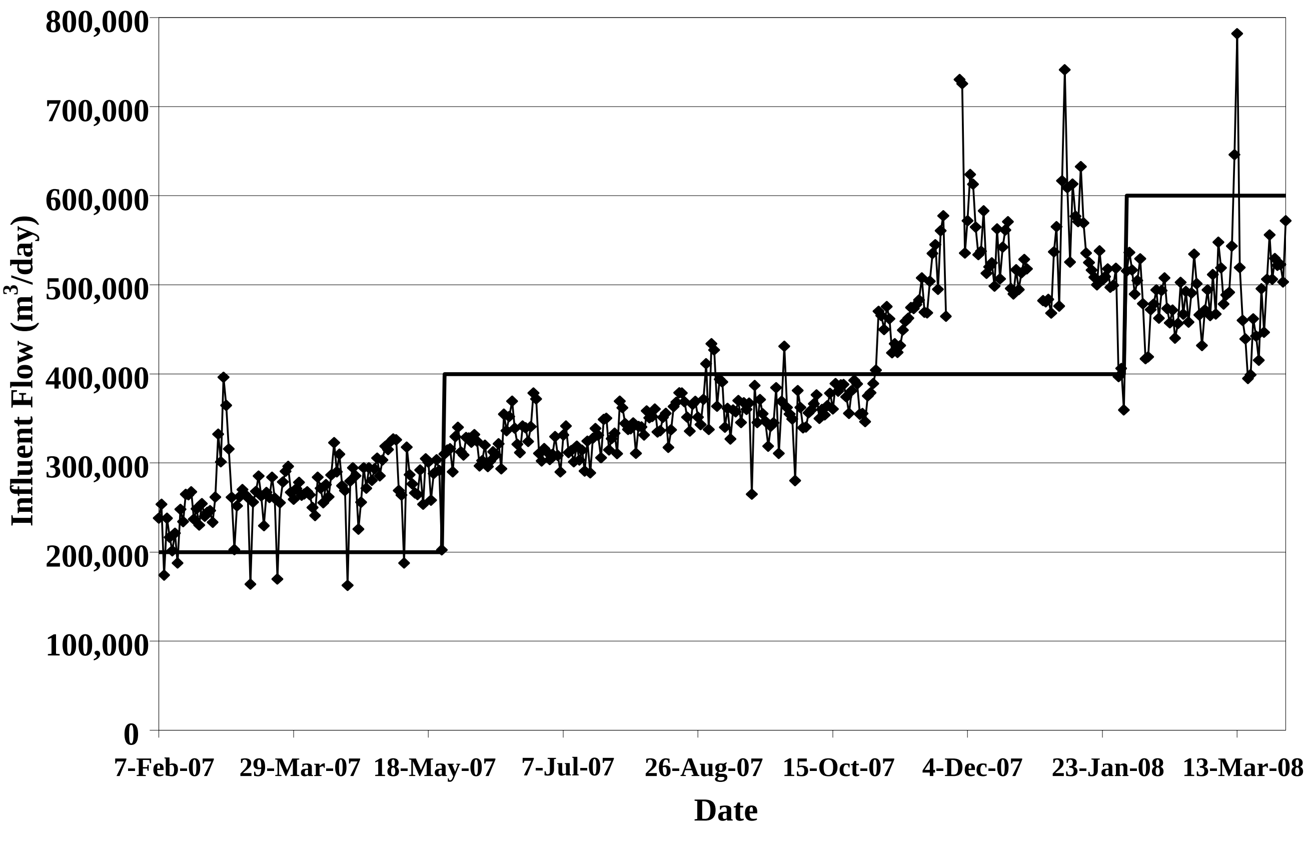

Figure 3. CWRP Influent Flow in Comparison to Nominal Design Values.

