Toward Long Solids Retention Time of Activated Sludge Processes: Benefits in Energy Saving, Effluent Quality, and Stability

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ABSTRACT: The activated sludge process is the most common method of secondary municipal wastewater treatment; solids retention time (SRT) is the key control parameter for this process. Typically, operating at long SRT is considered only for nitrification, but there are additional benefits of high SRT operation. This paper presents experimental and literature evidence to demonstrate three major additional benefits of long SRT operation: increased oxygen transfer efficiency; improved biomass particle size distribution, which results in more efficient clarification with fewer effluent particles and suspended solids; and enhanced removal of many emerging contaminants such as pharmaceuticals, personal care products, and endocrine disrupting compounds. This paper presents experimental results from several treatment plants that showed increasing oxygen transfer efficiency and particle size with increasing SRT, and evidence documenting improved removal of emerging contaminants and biodegradable organic carbon. A long-term survey of three treatment plants concludes that operating at higher SRT is not as energy intensive as typically assumed. *Water Environ. Res.*, **84,** 42 (2012).

KEYWORDS: activated sludge, wastewater, emerging contaminants, particle size, energy, solids retention time.

doi:10.2175/106143011X12989211841052

Introduction

The activated sludge process (ASP) was developed between 1912 and 1914 and has been continuously in use and improved upon since (Ardern and Lockett, 1914). Many municipal wastewater treatment plants (WWTPs) in the United States and Europe use ASP. Design and operation of WWTPs have been modified and improved to meet more stringent effluent quality standards and additional environmental goals such as improved energy savings and reliability, reduced carbon-footprint, biosolids production, and effluent concentrations of emerging contaminants. These process goals require maintaining the ''healthiness'' of microorganisms, and are related to the key process control parameter, solids retention time (SRT).

Conventional ASPs operating at shorter SRT (one to two days in warm climates) can remove more than 85 to 95% of the five-day biochemical oxygen demand (BOD_5) in wastewater, and are used in many WWTPs. Operation with longer SRT typically occurs only when nitrification is needed. There are other benefits of long SRT operation, however, such as improved aeration efficiency, more favorable biomass particle size distribution, and removal of emerging contaminants. The benefits of increasing SRT to each operation characteristics are discussed below.

Improved Energy Conservation. Wastewater treatment consumes significant amounts of energy. Power consumption varies widely and is affected by plant flow, wastewater characteristics, and treatment processes (Metcalf and Eddy, 2003). Conventional wisdom among treatment plant managers assumes operation at longer SRTs consumes greater energy because of increased oxygen loadings for nitrification and endogenous decay. Rosso and Stenstrom (2005) suggested, however, that energy consumption for nitrification/denitrification (NDN) processes has been overstated. The authors measured and calculated the energy consumption of several major unit operations of ASPs, including aeration, solids treatment, and energy recovery from digester gas, and compared the energy consumptions of three processes (i.e., conventional low-SRT ASP, nitrification only, and NDN processes). The authors showed that complete nitrogen removal requires about the same energy as conventional processes because of (1) increased α factors and improved oxygen transfer efficiency (OTE) with fine pore diffusers; (2) energy savings associated with reduced waste biomass production; and (3) denitrification to produce the well-known ''oxygen credit''. Rosso and Stenstrom (2005) provide a detailed discussion of the ''oxygen credit'', which is summarized as the use of nitrate as an electron accepter by heterotrophic bacteria that consume the readily degradable BOD in the short retention time of the anoxic zone under anoxic conditions. This BOD would otherwise be oxidized in the aerated zones, consuming oxygen. This benefit is sometimes called the denitrification credit and can be thought of as recovering some of the oxygen used to oxidize ammonia to nitrate. If all of the ammonia oxidized to nitrate is denitrified without using an additional carbon source, then the oxygen required is reduced from 4.55 to 1.71 mg O_2/mg-N (Metcalf and Eddy, 2003). Increased OTE results at higher SRT because the higher biomass concentration more rapidly degrades or sorbs oxygen transfer inhibitors, such as surfactants (Rosso and Stenstrom, 2006a; Rosso et al., 2006).

Improved Microbial Environment. Biomass quality is a key factor in determining overall ASP efficiency. It is well

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known that anoxic selectors, which are used in long SRT nitrogen removal processes, are effective in preventing many types of filamentous bulking (Jenkins et al., 2004). Parker et al (2004) showed the benefits of selectors, both anoxic and anaerobic, in improving the sludge volume index (SVI) values, and noted that as a group, plants with anaerobic selectors, outperformed plants with anoxic selectors, especially when MLSS dissolved oxygen concentration can be controlled at 2 mg/L or greater. Particle size distribution (PSD) of the biomass is also important. Residual fine particles or pin flocs in secondary clarifier effluent cause poor effluent quality, as measured by total suspended solids (TSS) or total BOD, and complicates disinfection processes, particularly UV disinfection. Particle size distribution analysis can become an appropriate tool to characterize the "healthiness" of activated sludge. The sizes of biomass particles or flocs range from 0.5 μm (single cell) to more than 600 μm. Higher quality biomass should consist of large flocs and fewer small particles. Bisogni and Lawrence (1971) provided an early observation of dispersed growth at low SRT, which has been supported by more recent observations that dispersed growth at low SRT (less than two to three days) creates poorly stabilized particles and causes poor effluent quality (Jenkins et al., 2004).

Enhanced Degradation of Emerging Contaminants. Emerging contaminants are manufactured, functional compounds such as pharmaceutical and personal care products (PPCPs) and endocrine disrupting compounds (EDCs) that may affect aquatic life at very low concentrations. These types of contaminants are often resistant to biodegradation and poorly removed by conventional wastewater treatment processes. Wastewater effluent is a potential major source of emerging contaminants (Cunningham et al., 2006). Some emerging contaminants accumulate in food chains, such as perfluoroalkyl contaminants (Jonathan et al., 2004); others, such as artificial hormones, modify reproductive organs in fish (Jobling et al., 1998). The environmental effect and the need to remove the emerging contaminants is a topic of current debate, and the success in removing these contaminants depends on the type of treatment. Advanced treatment with membranes or advanced oxidation is one alternative, but typically will increase cost.

Soliman et al. (2007) noted reduced concentrations of 9 of 11 emerging contaminants in reclaimed water from a long SRT plant compared to reclaimed water produced from two short SRT plants. Modification of ASP operation by increasing SRT significantly improves removals of emerging contaminants (Andersen et al., 2003; Batt et al., 2007; Carballa et al., 2004; Clara et al., 2005; Joss et al., 2005; Kreuzinger et al., 2004; Oppenheimer et al., 2007; Ternes et al., 2004). Microorganisms that are capable of degrading emerging contaminants may reproduce slowly, with low growth rate and biomass yields, and require longer retention time to accumulate. Co-metabolism activities also require a low food-to-mass ratio (F/M) to create a carbon-limiting environment. Both conditions are favored by operation at high SRTs (low F/M). Buttiglieri and Knepper (2008) concluded that SRT is the most important process parameter to remove many types of emerging contaminants, even though not all of the contaminants are removed by this strategy.

