TWO YEARS OF BIOLOGICAL PHOSPHORUS REMOVAL WITH AN ADVANCED MSBR® SYSTEM AT THE SHENZHEN YANTIAN WASTEWATER TREATMENT PLANT

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BACKGROUND

The Shenzhen Yantian WWTP is located in the Shenzhen Economic Development Zone near the Yantian port in China. The plant occupies 11.5 hectares and serves a municipal population of about 125,000 along with some commercial gold processing. Due to the limited space and environmental sensitivity of the port area, available land and stringent phosphorus discharge limits dictated the treatment plant's design. Therefore, an advanced high-efficiency modified sequencing batch reactor (MSBR®) system was installed. Plant construction was divided into two discrete phases. The first was built in early 2000 with a capacity of 80,000 m^3/day. The second began operation in December of 2001 and increased the plant's daily capacity by an additional 40,000 m^3.

The wastewater treatment plant incorporates a pump station, coarse and fine screening, grit removal, the MSBR® biological nutrient removal system and a sludge dewatering system. Waste sludge is sent to a short term storage tank and then processed by a centrifuge dewatering system. The dewatered sludge is sent to a municipal landfill. The key process component of the WWTP is the MSBR® technology. The enhanced biological phosphorus removal version of the technology was used for the first time in a large-scale system at Shenzhen Yantian. MSBR® features a combination of anoxic, anaerobic and aerobic cells with batch settling derived from sequencing batch reactor (SBR) technology. It eliminates the need for separate primary and secondary clarifiers while operating in a continuous flow/discharge mode with full reactor volume at a constant liquid level.

Operation of the entire plant is controlled by a central control system. The various instruments report all data to the central control system. The central control system can set correct parameters and issue commands for specific action to meet the wastewater treatment process requirements. Operators can adjust the operation parameters and maintenance schedules based on the data collected online. The monitoring system also observes the process conditions and major equipment operating conditions to ensure the safety of the plant.

The Shenzhen Yantian WWTP has now been operating for two years and has consistently met the phosphorus discharge limit through its MSBR® system's enhanced biological nutrient treatment capabilities. No chemical addition has been required to aid phosphorus removal.

PLANT CONFIGURATION

The MSBR® process configured for enhanced biological nutrient removal is shown in Figure 1. It consists of a pre-anoxic cell, an anaerobic cell, a sludge thickener cell, an anoxic cell, an aerobic cell and two cells that alternate between reaction and settling functions. Biological phosphorus removal occurs according to the traditionally understood mechanisms but under a significantly improved process environment. The typical enhanced biological nutrient removal (EBNR) process incorporates nitrogen and phosphorus removal objectives that may require elevated sludge recycle rates to achieve nitrogen removal. These increased sludge recycle rates can adversely affect phosphorus removal efficiency. A key MSBR® element is the high solids concentration achieved in the sludge thickener cell. This cell normally receives a 0.75Q to 1.0Q recycle flow from an alternating cell. Typically 20% to 30% of the recycle flow and 70% of the feed solids are recycled from the sludge thickener underflow to the pre-anoxic cell and then to the anaerobic cell. The balance of the feed flow and solids are directed to the aeration cell as overflow. This reduction in recycle volume to the anaerobic cell plus the effective removal of oxidized nitrogen in the pre-anoxic cell enhance efficiency of the anaerobic cell due to the absence of oxidized nitrogen and minimal volatile fatty acid (VFA) dilution. The sludge thickener overflow normally contains an elevated oxidized nitrogen level and is transported to the aeration cell and then to the alternating cell where it is subsequently discharged. The Shenzhen Yantian plant does not attempt to reduce its effluent total nitrogen content. However, mechanisms for effective denitrification are in place in the MSBR® on the specific internal flow streams that would impact effective phosphorus removal.

MSBR® PROCESS DESCRIPTION OF OPERATION

The sludge thickener cell is created by a baffle at the edge of the pre-anoxic cell with the baffle having an open space near the bottom of the pre-anoxic cell to allow the thickened sludge to properly move from the sludge thickener into the pre-anoxic cell. The thickened sludge is subjected to anoxic conditions in the pre-anoxic cell for removal of sufficient nitrate and nitrite based upon microbial endogenous respiration. The denitrified concentrated mixed liquor is pumped to the anaerobic cell, providing sufficient organisms to the anaerobic cell. All of the raw wastewater is added to the anaerobic cell where it undergoes anaerobic metabolism with the formation of short chain volatile fatty acids (VFA) as end products. Normal facultative bacteria convert more non-VFA materials to the primary short-chain fatty acid, acetic acid, under the longer anaerobic reaction time and higher sludge concentration, allowing VFA to accumulate in the anaerobic cell environment. The fact that phosphorus-removing organisms can assimilate the acetic acid in the anaerobic conditions provides the basis for the development of a dominant population of these organisms in the anaerobic cell. Since the cell is subjected to completely mixed flow through conditions the incorporation of the thickened sludge feed plus the raw wastewater provides the basis for an extended retention time in the cell as compared to a feed flow of non-thickened mixed liquor plus the raw wastewater. The Bio-P bacteria utilize the acetic acid while releasing phosphate that had been stored in the cell as polyphosphate. Growth of the phosphate-removing bacteria under anaerobic conditions produces a significant increase in the number of microbial cells with excess acetic acid stored inside the cells as poly-B-hydroxybutyrate (PHB) acid polymer. When the microbial mixture moves into the anoxic cell and then the aerobic cell, the facultative bacteria metabolize the carbonaceous organic compounds and the nitrogenous compounds as expected. In the presence of excess dissolved oxygen or nitrate as oxygen sources, the Bio-P bacteria metabolize the stored PHB acid polymer while taking up the excess soluble phosphorus and converting it to a polyphosphate polymer inside the microbial cells. This reaction takes place in both anoxic and aerobic cells although its rate is lower under anoxic conditions.