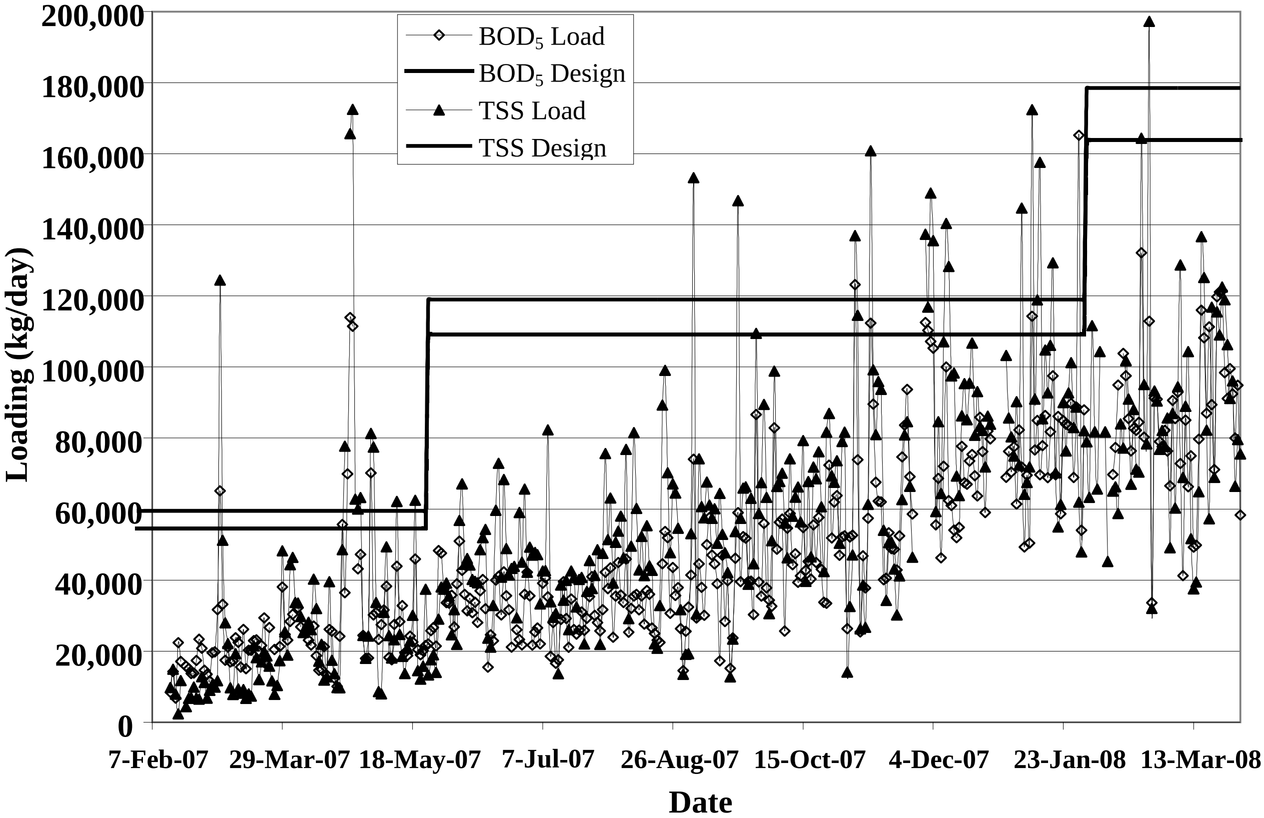

Figure 4. CWRP Influent Waste Loadings in Comparison to Design Values.

Plant Performance

Figure 5 presents plant effluent BOD_5 and TSS concentrations for this same period. Plant influent flow compared to plant capacity is also presented for comparison. Plant effluent quality during the initial operational period when only one train was in service was good following an initial acclimation period, even though the influent flow consistently exceeded the plant nominal capacity. Placing the second train in service provided sufficient capacity, and effluent quality was excellent. Increasing influent flow and load (see Figure 4) again resulted in deterioration of effluent quality in late 2007 and early 2008. Effluent quality then improved when the first train of module 2 was placed in service in early February of 2008. Effluent TSS generally exceeded effluent BOD_5. A plot of effluent BOD_5 versus TSS (data not included) indicated that they were generally linearly related with an intercept of 2.7 mg/L and a slope of 0.19 mg BOD_5/mg TSS. The detection limit for BOD_5 was 2 mg/L, which probably influenced the value of the intercept. In short, effluent TSS was found to be an excellent indication of effluent BOD_5. A plot of effluent TSS versus the ratio of plant flow to nominal plant capacity (data not shown) indicated that the plant could be loaded to 120 % of its nominal capacity before effluent quality began to deteriorate.

Figure 6 presents influent and effluent TN and effluent TKN and indicates that the anoxic step feed process performed as expected. Significant TN removal occurred, resulting in effluent concentrations which averaged 12.9 mg/L as N (from an influent of 34.3 mg/L as N). Stable partial nitrification was achieved, as indicated by effluent ammonia concentrations which average 7.2 mg/L as N. Effluent nitrate concentrations averaged 4.2 mg/L. This performance was achieved, in spite of an influent wastewater BOD_5/TKN ratio which averaged 3.2. The combination of stable partial nitrification and denitrification resulted in consistently acceptable effluent pH values which averaged 6.9 and generally ranged from 6.5 to 7.3.