Objectives

The goal of this paper was to investigate and evaluate the three additional benefits of longer SRT operation. The primary investigation includes the study of improved energy efficiency followed by discussion on particle size distribution analysis, both based on experimental results of full-scale systems. Improved removal of emerging contaminants and change in concentrations of effluent organic matter also was investigated. Long-term aeration measurements, collected from three full-scale WWTPs as they were upgraded from low to high SRT operation, were analyzed to calculate the energy consumption at different SRTs. Two of the plants were upgraded during the testing periods from conventional to NDN processes, and one plant was tested for nitrification on one occasion during which the SRT was increased from one to two days to more than 12 days. The effect of longer SRT operation on biomass quality was quantified using particle size distribution measurements from mixed-liquor samples collected from 23 WWTPs in or near California. Literature data were studied to classify the types of emerging contaminants that can be effectively degraded by longer SRT operation.

Materials and Methods

Off-gas testing with energy analysis and particle size distribution analysis were performed during the experimental investigation, and the methodologies are discussed in this section. Data regarding the techniques for quantifying the removal of emerging contaminants were collected primarily from the literature. Off-gas tests have been used to evaluate aeration efficiencies in the studied treatment plants since the early 1990s. Plants tested were typical, medium-size municipal WWTPs in California. Particle sizes of biomass under aeration were tested using a particle size distribution analyzer for 23 WWTPs throughout the West Coast of the United States. The following sections provide details of the testing methodology and operational conditions of tested WWTPs.

Background of Tested Wastewater Treatment Plants. Table 1 shows the operation conditions of different monitoring periods of the treatment plants. The total treatment plant capacities were between 75 000 to 300 000 m^3/d (approximately 20 to 80 mgd). The plants had multiple parallel aeration tanks and the ability to separate clarifiers and biomass recycle; therefore, the data are reported only for the tested tanks. The volumetric flow rate of primary effluent to each aeration tank averages from 11 400 m^3/d (3 mgd) to 80 000 m^3/d (21.1 mgd). In Table 1, the WWTPs are identified as Plant I, II, and III. Because the operation conditions or strategies were modified over time, the testing periods of each plant were classified as Phase 1, 2, 3, or 4 during different testing periods. During certain operation phases (Phases 1 and 2 of Plant I; Phase 1 of Plant II; and Phases 1 and 3 of Plant III), the WWTPs treated only carbonaceous BOD and did not remove ammonia. In Plant I, the SRT increased from 1.6 to 1.9 days to 2.6 to 3.5 days between Phase 1 and Phase 2 because of changes of plant loadings; during Phase 3, the plant was converted to NDN process with the modified Ludzack-Ettinger (MLE) approach, and the SRT was 6.4 days. The condition provided partial nitrification and little if any denitrification. The transition was completed in Phase 4, with the plant operating at 11 to 12 day SRT with complete nitrification and excellent denitrification. The final configuration used a small anaerobic selector followed by three anoxic stages. The inclusion of selectors reduced the aerated portion of the tanks.

Operating conditions of Plants II and III were similar to Plant I, except that at Plant III nitrification without denitrification was

Table 1—Different operational phases of the tested wastewater treatment plants (SRT = solids retention time; NDN = nitrification/gentrification).

Test plant	Phase	Treatment process	SRT (day)	Flow rate per tank ($10^3 m^3/d$)	Aeration area (m^2)
Plant I	1	Conventional	1.6–1.9	18.8	892
	2	Conventional	2.6–3.5	15.1	892
	3	NDN (partial)	6.4–7.0	17.0	568
	4	NDN (full)	11.0–12.2	16.3	568
Plant II	1	Conventional	3.1–4.1	15.5	714
	2	NDN (full)	12.5–14.0	11.4	526
Plant III	1	Conventional	3.3–4.5	79.8	3512
	2	Nitrification only	14.0–17.3	37.2	3512
	3	Conventional	1.8–2.5	37.2	1756

practiced. Plant II was upgraded directly from conventional process to NDN process and the flow rate for each tank decreased from 15 500 to 11 400 m^3/day (4.1 to 3.0 mgd). With 4 to 5 tanks in services, the total capacity of Plant II was approximately 45 600 m^3/d (12 mgd). Plant III consists of two treatment trains and each had four aeration tanks. The length of each aeration tank is 82.3 meter (270 ft) and the width is approximately 10.7 meter (35 ft). During phases 1 and 2, Plant III was operated using four aeration tanks in series with separated clarification and biomass recycle. Phase 1 operation was at medium SRT and Phase 2 operation was at high SRT. During Phase 3, the plant operated with four sets of two-tanks in series, at low SRT. Plant control data such as flow rate, influent/effluent concentrations (BOD_5, NH_4^+-N, and NO_3^--N in mg/L), mixed-liquor suspended solids (MLSS, mg/L), dissolved oxygen (DO, mg/L) sludge recycle, and wasting rate were recorded with off-gas test results. This information was used to calculate plant load and power consumption.

Aeration Tests and Energy Calculations. Energy consumption of aeration processes typically is presented as the standard aeration efficiency (SAE, kgO_2/kWh), and is the ratio of the standard oxygen transfer rate (SOTR, kgO_2/d) to the wire power consumption of aeration equipment (Boyle et al., 1989). Wire power measurements typically are not available for treatment plant aeration systems because they often include power consumption of other equipment, or the aeration blowers provide air for other purposes, such as channel aeration. Tank-specific aeration efficiency was measured using off-gas testing (Redmon et al., 1983), and the method has been recommended as a standard method by American Society of Civil Engineers (1997).

The off-gas tests use a floating hood on the surface of the aeration basins to collect off-gas. Oxygen transfer efficiency (OTE, %) is calculated by comparing the oxygen content in the supplied air and the off-gas. The OTE measured in processing condition, adjusted to standard conditions, is the αSOTE (standardized alpha oxygen transfer efficiency, %), which accounts the effects of reducing OTE because of contaminants (i.e., surfactants) and diffuser fouling. The alpha factor (α) is calculated as the ratio of the αSOTE to the standardized OTE tested in clean water (Stenstrom and Gilbert, 1981). Total air flow rate of the aeration tank was calculated by multiplying the measured air flow rate captured by the hood by the ratio of the tank surface area to the hood area. Leu et al. (2009) describe the details of off-gas analysis and process-level analyzers suitable for 24-hour monitoring of plant performance, which considerably simplifies the test. Blower power was calculated using the adiabatic compression equation based on a combined motor-blower efficiency of 75% (Metcalf and Eddy, 2003). Static air pressure and line losses were 151 kPa (21.9 PSI). The dynamic wet pressure (DWP) for the diffusers ranged from 3.0 to 5.0 kPa (12- to 20-inch water column) and was based on plant and laboratory measurements of representative diffusers. The head pressure of diffusers is a function of air-flow rate and fouling condition measured in WWTPs. After a period in operation, the diffusers typically become fouled, reducing efficiency and increasing DWP with resulting higher energy consumption. With the given parameters, the adiabatic blower energy for cleaned diffusers was approximately 0.016 kWh per cubic meter of air flow (0.037 hp/SCFM).