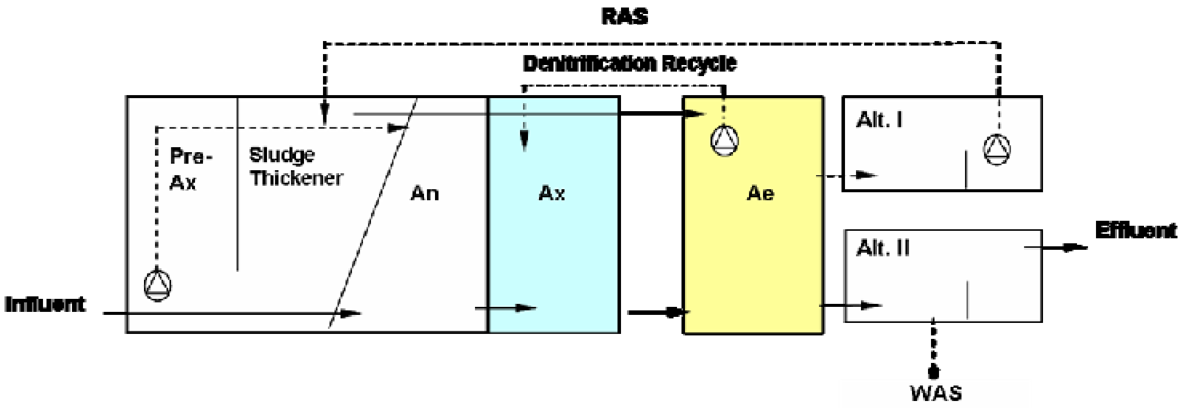

Figure 1. MSBR Process Configured for Enhanced Biological Nutrient Removal

The mixed liquor from the anaerobic cell is then mixed with the recycle flow from the aeration cell in the anoxic cell where carbon is metabolized with the oxidized nitrogen compounds from the aeration cell while the Bio-P organisms metabolize the stored PHB along with the excess phosphorus uptake using the oxygen source from nitrate and nitrite in the recycled mixed liquor. The denitrified mixed liquor then enters the aeration cell. Aeration in the cell supplies oxygen for microbial metabolism of the wastewater organic compounds and nitrification as well as the turbulence for complete mixing in the cell. The Bio-P organisms continue their process of PHB metabolism and excess phosphorus uptake at a higher rate in the aeration cell. The aerated mixed liquor then goes to two alternating cells. One alternating cell works as a continuous reaction cell with steps of mixing, aeration, and pre-settling, while the other one is in the sedimentation mode. Every half cycle, the alternating cells exchange functions. Alternating cell 1 in Figure 1 has a 30-minute pre-settling step in which mixing and aeration stops before it converts to the sedimentation cell. The full cycle concludes when the first alternating cell completes its sedimentation step. The normal time for a full cycle is four to six hours.

During the mixing only step of the alternating operation of the alternating cells, the nitrate and nitrite in the mixed liquor are denitrified with the organic carbon source derived mainly from the collective organism endogenous respiration. The aeration step nitrifies the ammonia remaining from the main aeration cell and any nitrogen released from the endogenous respiration during the mixing only step. The mixed liquor flowing through the alternating cell during its reaction steps is returned to the sludge thickener section with low head sludge pumps prior to moving into the anaerobic cell. The rate of mixed liquor return to the pre-anoxic cell is kept at a minimum (0.2 to 0.3 of the raw wastewater flow rate) to increase the denitrification reaction. This helps maintain the strongly anaerobic conditions in the cell as well as a high concentration of short chain volatile fatty acids, VFA. The thickened sludge at the bottom of the baffled section helps to maintain the complete removal of dissolved oxygen and oxidized forms of nitrogen in the return sludge from the alternating cell. The pre-anoxic cell is designed to permit greater denitrification in the return sludge flow to the anaerobic cell. With the sludge thickener, there is only a limited volume of mixed liquor with concentrated sludge that enters the pre-anoxic cell, providing a high denitrification rate and long actual detention time, which creates sufficient denitrification for the mixed liquor entering the anaerobic cell. Sludge thickening also allows a sufficient amount of activated sludge to enter the anaerobic cell without a large amount of fluid. This avoids the dilution of the VFAs in the anaerobic cell and a reduction of the actual anaerobic retention time.

The supernatant of the alternating cell in sedimentation, Alternating cell II in Figure 1 is discharged as final effluent with the displacement of the mixed liquor from the aeration cell. Excess sludge is removed from the alternating cells in the sedimentation mode by WAS pumps. A small, vertical baffle, about one third of the water depth, is placed midway in the alternating cells to help concentrate the settled sludge and provide a better hydraulic condition in the sedimentation cell (Bender and Crosby, 1984) . The use of common wall construction between cells keeps the complexity of construction in the MSBR® system to a minimum.

The water depth of the MSBR® reactors was 6 meters for the aeration and alternating cells and 8 meters for the other cells to limit the footprint of the reactors and maximize the efficiency of the sludge thickener. The footprint of the MSBR® system is shown in Figure 2. The tank size is 66.7 meters by 57.8 meters. Each unit has a volume of 23,500 cubic meters and handles a flow rate of 40,000 cubic meters per day. A total of three MSBR® systems were built to treat a wastewater flow of 120,000 cubic meters per day which reflects a design HRT of 14 hours. Cell 2 is the sludge thickener. Cell 3 is the pre-anoxic cell. Cell 4 is the anaerobic cell while Cell 5 can be used either as an anaerobic cell or an anoxic cell dependent upon the raw wastewater characteristics and the effluent requirements. Cells 1 and 7 are alternating cells while Cell 6 is the main aeration cell.