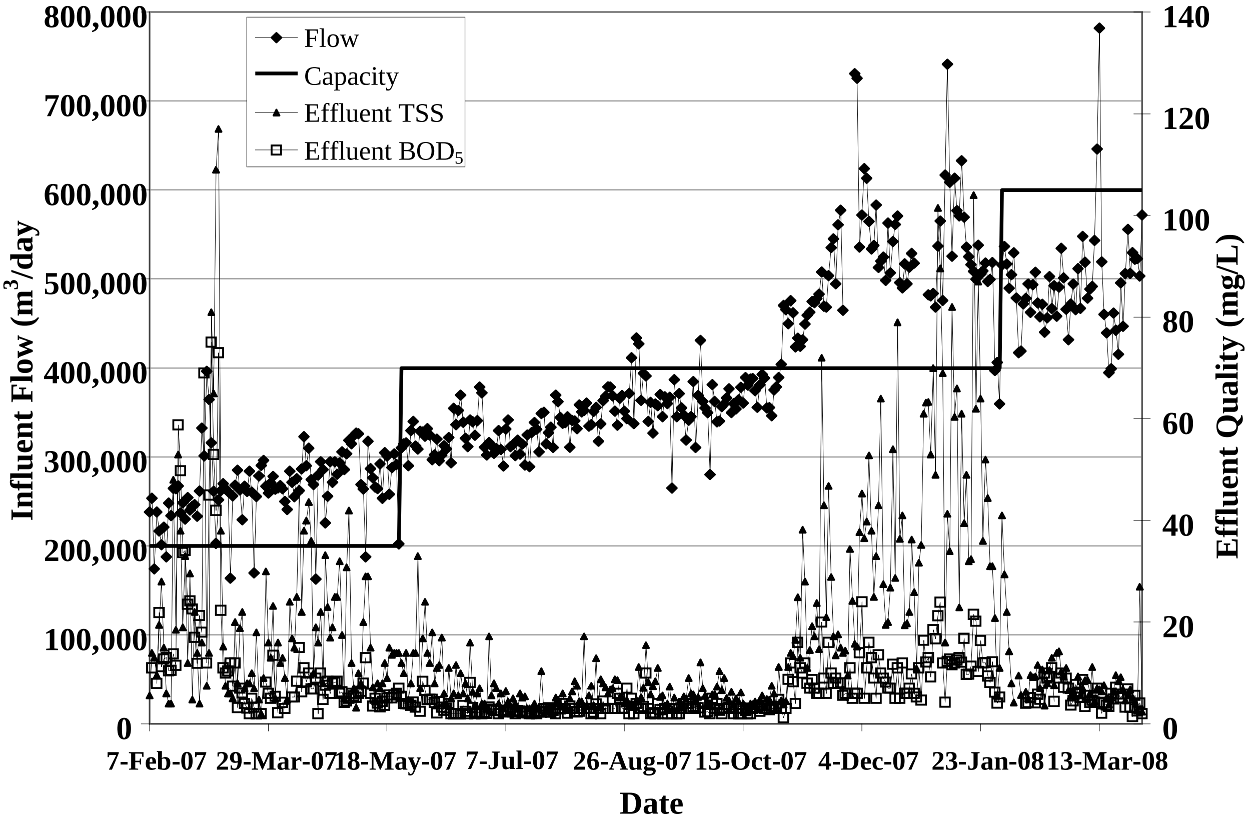

Figure 5. CWRP Effluent BOD_5 and TSS, with Plant Flow and Capacity Shown for Comparison.

Sludge settleability was excellent, as evidenced by SVI values which averaged 107 mL/g and were consistently below 150 mL/g, indicating that the anoxic selectors were functioning as expected (Jenkins, *et al.*, 2004). The solids processing system is in operation but is still being characterized and optimized as loadings have progressively increased over the present operating period (plant loadings in Figure 4).

Due to the reduced influent BOD_5 and TSS loadings the solids processing system has generally not been loaded to its design capacity. In fact, care has been taken during this start-up period to ensure that sufficient capacity is available so that solids processing is not an operational constraint. A unique feature of the CWRP design, enabled by the tropic location, is that the anaerobic digesters are not heated. Since the wastewater temperature is generally in excess of 30 ^{o}C, and air temperatures also generally average in this range, heating was judged to not be necessary. In spite of this, anaerobic digester performance has been as expected.

