WE&T
water environment and technology

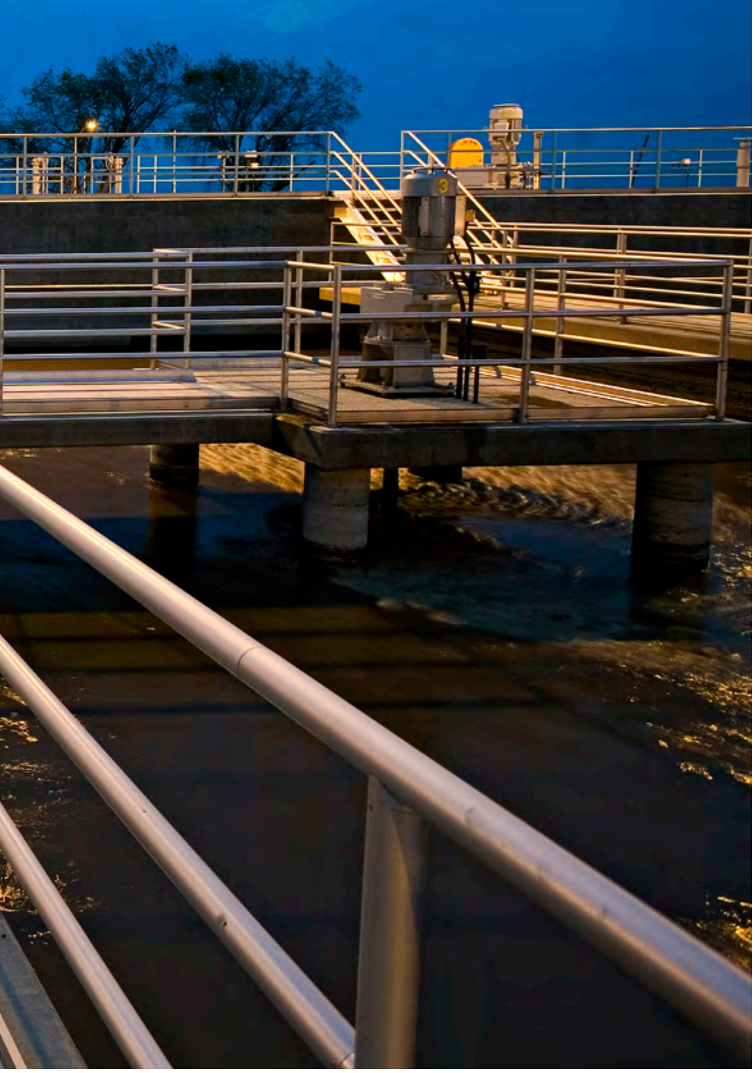
The oxidation index: a tool for controlling the activated sludge process

A common approach to controlling the activated sludge process involves adjusting the amount of biomass in the system according to season. As temperatures decline from summer to winter, operators usually try to raise mean cell residence time (MCRT), increasing biomass concentration to compensate for reduced bioactivity. The opposite is true from winter to summer. However, determining how much to increase or decrease MCRT is difficult. In part, the decision must be based on the wastewater treatment plant (WWTP) capacity – that is, the treatment power – required to adequately treat the influent wasteload.

This article evaluates the oxidation index (OXI), a relatively simple process control parameter that can be used as a basis for making such decisions. Furthermore, the authors relate this process to activated sludge settleability and compare three approaches for calculating a control parameter based on OXI. The goal is to develop a relatively simple model that operators may use to decide quickly how much treatment power to apply in order to achieve the desired solids settleability and effluent quality as cost-effectively as possible.

Three versions of a relatively simple process parameter can be used to determine the treatment power needed for particular wasteloads

Ronald G. Schuyler, Joseph R. Tamburini, and Steven J. Tamburini



Paul Cockrell

Analyzing treatment power

Activated sludge capacity is based on the size of the biological treatment tanks in use and the mass of microorganisms they contain. This capacity must be able to treat organic and ammonia loads applied to the tanks while developing an activated sludge that settles well. As the tanks deviate from optimal values, various environmental factors – such as dissolved oxygen (DO), temperature, and pH – reduce treatment capacity. Thus, treatment power required to meet effluent criteria is based on the hydraulic, organic, and nutrient loads of the influent and environmental conditions affecting the microorganisms.