All of the equipment used in the system is retrievable so that the system operation is continuous during equipment maintenance and there is no need to empty the tank during maintenance. AquaDDM mixers are used in Cells 1,3,4,5,6 and 7. Aqua retrievable fine bubble diffusers are used in Cells 1,6 and 7 providing aeration. Flygt cross wall low head PP pumps were used as RAS and sludge transfer pumps while submersible CP pumps were used as WAS pumps. Single stage centrifugal blowers are used for the air supply to the system.

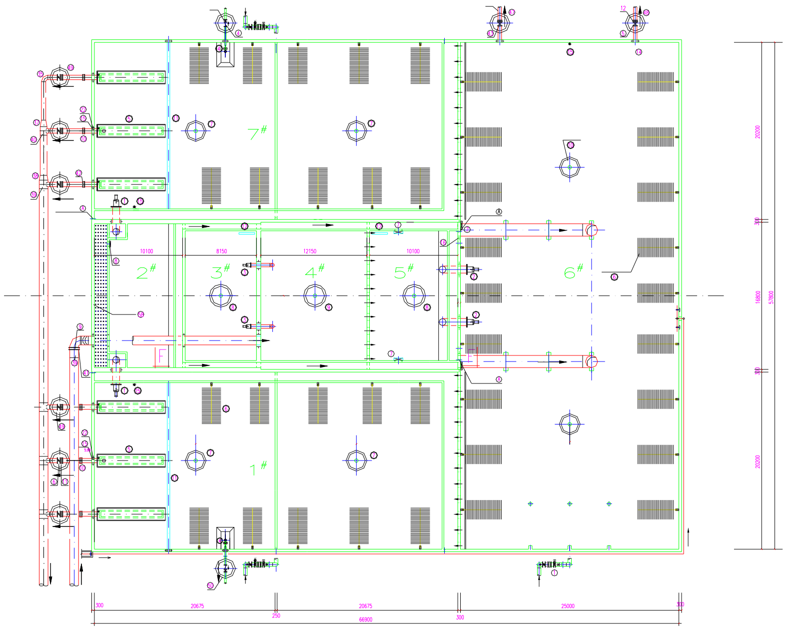

Figure 2. MSBR System for Yantian Wastewater Treatment Plant

Effluent discharge is controlled by air weirs installed in the alternating cells. When low-pressure air is supplied under the air weir hood, the air pressure decreases the water level under the hood to an elevation below the weir crest, and terminates the effluent discharge cycle. By simply venting the hood, the water level under the hood is restored and an effluent discharge cycle is initiated. The air weir system is controlled by an individual control system. The operation of the MSBR® is controlled by a PLC in a separate control system. The PLC and MCC were supplied by Rockwell with the logic designed by the lead author.

SYSTEM PERFORMANCE

Table 1 summarizes the annual treatment results of the plant. The data shows that the plant achieved good treatment results with high removal efficiency for the first 11 months of the year. The system removed more than 95 percent of BOD5 and more than 85 percent of the COD with a low effluent discharge. About 94 percent suspended solids removal was achieved with an effluent of less than 10 mg/l. The average effluent ammonia nitrogen was below 8 mg/l with an influent total nitrogen of 30 mg/l. During that period, the system removed 92 percent of the total phosphorus, indicating a great phosphorus removal capacity. The plant demonstrated stable operation with excellent effluent until late November when a shock load of oil and grease was discharged to the plant which created significant operational problems.

Table 1. Annual Average Data

Item	pH	BOD_5 mg/L	CODcr mg/L	TSS mg/L	NH_3-N mg/L	NO_3-N mg/L	NO_2-N mg/L	TN mg/L	TP mg/L
Influent	7.3	135	255	148	23	1.5	0.1	30	3.8
Effluent	6.8	6.5	35	9.2	7.6	9	0.1	16	0.33
Removal,%		95	86	94	67		0.0	47	92

Influent and effluent COD results are illustrated in Figure 3. Typical influent COD values are 255 mg/l with a deviation of 75 mg/l. Typical effluent COD performance is shown as less than 50 mg/l with an annual average value of 35 mg/l. A seasonal variation can be identified favoring the summer months with an average effluent COD value of 25 mg/l. Influent and effluent BOD_5 results are illustrated in Figure 4. The overall average influent BOD_5 value is 135 mg/l with an associated deviation of 47 mg/l. The Yantian plant experienced an industrial spill containing oils and grease during the month of November. The average influent BOD_5 adjusted for the industrial spill is very stable at 135 mg/l with an associated deviation of 38 mg/l. Effluent BOD_5 performance was maintained at a 94% removal rate. The corresponding effluent BOD_5 values ranged from 4 to 10 mg/l with an associated deviation of 3 mg/l.