Particle-Size Analysis. Particle-size analysis was performed using a Nicomp particle sizing systems AccuSizer 780 optical particle sizer module equipped with an auto-dilution system and a light scattering/extinction sensor (Santa Barbara, California; model LE1000-2SE). This instrument was selected for its wide detectable limits (0.5 to 500 μm particle size), rapid analysis (two minutes per sample), and auto-dilution capability. Representative samples from the well-mixed original mixed liquor samples were collected using a wide-bore glass pipette and then injected to the analyzer. The system was flushed with deionized water at least three times between samplings, which reduced background particle concentrations to less than three particles per milliliter. Li et al. (2005) and Chan et al. (2008) discuss the testing methodology in detail.

Duplicate samples were collected from 23 treatment plants over a range of operating SRTs, and the PSD of the mixed liquor was measured within 24 hours of sample collection. A well-mixed sample and the supernatant of a sample were measured and allowed to settle for 30 minutes. Mean particle size was calculated from the particle-size distribution from 0.5 to 200 μm; 200 μm was selected as an upper limit because bioflocs larger than 200 μm can be broken apart during analysis. Also 200 μm and larger particles should be well-removed by clarifiers and should not contribute to effluent turbidity or pin floc. The particles larger than 200 μm typically are created through flocculation in clarifiers in 20 minutes or less and are easily broken apart by mixing, sample handling, and pumping (Das et al., 1993; Wahlberg et al., 1994) For the 30-minute settled samples, the total number of particles was counted. None of the plants was experiencing filamentous bulking or other process upsets when the samples were collected.

Results and Discussion

Longer Solids Retention Time and Energy Consumption. The effect of SRT on energy consumption was studied at the three plants described in Table 1. Table 2 shows the additional

Table 2—Test results of the studied treatment plant at different operational phases (SRT = solids retention time; BOD5 = five-day biochemical oxygen demand; MLSS = mixed-liquor suspended solids; DO = dissolved oxygen concentration; α = alpha factor; SOTE = standardized oxygen transfer efficiency; HRT = hydraulic retention time).

Test plant	Phase	SRT (day)	BOD_5 (mg/L) In	BOD_5 (mg/L) Eff	NH3 (mg-N/L) In	NH3 (mg-N/L) Eff	MLSS (mg/L)	DO (mg/L)	Air flux ($m^3/h \cdot m^2$)	Total air (m^3/h)	αSOTE (%)	Aerobic HRT (hour)	Solids flux ($kg/m^2 \cdot d$)	Aeration power ($MJ/10^3 m^3$)
Plant I	1	1.6–1.9	132	11.0	21.2	13.4	850	1.2	5.30	4728	11.8	5.2	50.3	553
	2	2.6–3.5	146	17.6	21.7	13.7	1,030	1.3	5.12	4567	14.0	6.5	45.5	669
	3	6.4–7.0	181	11.0	31.5	9.6	2,500	1.4	8.05	4572	17.2	3.7	142.7	591
	4	11.0–12.2	168	8.0	28.7	0.4	3,680	2.4	10.24	5816	19.5	3.8	214.3	782
Plant II	1	3.1–4.1	141	~10	23.4	16.3	1,669	0.9	4.57	3263	12.7	4.7	103.0	543
	2	12.5–14.0	144	~10	26.2	0.5	3,208	3.5	12.80	6733	18.9	4.7	189.5	806
Plant III	1	3.3–4.5	160	~5	27.2	–	1,100	3.2	8.78	30835	8.3	5.1	60.7	817
	2	14.0–17.3	160	~5	27.2	19.3	1,933	0.6	7.50	26340	8.0	10.8	64.7	1224
	3	1.8–2.5	160	~5	27.2	0.4	2,551	4.1	8.41	14768	13.0	5.4	142.6	762

operating information and the experiment results of the off-gas tests. Traditionally, it is assumed that increasing SRT increases energy consumption of wastewater treatment processes and reduces waste biomass production. Additional energy is required to provide the oxygen needed for nitrification and for the increased mass of biosolids endogenously respired (e.g., lower observed biomass yield). What has not been described previously is the increased OTE associated with higher SRT, which partially offsets the need for additional oxygen transfer. Furthermore, the denitrification credit also reduces the need for additional oxygen transfer. Well-operating DO control systems improve energy conservation and process stability.

For the three plants described in Table 1, the benefits of DO control are not well utilized because of over-aeration from poor control system performance, or limited blower turn-down capability. This means that the short SRT processes did not take advantage of lower DO operation. Figures 1 and 2 show the DO measurements of the tested tanks measured by portable DO probes. Figure 1a shows the effluent ammonia concentration as a function of DO. Ammonia removal increases with DO concentration, but in conventional treatment processes less than 1 mg/L of DO concentration is needed, because nitrification does not need to be supported. The DO concentration higher than 1 mg/L accompanies partial nitrification and increases oxygen demand. With no denitrification credit, higher oxygen demand increases energy consumption and unwanted denitrification in secondary clarifiers can cause sludge settling problems. Figure 1b shows the derivatives of effluent ammonia versus DO concentration, calculated from the trend line of Figure 2a. The minimum value of the curve shows the optimal DO concentration for nitrification, which begins at 1 mg/L and is most effective at 2 to 2.5 mg/L in NDN processes. Figures 2a and 2b show the numbers of observations of WWTPs as

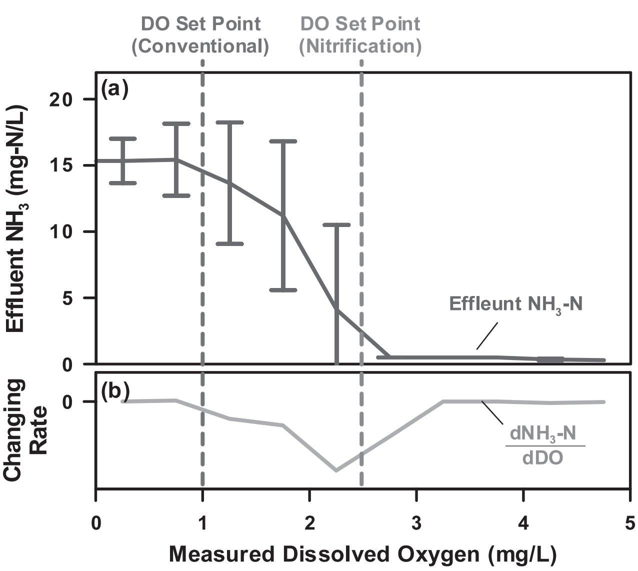

Figure 1—(a) dissolved oxygen (DO) measured from different wastewater treatment plants versus effluent ammonia (number shows the solids retention time of treatment processes); (b) derivative of changing effluent ammonia versus dissolved oxygen.