Adequate treatment of carbonaceous biochemical oxygen demand (CBOD) requires a sufficient amount of microorganisms to feed on the CBOD. Another critical factor concerns the extent to which the resulting solids settle. Even though microorganisms may adequately convert CBOD, little overall treatment occurs if the resulting biomass cannot settle and be removed from the flow. Therefore, plant capacity relates to removal of organic and nutrient loads, as well as the system's ability to develop a settleable biomass.

Mathematical models estimate well the amount of biomass required to meet CBOD and ammonia limits. Based on these estimates, the concentration of microorganisms can be calculated. However, because the biology is complex, estimating settleability based on those parameters is quite difficult. Therefore, the models must assume satisfactory settleability. But what happens when solids do not settle well? Is a parameter or analysis available that could be used to predict the characteristics needed to achieve good settleability?

From a design standpoint, treatment power can be used to determine tank sizing and biomass requirements to treat design hydraulic and organic loads. However, from an operational standpoint, a slightly different question must be addressed. An operator must determine how much of the plant's existing treatment capacity to use to meet treatment demand at any time. If the operator does not use enough available capacity, effluent quality may suffer. However, using too much available capacity is costly and may result in poor effluent quality.

For WWTPs that must remove ammonia, a higher MCRT is required to enable the slow-growing nitrifying organisms, or nitrifiers, to proliferate. Furthermore, because they cannot store food, nitrifiers must complete the process of converting ammonia to nitrite and then to nitrate before they reach the aeration tank discharge point. Otherwise, the remaining ammonia will discharge in the effluent. Clearly, treatment power is related to availability of microorganisms and the time in which they have to function. This relationship is known as OXI.

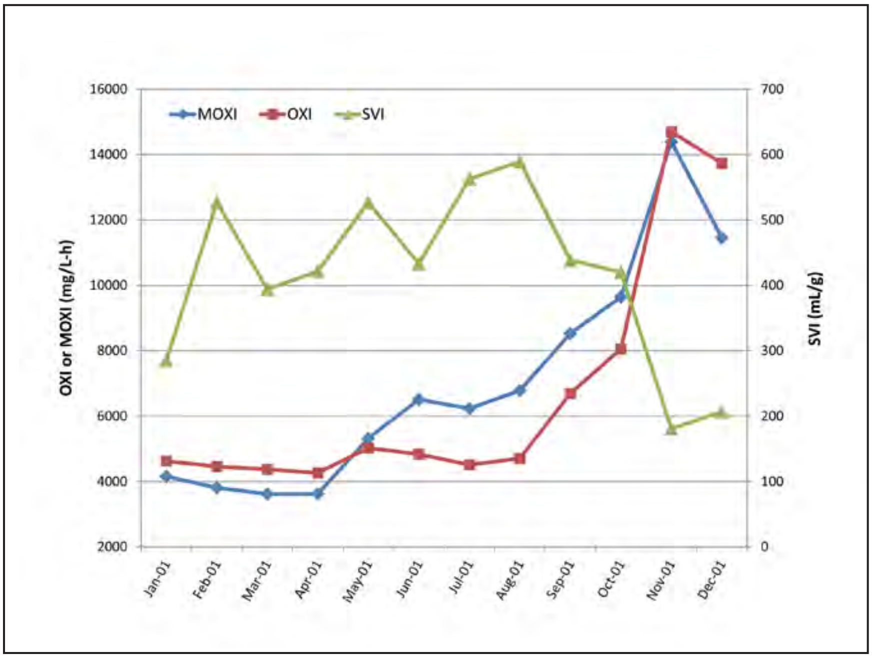
Oxidation index: The basic concept

OXI can be thought of as the treatment power provided by a WWTP at a specific time. Therefore, OXI must be equal to or greater than the treatment power required to treat influent load at that time. OXI, then, is defined by Equation 1 (see p. 6).

Of course, temperature, DO, and pH will affect microorganism activity. However, accounting for all these factors in the equation would complicate it significantly, reducing its usefulness to operators. Therefore, despite the difficulty of predicting specific results from this relationship over an extended time, the relationship may be valuable in predicting daily treatment capabilities, where variations in environmental conditions can be minimized from day to day. Many operators already have been using a version of this when varying MCRT with temperature.

To control OXI, one must control mixed liquor suspended solids (MLSS) and solids detention time in the aeration basin (SDT_A). MLSS is controlled through targeting MCRT and maintaining the target by wasting. However, changes in MCRT affect OXI relatively slowly unless major modifications in wasting or organic or ammonia loadings are involved. SDT_A, which is controlled by the

Figure 1. Fresno–Clovis short-term OXI, MOXI, and SVI



OXI = oxidation index.
MOXI = modified oxidation index.
SVI = sludge volume index.

return sludge flow (RSF) rate and the number of bioreactors on-line, responds to variations in influent flow rate. These variations can change OXI quickly. Major changes in OXI result when wasting and modifications to RSF are used together.