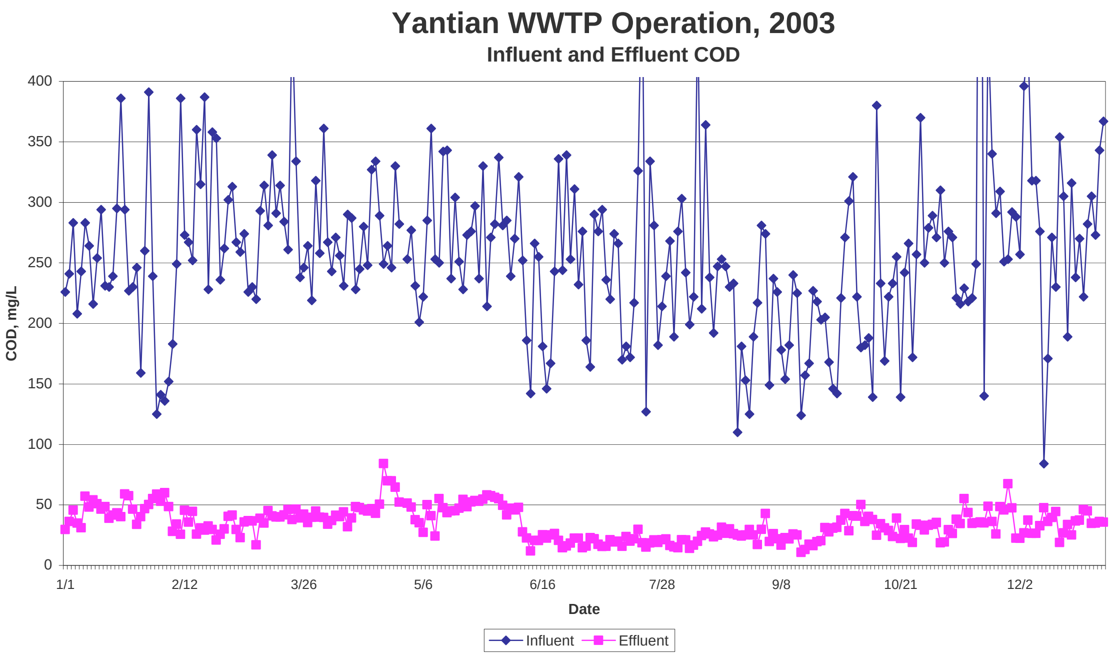

Figure 3. Influent and Effluent COD

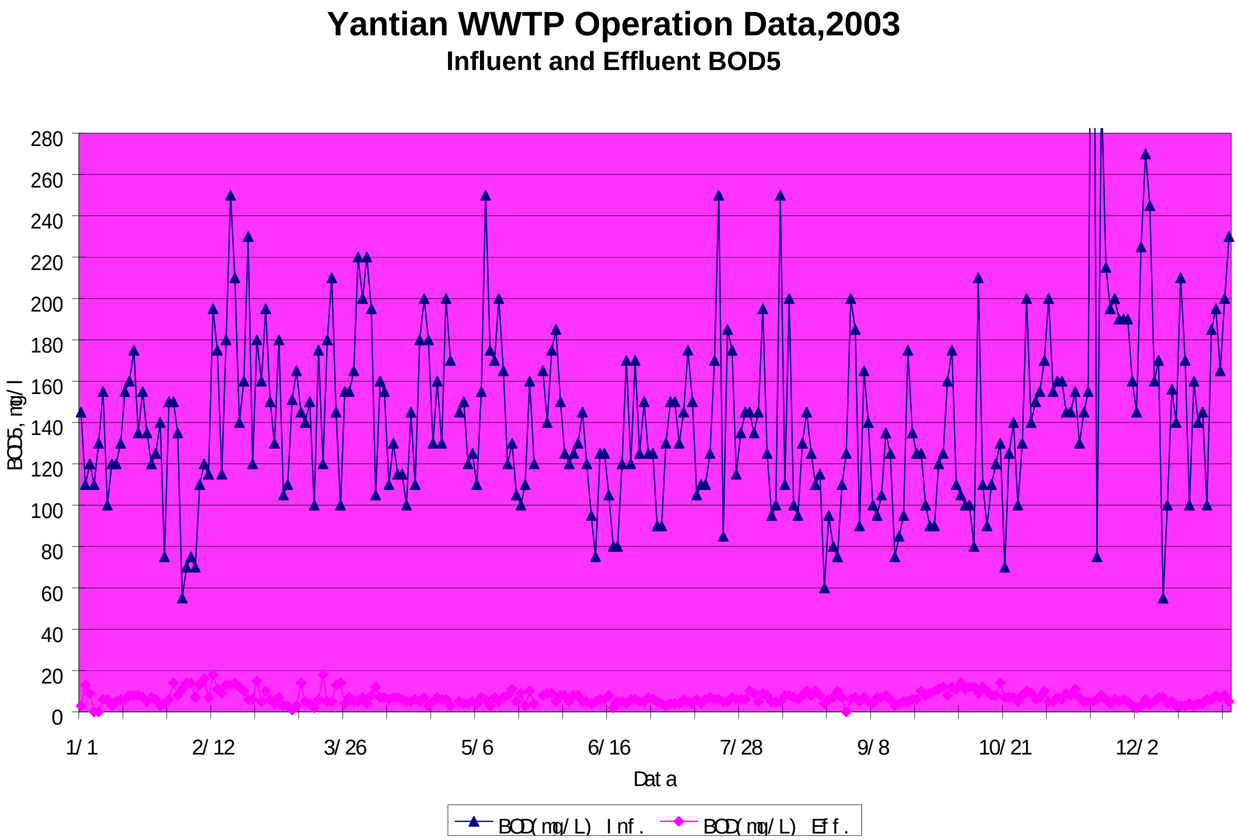

Figure 4. Influent and Effluent BOD_5

Influent and effluent total suspended solids (TSS) results are illustrated in Figure 5. The TSS values are similar to the COD with an average influent value of 148 mg/l with an associated deviation of 82 mg/l. The influent TSS variation is slightly higher than the COD which is also attributed to the industrial contributions. The effluent TSS remained very stable, normally achieving 94% removal. The typical effluent values ranged between 3.5 mg/l and 15 mg/l with an annual average of less than 10 mg/l.

Denitrification is not required for the Yantian WWTP. Influent and effluent total nitrogen (TN) data is illustrated in Figure 6. The average influent TN is 30 mg/l with an associated deviation of 6.5 mg/l. The effluent TN averaged 16 mg/l with an associated deviation of 4 mg/l. This represents an overall average removal of 47%. Nitrogen speciation of the influent indicated only 1.5 mg/l of nitrate and nitrite; the remaining components are ammonia and organic nitrogen. Influent and effluent ammonia data is illustrated in Figure 7. Influent ammonia averaged 23 mg/l, therefore the organic nitrogen is typically 6 mg/l. Again, the industrial oil and grease spill is detected in the month of November due to low dissolved oxygen and the associated loss of the nitrifier population in the bio-reactor. Effluent values ranged between 3.5 and 10 mg/l.