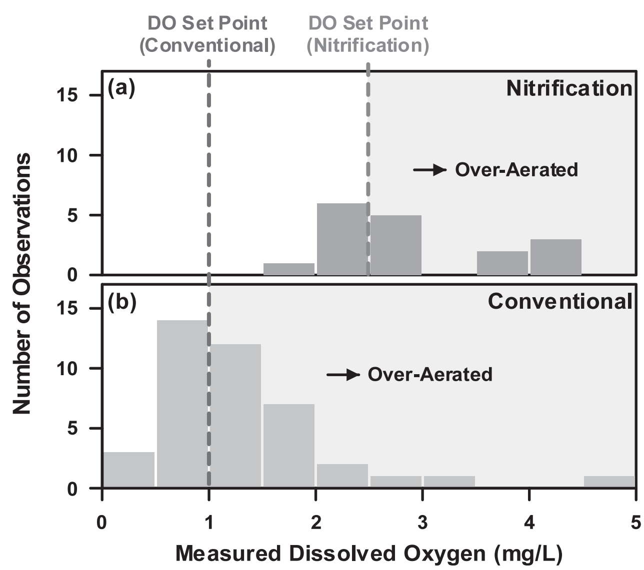

Figure 2—Number of observations for different dissolved oxygen (DO) for two activated sludge process (ASP) modifications: (a) nitrification processes (b) conventional low-solid retention time ASP. The results show that more than half the aeration tanks have dissolved oxygen higher than the set points and are typically over-aerated.

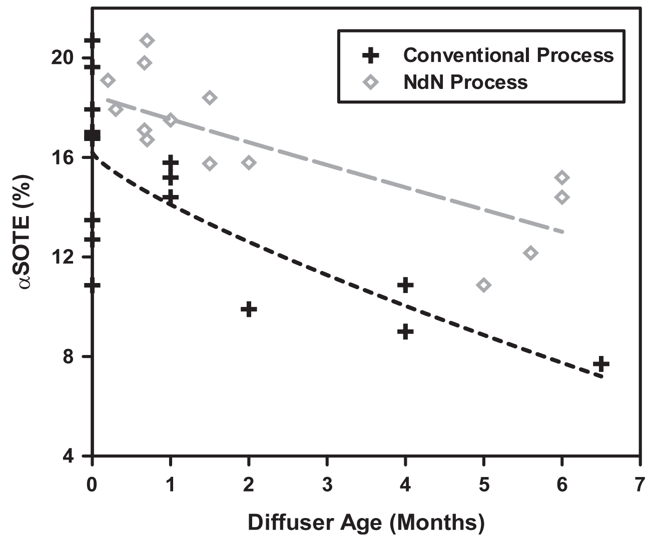

Figure 3—Diffuser fouling conditions of wastewater treatment Plant I. Data collected from two operation conditions—conventional and nitrification/denitrification process—are plotted separately as a function of diffuser operation time after installation or cleaning. Dashed curves show the power fits of the measurements with given average starting αSOTE (when diffuser age = 0).

a function of DO concentration for nitrifying processes (NDN and nitrification only) and conventional ASPs, respectively. Over-aeration occurred in 10 of 17 observations with nitrifying processes and in 24 out of 41 observations with conventional ASPs, which show higher DO concentration than the set point (greater than 2.5 mg/L for nitrifying processes and greater than 1.0 mg/L for conventional ASPs). Although high dissolved oxygen is needed for ammonia oxidation, excessive dissolved oxygen wastes energy. At average temperature (20 to 25 °C), average DO concentration greater than 2 to 2.5 mg/L (whole-tank average) should remove at least 90% of ammonia at medium to high SRT.

Diffuser fouling can also affect energy consumption of wastewater treatment. Aeration tanks with fouled diffusers require 30 to 50% more air flow than cleaned diffusers (Rosso and Stenstrom, 2006b). The rate of diffuser fouling is site-specific and no model has been published to effectively predict diffuser fouling. Alpha factor and αSOTE are typically used indices to evaluate diffuser fouling and to provide information for diffuser replacement or maintenance. Figure 3 shows the αSOTE measured from Plant I as a function of diffuser operating time after cleaning. The rate of fouling after conversion to NDN operation is lower than that which occurred when the plant was operating as a conventional process. Typically, higher fouling rates are associated with soluble BOD, and fouling is always most severe at the aeration tank feed points, which is observed in both step-feed and plug-flow aeration tanks. With higher SRT plants, the most severe fouling zones are smaller because of the more rapid removal of soluble substrate. The trend lines in Figure 3 show the power fits of the measurements with given average starting αSOTE. The starting αSOTE were 18.5% and 16.2% for NDN process and conventional process, respectively. Although the relationships are only applicable for the specific

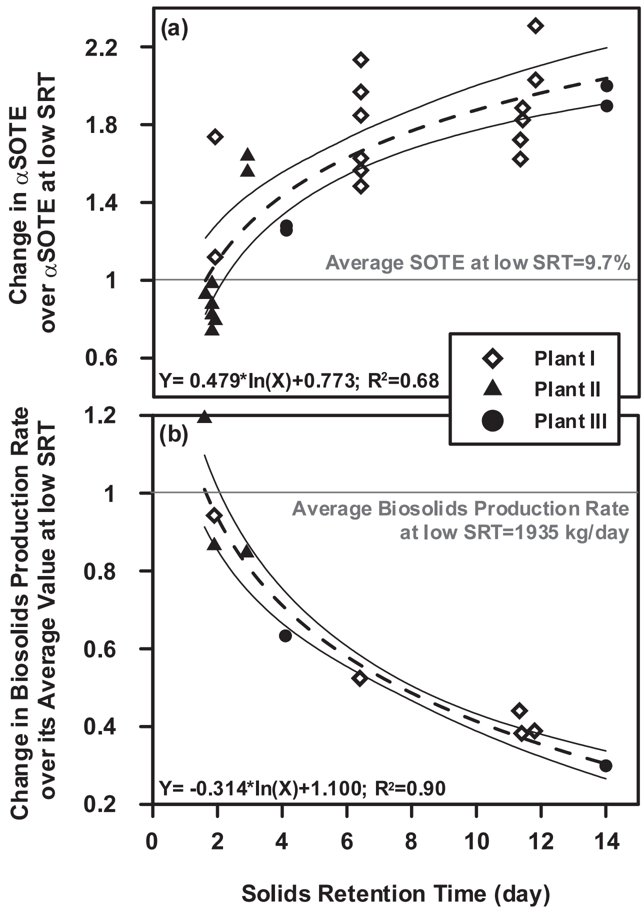

Figure 4—Experiment results of energy conservation characteristics in the studied wastewater treatment plants. The parameters plotted as a function of solids retention time (SRT) are the ratio of measurement results versus the values measured at lowest SRT. The two plotted parameters are: (a) process oxygen transfer efficiency adjusted for dissolved oxygen, temperature, etc. (αSOTE, %); and (b) biosolids production rates of secondary process. The dashed curves show the logarithm fits and the solid curves are 95% confidence intervals.

case of Plant I and more investigation is needed to develop a sophisticated diffuser fouling model, it is clear that αSOTE decreased over operation time after diffuser cleaning and was higher in NDN processes.