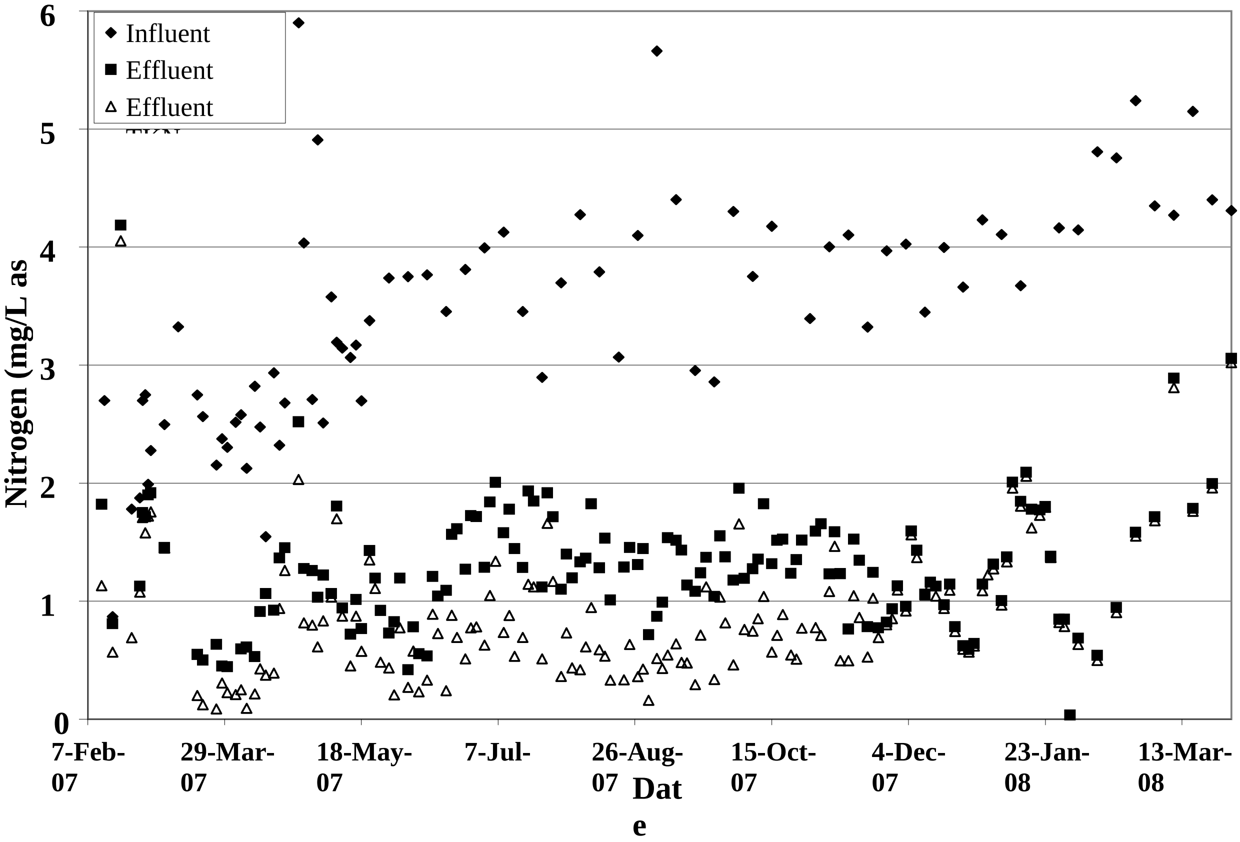

Figure 6. CWRP Influent and Effluent TN and Effluent TKN.

CONCLUSIONS

In conclusion, the CWRP has generally performed as expected during the more than one year long start-up period, in spite of on-going construction. Periods during which influent flows consistently exceeded the nominal design capacity of the plant occurred in early 2007 and late 2007/early 2008. Excellent effluent BOD_5 and TSS concentrations were consistently maintained until the plant hydraulic loading exceeded about 120 % of the nominal design capacity. Effluent BOD_5 was linearly related to effluent TSS with an intercept of 2.7 mg/L and a slope of 0.19 mg BOD_5/mg TSS.

Stable partial nitrification and denitrification was established, as expected for an anoxic step feed facility, which allowed stable performance and effluent pH values in the acceptable range. Good sludge settleability was achieved, as indicated by SVI values which averaged 107 mL/g and were consistently less than 150 mL/g. In summary, it can be concluded that the design features incorporated into the plant to address the operational problems conventionally experienced when treating tropical wastewaters (effluent pH depression, poor sludge settlability) can be avoided by the design of features specifically intended to address these problems. For the CWRP the principal feature was the anoxic step feed process. The compact facility also provided the intended treatment capacity.

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