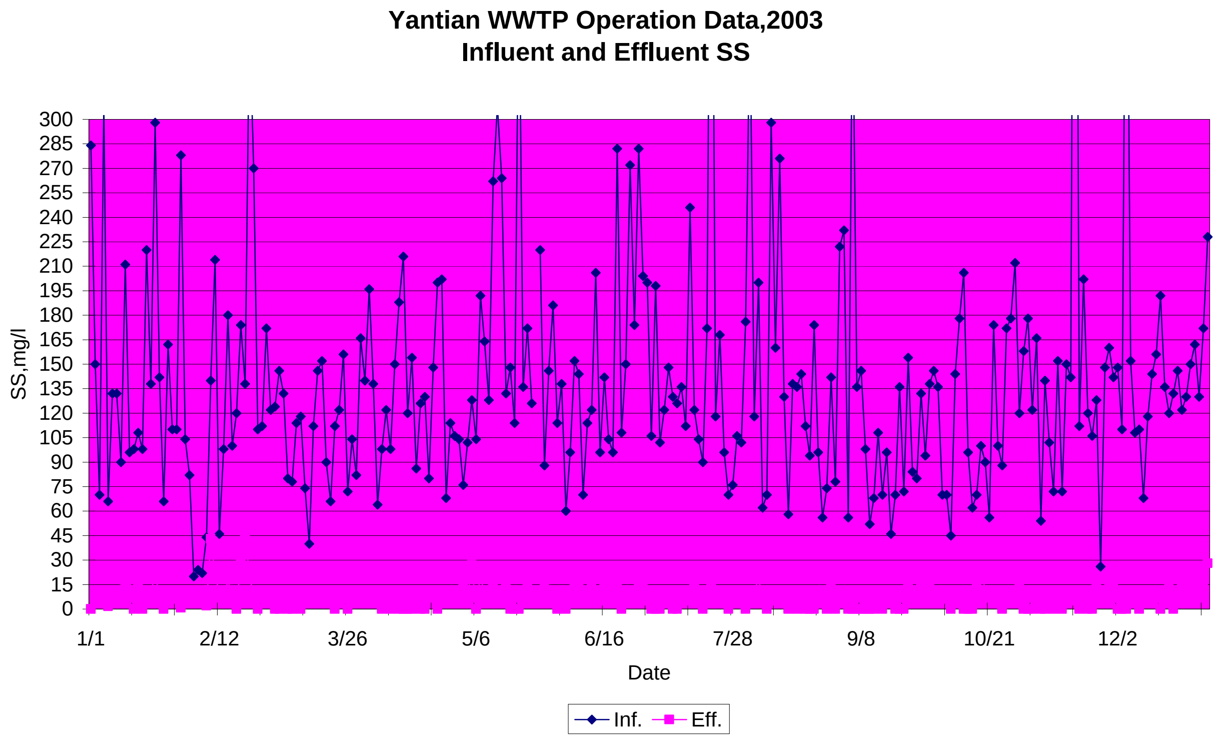

Figure 5. Influent and Effluent TSS

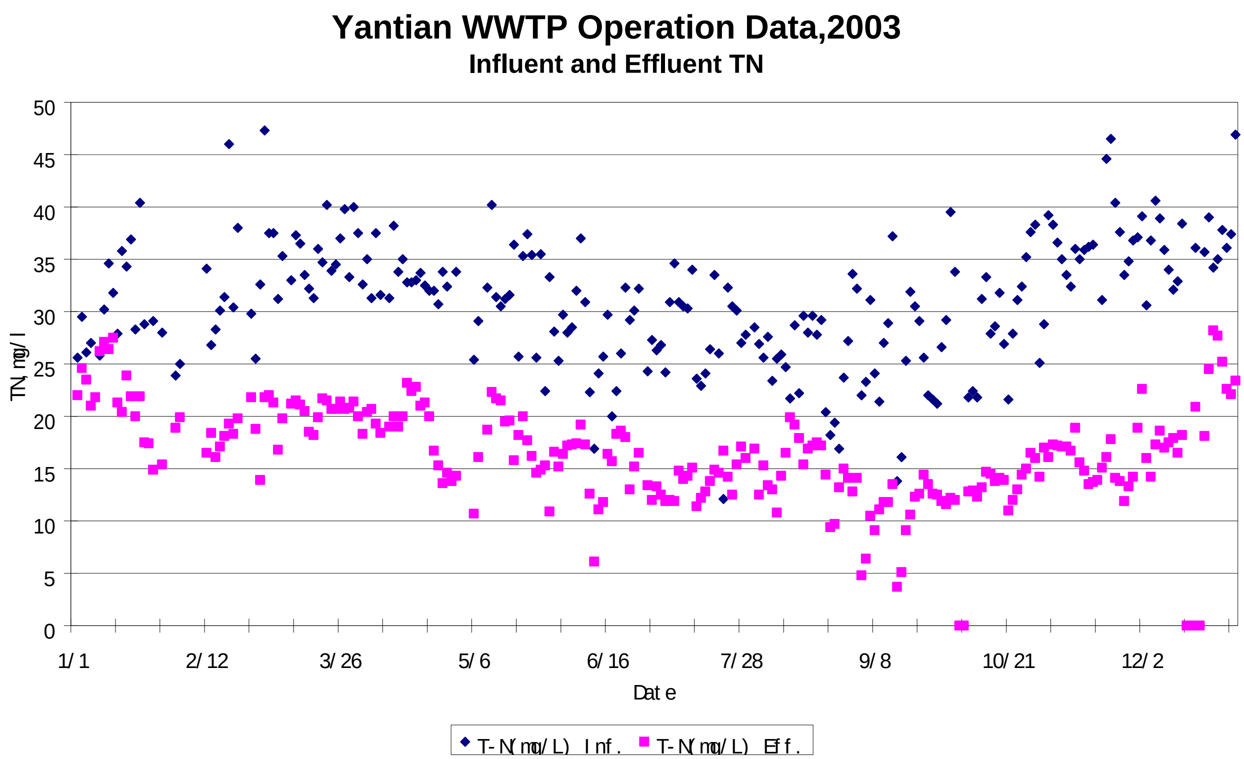

Figure 6. Influent and Effluent TN

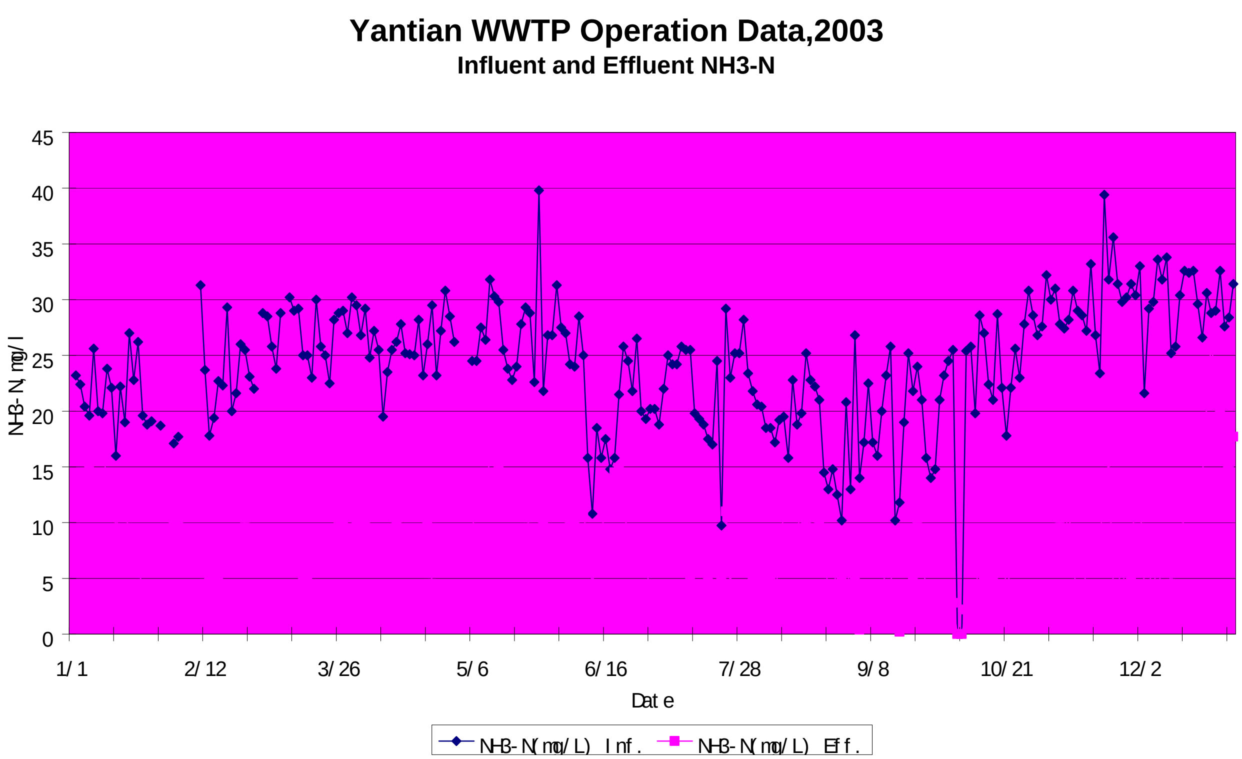

Figure 7. Influent and Effluent NH_3-N

Influent and effluent total phosphorus (TP) data is illustrated in Figure 8. The majority of the influent TP ranged between 2.5 and 5 mg/l, typically averaging 3.8 mg/l. Total phosphorus performance shows some variation on the weekends and was also affected by the industrial oil and grease spill. Adjusting the data to remove the oil and grease event but retaining the weekend performance, the effluent TP averaged 0.36 mg/l with an associated deviation of 0.36 mg/l. The high deviation is believed to be a result of the weekend performance variations.

Overall, the Yantian WWTP demonstrated successful treatment capability by achieving 95, 94, and 92% removal efficiency for BOD_5, TSS, and TP respectively.