Figure 4 shows the plant data and experiment results of off-gas tests, plotted against SRT. Figure 4a shows the change of αSOTE over the initial αSOTE measured at lowest SRT. The dashed lines show the logarithm fits of the two parameters, and the solid lines show the 95% confidential intervals of the data, calculated to include the true mean of the underlying population 95% of the time. To separate the effects of diffuser fouling and SRT on transfer efficiency, Figure 4a includes only new and recently (less than 6 months) cleaned diffusers. Longer SRT operation increases the αSOTE by 60% to 120% (from 10% to 15 to 22% αSOTE). The effect of SRT on biosolids production is also shown in Figure 4b. The plotted results were calculated from measured biosolids waste flow rate multiplied by measured biosolids recycle concentration. Effluent TSS is not included in the calculation. All plants used primary clarification, but an

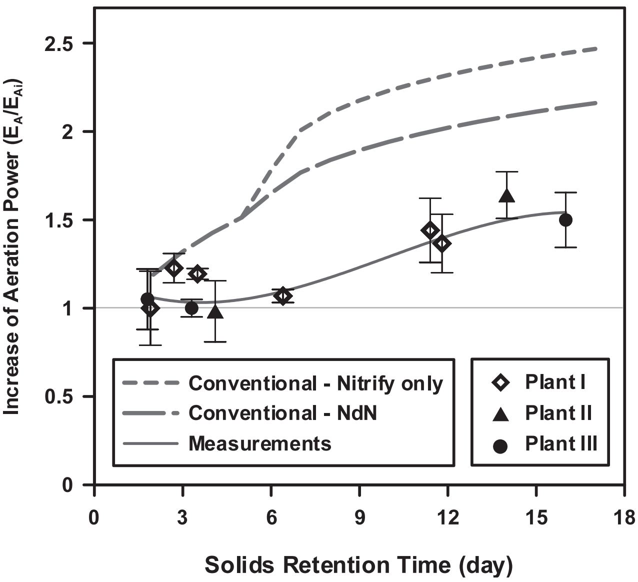

Figure 5—Ratio of aeration power per volume wastewater treated at different operation conditions versus the initial power consumption at low solids retention time. The experiment results were measured from three wastewater treatment plants and are shown with different symbols. The dashed curves show the calculated energy requirement based upon convention models, and the solid curve shows the third-order polynomial fit of measurement data.

analysis of the effect of nondegradable primary waste biosolids is not included in Figure 4b. Table 2 shows the average values of three WWTPs at different operation phases. In Plants I and II, the air fluxes of NDN process are higher than conventional processes because of the anoxic zones, which reduced area and volume for aeration. The last column of the table provides the information required to calculate the aeration energy consumption. Aeration energy was approximately between 550 MJ/10^3m^3 to 1200 MJ/10^3m^3 (578 to 1262 kWh/MG) and was highest at Plant III. The information was used to plot Figure 5, which shows a comparison between conventional model and measurement data. Figure 5 shows the change of aeration power of treating 10^3m^3 wastewater (compared to initial power consumption) of the tested WWTPs and under different operation phases. The different symbols show the measurements at different treatment plants, but the solid trend line includes all measurements of three WWTPs. The two dashed lines show the power consumption calculated based upon conventional methods. The conventional method assumes constant αSOTE (10%) for all SRTs. The ASP with nitrification only oxidizes ammonia and nitrite but does not denitrify; this process requires more oxygen than conventional ASP and NDN processes. Calculations using constant aeration efficiency and conventionally accepted kinetic and stoichiometric parameters suggested the increase would be as much as 100% for NDN and 150% for nitrification only. Measured results showed, however, that the increase in aeration power from conventional to NDN mode was approximately 50%.

Power consumption did not increase with increasing SRT as greatly as expected. The maximum power increase was approximately about 41% (Plant I) to 50% (Plant III) higher than low SRT operation. Because solids treatment accounts for more than 20% of total energy consumption and sludge production is less at higher SRT (Figure 4b), the total energy consumption of overall wastewater treatment for NDN process ranged from 1 to 1.3 times the energy consumption of the conventional treatment process. These results differed from ''conventional wisdom'' and were less than the values proposed in Metcalf and Eddy (2003). The plants shown in Figure 5 were denitrifying well, but not to 100%. The results will vary depending on denitrification efficiency.

The typical power consumption of wastewater treatment for 1000 m^3 of wastewater using ASP ranges from 1000 to 2500 mega joule (MJ, 1000 to 2500$\times10^6$ J, or 277.8 to 694.4 kWh; Metcalf and Eddy, 2003). Oxidation ditches typically are more energy consuming than ASPs. Reardon et al. (2003) compared side-by-side energy consumption of a step-feed biological nutrient removal (BNR) process and an oxidation ditch with simultaneous nitrification/denitrification. The power consumption of the step-feed BNR was approximately 730 MJ/10^3m^3, which was approximately half the energy used in a traditional oxidation ditch with simultaneous nitrification and denitrification (1550 MJ/10^3m^3). Boyle et al. (1989) reported a similar number (1645 MJ/10^3m^3) for energy consumption in oxidation ditch using downdraft turbine aerators.

Solids Retention Time and Biomass Particle-Size Distribution. Table 3 shows a survey of the average particle sizes of all tested West Coast WWTPs (Chan, 2010; and Chan et al., in press). The results show a monotonic increase in mean particle size as the SRT increases from less than 2 to 12 days. At more than 12 days SRT, the mean particle size was smaller, suggesting that pin floc formation or ''ashing'' occurred at long SRT. The right side of Table 3 shows the number of particles remaining in the supernatant after 30-minute settling, which simulates ideal clarification. At low SRT there are many more suspended particles, which will contribute to effluent TSS and turbidity. Clearly the SRT had a significant impact on effluent quality.

Table 3—Average particle sizes of mixed-liquor suspended solids (MLSS) from different wastewater treatment plants (SRT = solids retention time; NDN = nitrification/gentrification).