Modified OXI concept

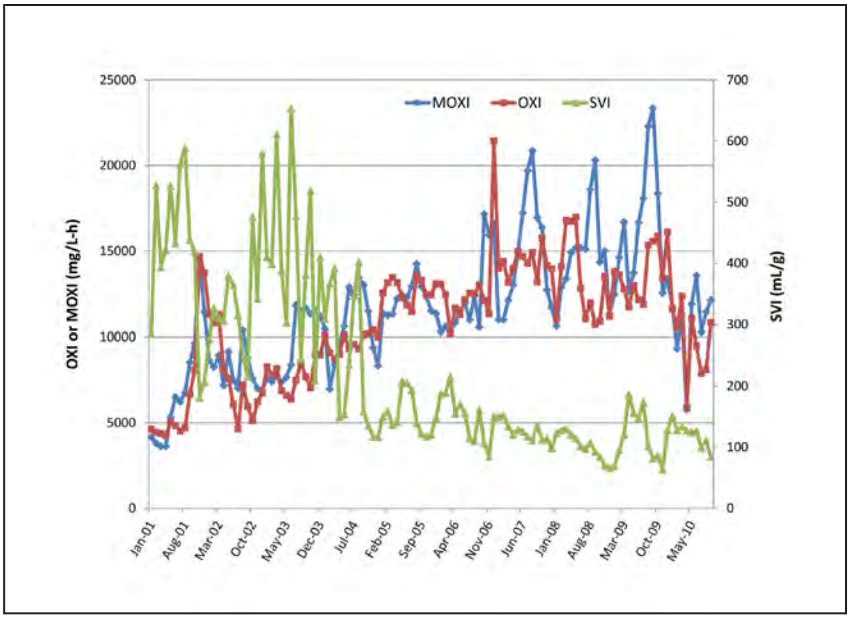
The basic OXI calculation accounts only for MLSS and SDT_A, raising the question of whether modifications could be made to better account for actual conditions while maintaining the relatively simple method for calculating OXI. The required mass of microorganisms is defined by the food-to-microorganism ratio (F:M), which is defined as the mass of CBOD removed by the available mass of microorganisms. The appropriate F:M depends on the desired solids settleability, effluent quality, system design, or environmental conditions. However, it is nearly impossible for a system to maintain the optimal narrow range of F:M because of the variability of influent loading and environmental conditions. Because MCRT is inversely related to F:M, MCRT often is used for process control.

As shown in Equation 2 (p. 6), MCRT is defined as the mass of microorganisms contained in an activated sludge system divided by the mass of microorganisms wasted per day intentionally and in the plant effluent.

Because MLSS concentration is related to mass in the aeration tank, it is related to MCRT and F:M. However, this relationship is not direct, because MCRT depends on biomass in the clarifier, as well as that in the aeration tank. Therefore, it is important to differentiate between mass in the aeration tank that is actually treating at any moment from that which is idle in the clarifier. However, over the course of a day, all organisms feed on the organic load and, therefore, must be included in the MCRT calculation and its related F:M.