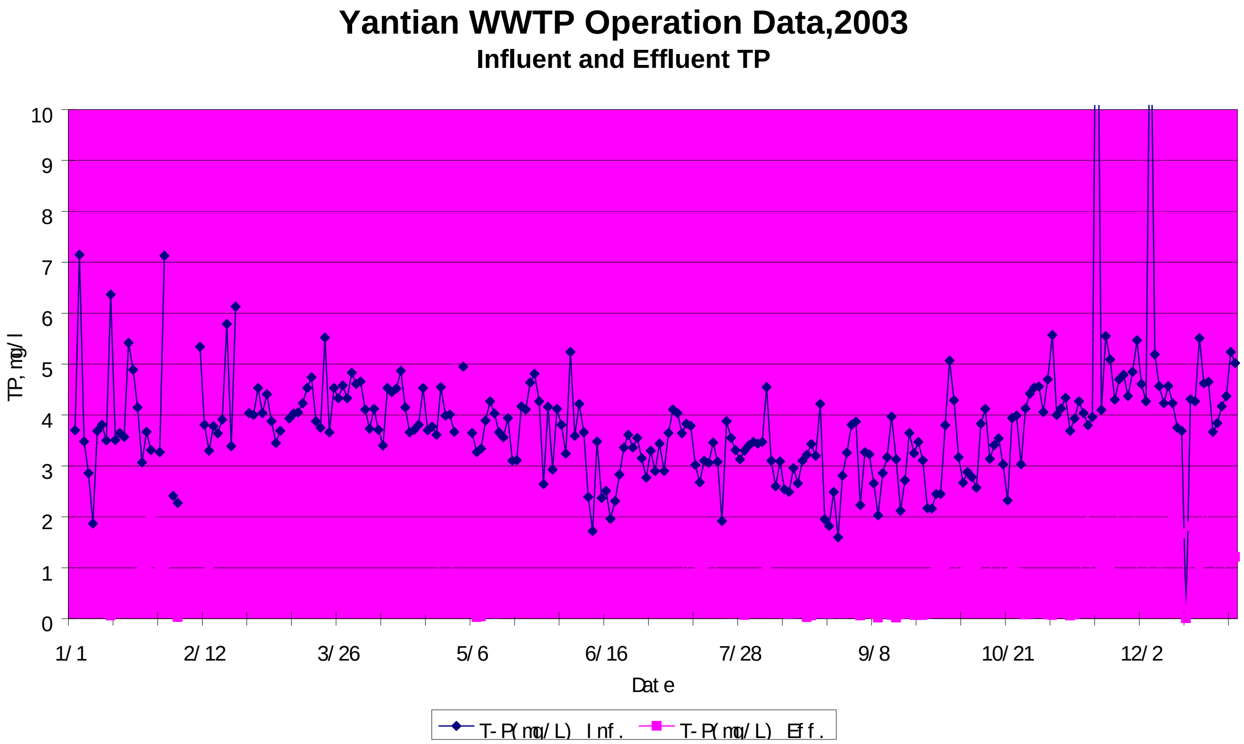

Figure 8. Influent and Effluent TP

DISCUSSION

The MSBR® system is an advanced activated sludge treatment technology utilizing fundamental biological wastewater treatment and nutrient removal processes. The combination of a standard flow-through approach coupled with isolated batch reactor treatment and pre-settling steps, provides stable and high quality effluent performance.

The Yantian WWTP is located in the eastern suburbs of the Shenzhen community. The plant is partially surrounded by light industrial businesses and several small jewelry factories. The plant influent is generally stable throughout the year, however the plant experiences oily and often toxic influent conditions during major holiday events. Examples can be noted in the effluent phosphorous data. The Chinese New Year is in January, May has a weeklong holiday and in October, the National Day is observed. Additionally, the plant influent has had an unidentified oily component that started in November and persisted on into this year. Attempts are being made to locate the source and have it corrected. The oil creates excess scum and has reduced the aeration efficiency. Dissolved oxygen levels as low as 0.5 mg/l are common. There is a phosphorous excursion in July corresponding to in-house plant testing of the maximum sludge age. During this test period, the plant effluent TP reached 1 mg/l and the ammonia nitrogen dropped to less than 5 mg/l. When the plant resumed its normal sludge-wasting program, the TP returned to normal levels of 0.3 mg/l

The data shows the Yantian wastewater treatment system achieved excellent removal of COD and BOD_5 of 35 and 6.5 mg/l respectively. The combination of anaerobic and aerobic bio degradation contributed to the efficient removal of the organic components. Effluent suspended solids data indicate an average of 9.2 mg/l also contributed to the COD and BOD_5 removal performance. The suspended solids and organic carbon removal were not dramatically effected by the industrial influences during the major holidays. The high quality effluent TSS is related to the design of each side cell. A baffle is located at the mid-point that controls the forward flow energy. Additionally, the process has a cycle time associated with the side cell operation. The cycle time can be operator adjusted to accommodate seasonal flow variations.

Control of the effluent suspended solids is maintained by controlling the side cell energy and preventing density currents by the unique baffled cell design. Figures 9a and 9b depict the side cell flow patterns showing how the MLSS travel through the cell. In high flow conditions the sludge blanket will lift but settles very effectively prior to discharge. Another feature is the process cycle structure. Flow is introduced to the side cell for a predetermined time that elapses before the complete side cell volume is displaced. The time for the process cycle structure is operator controlled. Yantian WWTP data demonstrates the TSS removal efficiency, which also is evident in the COD and BOD_5 removal efficiencies. The summer temperatures resulted in higher reaction rates, which permitted shorter recycle periods from the alternating cell. With the shorter recycle periods, the balance of the time was dedicated to the pre-settle step to accommodate storm flow conditions.