		Particle size in mixed liquor (μm)		Particle number in supernatant ($\times10^5$)	
SRT (day)	Process	range	average	range	average
<2	Conventional	7.7–18.1	12.0	4.5–58.6	29.2
2–5	Conventional	8.5–45.9	20.9	4.5–67.9	20.4
6–9	Partial Nitrify	28.7–66.6	52.6	1.1–3.1	1.9
10–12	NDN	37.5–64.7	53.5	1.1–1.8	1.3
30	NDN	34.5–60.7	44.3	0.7–3.6	2.0

Solids Retention Time and Removal of Emerging Contaminants. Figure 6 shows the removal of four classes of emerging contaminants that have varying removal rates as a function of SRT, based upon literature observations and laboratory results (Soliman et al., 2007). Emerging contaminants are used for sunscreens, household cleaners, hormones, and other pharmaceuticals. Increasing SRT to more than 10 days can effectively remove more than 90% of the emerging compounds in sunscreens, and achieve approximately 80% removal of household chemicals. For hormones, the removal performances were not consistent, especially for 17α -eithinylestradiol, but the removal efficiency still improved with increasing SRT. For the other pharmaceuticals, with the exception of ibuprofen, removal efficiency was inconsistent, and may not be related to SRT. Ibuprofen is an illustrative example of the benefits of higher SRT; at one-to-two day SRT, which can easily meet traditional secondary treatment goals in warm climates such as Los Angeles, ibuprofen is poorly removed, if at all. At SRTs greater than five days, however, it is removed to detection limits.

Table 4 classifies the emerging contaminants into three groups: (1) contaminants that can be effectively removed at low to medium SRT; (2) contaminants that can be removed at high to extremely long SRT (15 to 200 days); and (3) contaminants that can only be partially removed or are not removed by ASP. The parameter SRT_{80} is defined as the lowest SRT to remove more than 80% of the emerging contaminants. Conventional ASP removes only 8 of the 38 selected emerging compounds in municipal wastewater, and operation at longer SRT can effectively remove 24 contaminants and partially remove 5 contaminants; only 9 contaminants were not removed. Notable exceptions are antibiotics such as tetracycline, trimethoprim, ciprofloxacin, roxithromycin, sulfamethoxazole, carbamazepine, and diclofenac; the fire retardant trichloroethyl phosphate and triphenylphosphate; tranquilizer diazepam; and X-ray contrast media iopromide. These contaminants might be candidates for improved source control or replacement.

Mechanisms for improved removal of emerging contaminants in ASP include sorption on biomass particles and biodegradation (Andersen et al., 2003; Carballa et al., 2004). Enhanced substrate removal through biodegradation at higher SRT is predicted by concurrent ASP models, but is often not observed experimentally. Part of the reason for lack of experimental evidence of improved removal at higher SRT is the use of BOD, which is far too imprecise to detect the differences in soluble effluent substrates among processes operating over the range of medium to long SRT. Standard methods provided by the American Public Health Association et al. (1998) reports the coefficient of variation for high concentration samples (180 to 220 mg/L BOD_5), which ranges from 5 to 17%, with the higher range being observed in multilaboratory comparisons. Soluble substrates in the effluents of high SRT processes may be 5 mg/L or less, which is at or below the detection limit for BOD. Babcock et al. (2001) used biodegradable dissolved organic carbon (BDOC) to show that effluent BDOC decreased with increasing SRT for both laboratory ASPs operating over a 2 to 15 day range, and for 21 full-scale plants surveyed in California and Hawaii (Khan, et al., 1998, 1998). Longer SRT operation reduces effluent soluble substrates.

In addition to measurements of BDOC, a novel technique to analyze the soluble microbial products (SMP) and effluent organic matter (EfOM) of ASP effluents is to measure the specific ultraviolet absorbance (SUVA) of the water samples (Jarusutthirak and Amy, 2007; Weishaar et al., 2003; Zhang et al., 2009). The $SUVA_{254}$, presented in the units of L/mg-m, was calculated as the ratio of UV absorbance at a specific wavelength (254 nm) divided by the DOC of the water sample. Weishaar et al. (2003) measured SUVA of various water samples and detected a positive correlation between $SUVA_{254}$ and the aromaticity of dissolved organic matter. Aromatic SMPs are generated from biomass decay and have been considered reactants of disinfection by-products (DBPs). Weishaar et al. (2003) suggested a weak, significant correlation between $SUVA_{254}$ and specific trihalomethane (THM) formation. Zhang et al. (2009) confirmed a linear relationship between SUVA of DOM and formation of DBPs in organic compounds recovered from reclaimed wastewater. These studies suggest a relationship between SUVA and DBP formation even though a conclusive model has not yet been developed.

Jarusutthirak and Amy (2007) measured the SUVA of effluent samples collected from sequencing batch reactors (SBRs) operating at different SRTs and wastewater treatment plants. Higher SUVA values were measured from SBRs operating at longer SRT (10 to 30 days) at the beginning phases (2 to 7 hours) of an SBR cycle. After a full SBR cycle (12 hours), DOC and SUVA showed no significant differences in the effluent of different SBRs. Yoon et al. (2009) measured the SUVA and DOC of batch-scale ASPs operating at different SRTs and found that SUVAs increased with increasing SRT. With the greater removal of DOC, however, the total UV absorbance of the same unit volume water samples are at constant. The study suggested no direct correlation between increasing risks of DBP formation in long SRT systems, especially in the range of 1 to 10 days. The correlation among SUVA, SRT, and DBP formation potential is of great interest for future research, especially if direct water reuse is considered.

Sorption onto biosolids is another removal mechanism. Ternes et al. (2004) and Carballa et al. (2004, 2005) studied the fates of emerging compounds in ASPs. Carballa et al. (2005) investigated the removal of three major types of emerging compounds (i.e., lipophilic, neutral, and acid compounds) using the coagulation-flocculation and flotation processes. Lipophilic compounds and molecules with positive charge or high sorption properties were better removed. Anaerobic digestion, perhaps the most common waste biosolids treatment process, can provide additional removal for biodegradable compounds, and create an opportunity for degradation using a different metabolism. Biosolids that are sequestered in landfills or are incinerated will permanently isolate the emerging contaminants. Biosolids that are composted undergo another opportunity for biodegradation, but composted biosolids are often reused as fertilizers or soil amendments, and may reintroduce contaminants to the environment. Removal by sorption onto biosolids is desirable but not as desirable as biodegradation. Increased SRT operation typically creates greater contact between wastewater contaminants and biomass, increasing the probability of sorption, as well as biodegradation.

Operation at longer SRT typically involves nitrification and denitrification. Ren et al. (2007) suggested that the degradation of estrone, estradiol, and ethinylestradiol are associated with the co-metabolisms of ammonia oxidizing bacteria, although Gulke

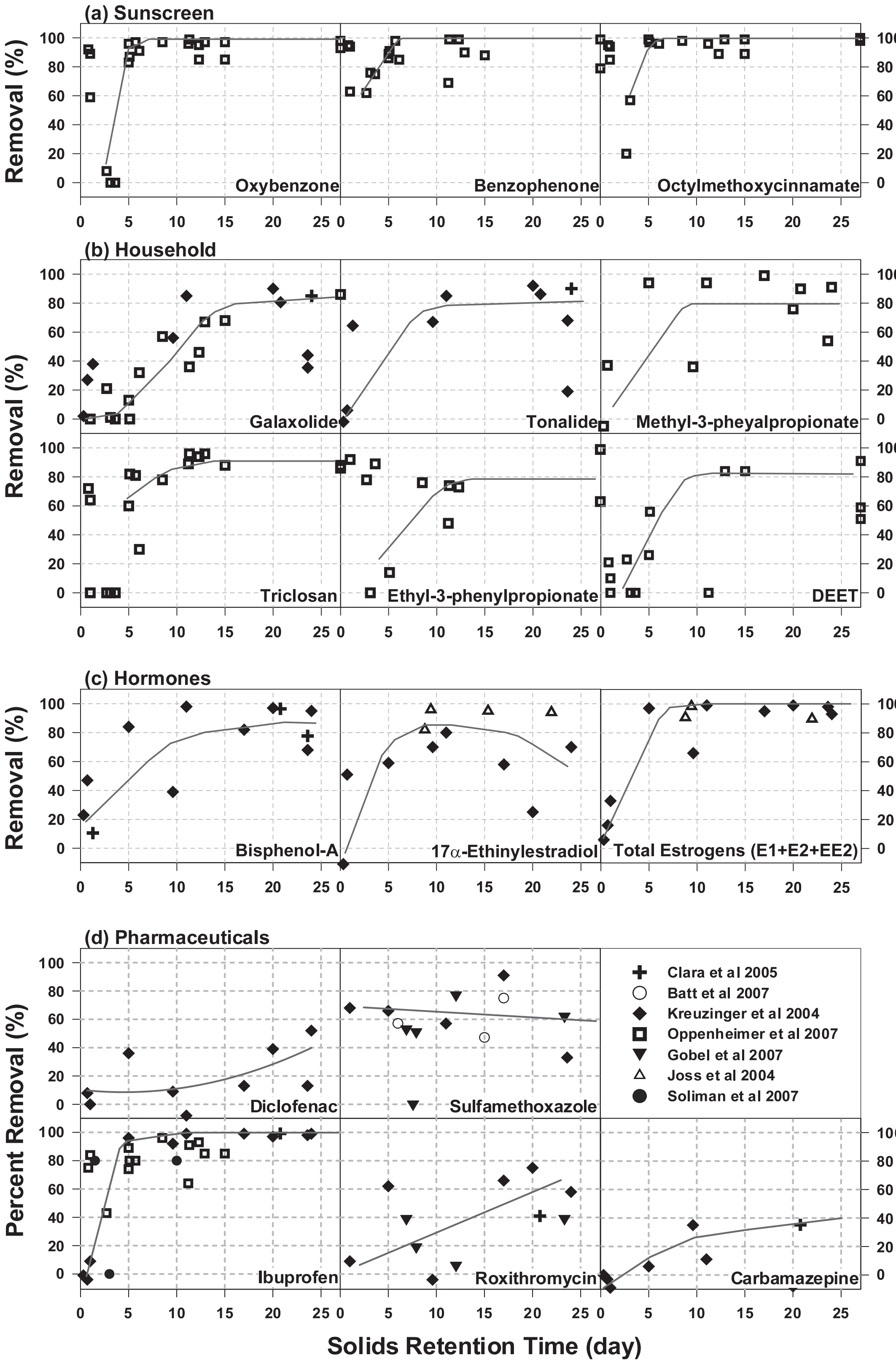

Figure 6—Removal of emerging contaminants at different solids retention time.

Table 4—Removal performance of emerging contaminants in wastewater treatment plants (WWTPs) (SRT = solids retention time).

Application	Compound name	SRT_{80}[1] (day)	Removal[2] (%)	References
Effectively removed components at longer SRT				
Anti-inflammatory	Ibuprofen	5	92–96	Kreuzinger et al., 2004
		5	43–96	Oppenheimer et al., 2007
		1.5	0–80	Soliman et al., 2007
Antioxidant	Methylparaben	1	86–98	Oppenheimer et al., 2007
Endocrine disrupting compounds	Bisphenol-A	5	39–98	Kreuzinger et al., 2004
	Nonylphenol	1	78–90	Clara et al., 2005
	Octylphenol	5-28	99	Oppenheimer et al., 2007
Estrogens	17α- Ethinylestradiol	11	25–81	Kreuzinger et al., 2004
	17β- Estradiol	9	93	Andersen et al., 2003
	Estrone	9	98	Andersen et al., 2003
Fragrance	3-Phenylpropionate	<5	63–99	Oppenheimer et al., 2007
	Ethyl-3-phenylpropionate	1	14–99	Oppenheimer et al., 2007
	Methyl-3-phenylpropionate	1	95–100	Oppenheimer et al., 2007
	Tonalide	11	67–92	Kreuzinger et al., 2004
Germicide	Chloroxylenol	5	15–99	Oppenheimer et al., 2007
	Triclosan	11	88–96	Oppenheimer et al., 2007
Herbicide	Clofibric acid	1.5	50–100	Soliman et al., 2007
Insect repellent	N,N-diethyl-m-toluamide	13	51–91	Oppenheimer et al., 2007
Lipid regulator	Bezafibrate	5	36–99	Kreuzinger et al., 2004
Pharmaceutical	Caffeine	1	79–100	Oppenheimer et al., 2007
		1.5	40–100	Soliman et al., 2007
	Carisoprodol	1.5	60–100	Soliman et al., 2007
Plasticizer	Butylbenzyl phthalate	1	20–97	Oppenheimer et al., 2007
	Benzophenone	1	62–99	Oppenheimer et al., 2007
	Benzyl salicylate	5	88–99	Oppenheimer et al., 2007
	Octylmethoxycinnamate	5	20–99	Oppenheimer et al., 2007
	Oxybenzone	1	83–98	Oppenheimer et al., 2007
Compounds removed at long SRT				
Antibiotics	Tetracycline	17	33–81	Batt et al., 2007
	Trimethoprim	15	68–97	Batt et al., 2007
		>200	74	Yu et al., 2009
Antioxidant	Butylated hydroxyanisole	28	56–99	Oppenheimer et al., 2007
Fragrance	Galaxolide	27	86	Oppenheimer et al., 2007
	Musk ketone	27	0–85	Oppenheimer et al., 2007
Compounds of partial removal or no removal at longer SRT				
Antibiotics	Ciprofloxacin	–	50–76	Batt et al., 2007
	Roxithromycin	–	0–75	Kreuzinger et al., 2004
	Sulfamethoxazole	–	33–75	Batt et al., 2007
		17	91	Kreuzinger et al., 2004
		>200	65–96	Yu et al., 2009
Antiepileptic	Carbamazepine	–	Poor	Kreuzinger et al., 2004
Anti-inflammatory	Diclofenac	–	3–69	Kreuzinger et al., 2004
Fire retardant	Trichloroethyl phosphate	–	0–50	Oppenheimer et al., 2007
	Triphenylphosphate	–	0–50	Oppenheimer et al., 2007
Tranquilizer	Diazepam	–	Poor	Kreuzinger et al., 2004
X-ray contrast media	Iopromide	–	25–50	Kreuzinger et al., 2004