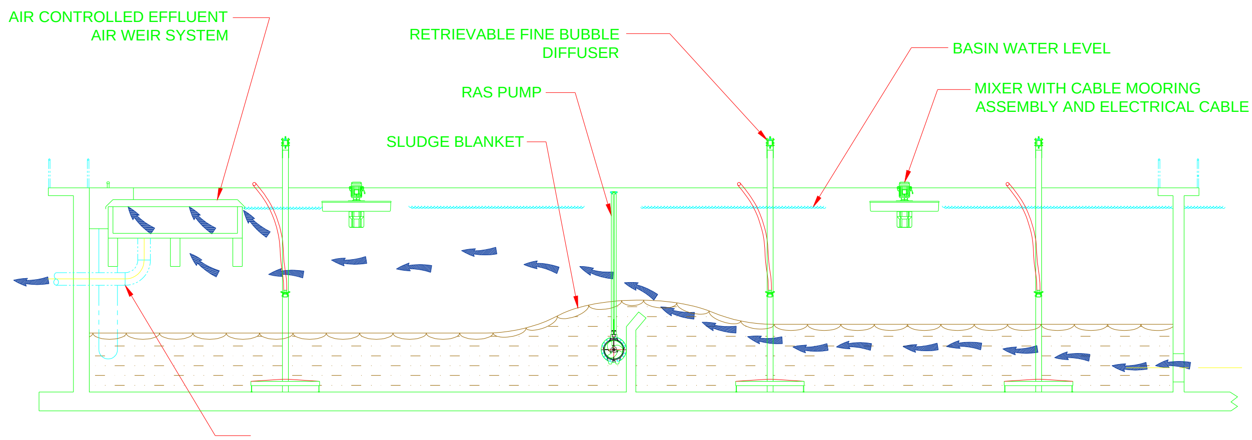

Figure 9a. Side Cell Average Flow Pattern

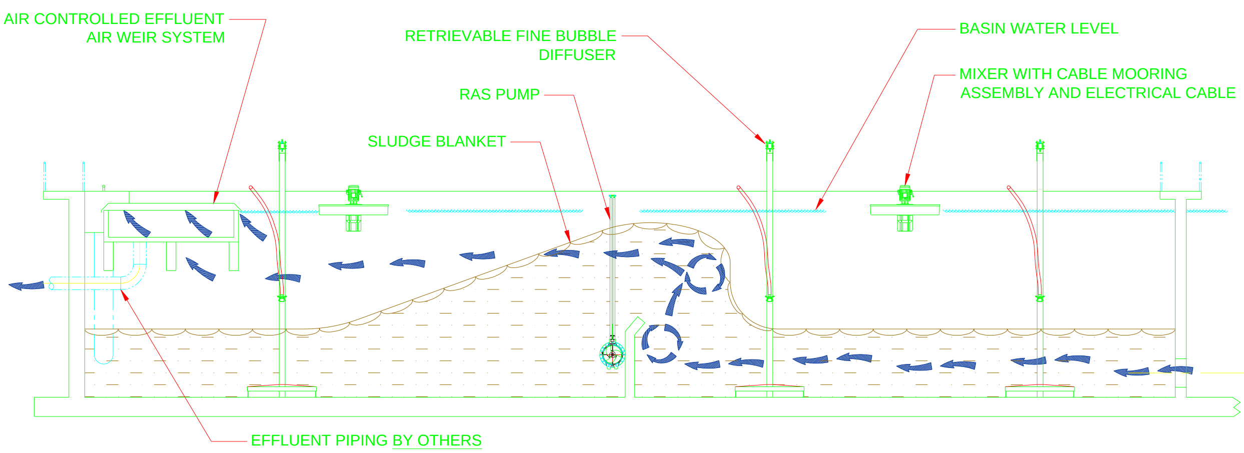

Figure 9b. Side Cell Peak Flow Pattern

The nitrogen requirement for the Yantian WWTP is <15 mg/l of ammonia. The nearby gold jewelry industry consumes most of the available alkalinity. To achieve improved nitrogen removal, alkalinity would have to be added to the influent stream. Nitrogen removal capability was tested for two weeks by adding sodium carbonate. The effluent ammonia values dropped to 1 mg/l during the test period. The average effluent ammonia nitrogen was 7.9 mg/l with a standard deviation of 4.3 mg/l. This represents 94% removal and is well below the 15 mg/l objective. Additionally, cell 5 provided excellent removal of nitrates by turning on the recycle feature between cells 5 and 6. Effluent nitrate and nitrite nitrogen averaged 8.4 mg/l and <0.1 mg/l respectively.

The oxidized nitrogen is controlled in the RAS fluid stream by the phase separator step. The return activated sludge is separated into two fluid streams, one containing 70% of the fluid with 30% of the mixed liquor suspended solids (MLSS) and the other 30% of the liquid and 70% of the MLSS. This unique flow split minimizes nitrogen/oxygen contamination of the anaerobic cell where phosphorus release is maximized. The total oxidized nitrogen concentrations in the pre-anoxic cell was controlled to 0.5 to 1.5 mg/l. Additionally, the anaerobic step contributes to organic pretreatment, which is reflected in the stable removal of COD and BOD_5

The phase separator step provides the opportunity to concentrate the return MLSS in an anoxic environment that creates an ideal feed source to combine with the raw wastewater entering the anaerobic cell. Incoming VFAs are not diluted by the recycle stream therefore, higher VFA uptake along with high PHA production are maintained in the anaerobic cell creating a higher driving force for bio-phosphorus release. An additional benefit of the anaerobic step is its contribution to improved settling characteristics of the MLSS. Typical sludge volume indexes (SVI) are 50 ml/g. During the November oil and grease event the SVI rose to 140 ml/g, resulting in the higher COD, BOD_5 and TSS values.

The Yantian WWTP has demonstrated an average phosphorus removal efficiency of 92%. The typical effluent TP value of 0.33 mg/l was achieved without chemical addition. Adjusting the data to exclude the holiday events, the effluent TP was 0.3 mg/l with a standard deviation of 0.3

mg/l. This represents a 94% confidence level that TP will be < 0.6 mg/l. The enhanced nutrient removal is a result of the phase separator step where the return activated sludge is managed by preventing dilution of VFAs and contamination of the anaerobic environment with oxygen. Evaluation of the waste activated sludge characteristics indicated that the waste solids contained 3.6 percent phosphorus. The organic portion of the waste solids was 39% with associated phosphorus content of 9.2%. This is much higher than the typical microorganism phosphorus content of 2%.

Other features include an operator selected WAS discharge control. WAS discharge can be cycled to enhance higher waste solids concentrations. The Yantian annual average WAS discharge concentration is 2%. Benefits of higher WAS solids concentration are realized in the lower operating costs of the WAS de-watering operation. Waste activated solids are de-watered by a centrifuge. The annual average cake solids are 29%, which has significantly reduced the total quantity of waste solids.

CONCLUSION

The two years of operating history from the Yantian WWTP utilizing MSBR® process technology has demonstrated stable and reliable treatment of municipal wastewater. The technology is suitable for both small and large facilities that require enhanced nutrient removal coupled with high performance organic removal.