[1] SRT_{80} = lowest SRT observed in WWTPs to achieve 80% removal.
[2] Ranges of percent removal recorded from WWTPs with SRT longer than SRT_{80}.

et al. (2009) have proposed a different explanation. Denitrification requires an anoxic reactor to be used in the process train, which provides a different metabolism and may improve biodegradation.

Process Modifications to Increase Solids Retention Time. This research has demonstrated the operational benefits of converting conventional ASPs to NDN processes, including improvements in effluent quality, plant operation, and oxygen transfer efficiency. Before converting a WWTP, however, capital improvements needs must be evaluated. Although conversion of an aerobic section of an aeration tank to an anaerobic or anoxic selector can be easily performed, the loss of aerated volume will reduce aerobic hydraulic retention time (HRT) and SRT. This may be especially important in cold regions, where low HRT can reduce nitrification capacity and result in ammonia breakthrough (Poduska and Andrews, 1975). Increasing SRT requires a greater amount of biomass, which can be achieved with greater MLSS concentration or increased aeration tank volume. Increased MLSS concentration increases solids-flux to the secondary clarifier. It is beyond the scope of this paper to evaluate the capital changes necessary to ensure reliable nitrification at upgraded plants. An analysis, however, is provided below to illustrate the potential needed process modifications using Plant I as an example.

The average water temperature of Plant I is approximately 20 to 22 °C. Table 1 shows the before and after process parameters of SRT and influent flow rate, and Table 2 shows the influent and effluent water quality parameters (BOD_5 and ammonia), MLSS, air flow rate per tank, aerobic HRT, and solids flux. The plant was able to perform reliable NDN operation at 80 to 85% of the preconversion flow rate (i.e., a reduction of 18 800 to 16 300 m^3/d). After conversion to NDN, the aerobic HRT decreased to 3.8 hours and the SRT of whole tank (aerobic and anoxic volumes) increased to 11 days. Because the size of anoxic section of Plant I is approximately 36% of the whole aeration tank, the aerobic SRT was approximately seven days, which is adequate to ensure reliable nitrification at these temperatures. The calculated critical or minimum aerobic SRT to prevent washout was approximately five days, based on typical reaction kinetics for nitrifying bacteria (Poduska and Andrews, 1975). Converting Plant I from conventional to NDN process, the aerobic HRT, including the effect of reduced wastewater flow rate, was reduced from 5.2 to 3.8 hours. No further modifications were required for tank size for the aeration tank or secondary clarifiers. Solids flux to the secondary clarifiers increased but did not require additional tankage because of improved settling and higher recycle rate. Plants II and III showed similar but modest effects on plant capacity.

At lower temperatures, the reduction in plant capacity or the need for capital expansion will be greater. At 10 °C, for example, the critical aerobic SRT increases to 11 days for full nitrification and to 17 days for the whole plant. To achieve critical SRT, MLSS concentration would increase from 3400 mg/L to approximately 4000 mg/L, which increases the solids flux to the final clarifiers by 18%, assuming the return activated biosolids flow rate does not change. A state-point analysis would have to be performed to determine if this increase is feasible. Alternatively, the volume of the aeration tanks would need to be increased by 18%, which means the aerobic HRT must increase from 3.8 hours to 4.4 hours. If existing tankage is not available, then capital improvements will be needed. Each case will be site specific and will depend on the temperature, influent wastewater quality, and conservatism of the original design.

An additional consideration, which is not quantified in the tables, is the effect of shock loading and variable process flow. Poduska and Andrews (1975) evaluated the effect of variable process inputs and showed that an increase in the critical SRT was needed to obtain reliable nitrification. Plants that practice step feed, perhaps to reduce the effect of shock or storm flows, may need to reevaluate their operating strategy (Stenstrom and Andrews, 1979). The configuration of the tanks with selectors and a modified aeration system may not accommodate step feed operation.

Conclusions

This study investigated the benefits of increasing SRT of activated sludge processes in additional to the need for ammonia removal. Increasing SRT improves several aspects of plant operation but the most significant is related to energy consumption. It has been assumed that increasing SRT from low to high and providing nitrification will more than double aeration energy consumption; experimental observations suggest, however, only a 30 to 50% increase based on site-specific conditions. This energy can be more than offset by energy savings associated with reduced biosolids production.

This study has also reviewed other benefits such as greater removal of emerging contaminants and improved biomass quality because of a reduction in the numbers of fine particles in the mixed-liquor and effluent. Wastewater treatment plants may be an important source of emerging contaminants to the environment. The literature results showed that low-SRT ASPs removed only 8 of 38 selected emerging contaminants in municipal wastewater. After increasing SRT to more than five days, however, 16 additional contaminants can be effectively removed (>80%) and 29 out of the 38 emerging contaminants are almost completely removed at SRTs higher than 17 to 28 days. The contaminants that can be effectively removed by increasing SRT include most estrogens, plasticizers, lipid regulators, germicides, and some pharmaceuticals. Some antibiotics, anti-inflammatory or fire retardants, X-ray contrast media, antiepileptic, and tranquilizers are not removed or are only poorly removed.

For some situations, plant modification by increasing either clarifier area or aeration tank volume may be required. This will be more severe in colder climates or when the initial design of the plant was less conservative. A site-specific analysis will be required. For plants in warm Southern California, increases in clarifier area or aeration tank volume have not always been necessary.

Acknowledgments

The authors thank Diego Rosso's comments and discussion; and Sheng-Chieh Wang for the literature review of emerging contaminant study. Shao-Yuan Leu is a postdoctoral fellow, and Michael K. Stenstrom is a Distinguished Professor in the Civil Engineering Department at the University of California, Los Angeles (UCLA). Licheng Chan was a Ph.D. candidate in UCLA when the research work was performed.

Manuscript submitted for publication February 28, 2011; revised manuscript submitted March 9, 2011; accepted for publication March 14, 2011.

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