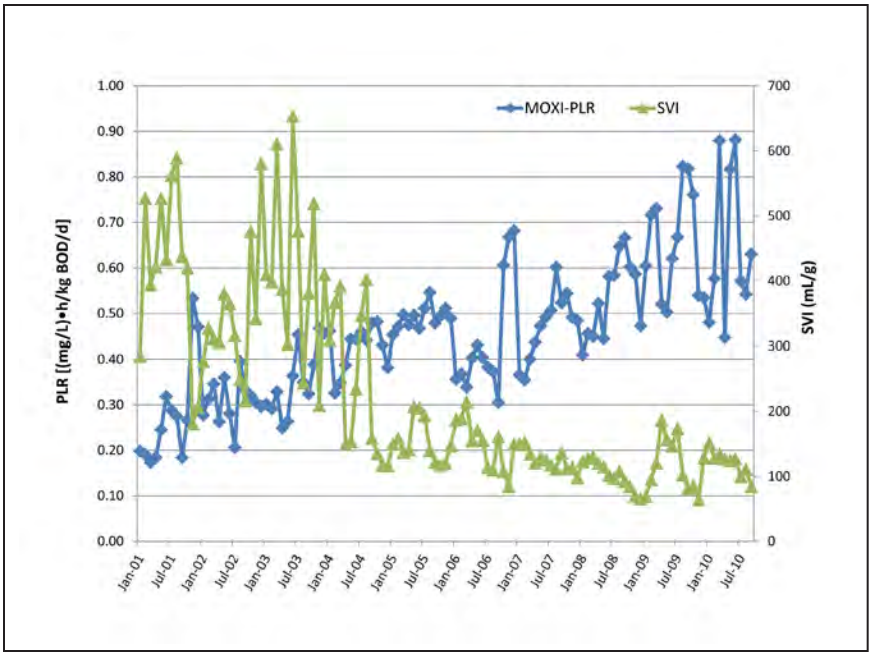
Because MLSS and mixed liquor volatile suspended solids (MLVSS) are proportionally related, either can be used in the MCRT calculation. Although active biomass concentration in an aeration tank relates more to MLVSS than to MLSS, MLVSS represents active microorganism mass, as well as dead cells, particulate biochemical oxygen demand (BOD), and other debris. However, because the volatile fraction typically does not change significantly unless MCRT changes significantly, MLVSS is only somewhat more representative than MLSS on a day-to-day basis. From the practical standpoint of an operator, volatility should be determined weekly. Then, the operator can determine MLSS using a total suspended solids (TSS) meter and multiply that value by the volatility to estimate MLVSS. Because MLVSS can be determined quickly this way, this discussion will use MLVSS as a representative estimate of the active biomass concentration. Therefore, OXI can be modified to provide a more representative value for treatment capacity by replacing MLSS with MLVSS as shown in Equation 3 (p. 6).

Figure 2. Fresno–Clovis long-term OXI, MOXI, and SVI



OXI = oxidation index.
MOXI = modified oxidation index.
SVI = sludge volume index.

Figure 3. Fresno–Clovis PLR and SVI



PLR = power-load ratio.
SVI = sludge volume index.

Treatment time and temperature

From a microbiological perspective, the mass of organisms available as related to MCRT and F:M must be considered in determining plant capacity. The time, in hours, under which organisms have to function in the bioreactor also is important. Known as SDT_A, this time also can be defined as the stabilization time – the time required for a particular MLSS concentration to feed on and completely stabilize BOD and, if applicable, ammonia. Except in step-feed systems, SDT_A is defined by the per-pass hydraulic detention time through the aeration tank as shown in Equation 4 (p. 6).

For a given MCRT and existing environmental conditions, a certain minimum stabilization time is needed. A stabilization-time test can be performed at the given aeration tank temperature and DO conditions to help identify the approximate time required to stabilize food ingested by the microorganisms. The test requires mixing appropriate volumes of return activated sludge (RAS) and aeration tank influent to provide an MLSS concentration equal to the MLSS in the aeration tank. The required RAS volume is given by Equation 5 (p. 6).

The appropriate amounts of RAS and influent are mixed and aerated until hourly oxygen-uptake testing shows the oxygen-uptake rate to be at its minimum continuous or endogenous rate. This test simulates actual aeration tank conditions and identifies the time required for the given microorganism concentration at the test temperature and DO to completely stabilize CBOD and ammonia, if nitrification is occurring. When compared to actual solids detention time in the aeration tank (SDT_A), the test indicates whether existing WWTP conditions will stabilize biomass completely before discharge to the clarifier.

The final factor to be applied to OXI is temperature, recognizing that DO, pH, or other issues must be considered individually if they deviate too far from "normal" conditions. For purposes of this article, the temperature factor, $\theta^{(T-20)}$, will rely on the Arrhenius Equation, which suggests that the chemical reaction rate approximately doubles with each increase in temperature of 10°C and is halved with each reduction in temperature of 10°C. To double the reaction rate with an increase of 10°C, the value of θ used is 1.0718, based on a temperature factor of 1.0 at 20°C. Equation 3 can be rewritten as the modified OXI (MOXI) to account for solids volatility and treatment temperature variations. See Equation 6 (p. 6).

Power-load ratio

Measuring the quantity of treatment power being applied may be considered only part of the equation. The remaining issue involves calculating the power-load ratio (PLR), which is the treatment power required to treat the incoming load divided by the mass of material to be treated. For treatment systems that nitrify, the mass of ammonia also may have to be considered in defining treatment power. Therefore, either Equation 7 or Equation 8 (p. 6) may be used, depending on whether nitrification is occurring.

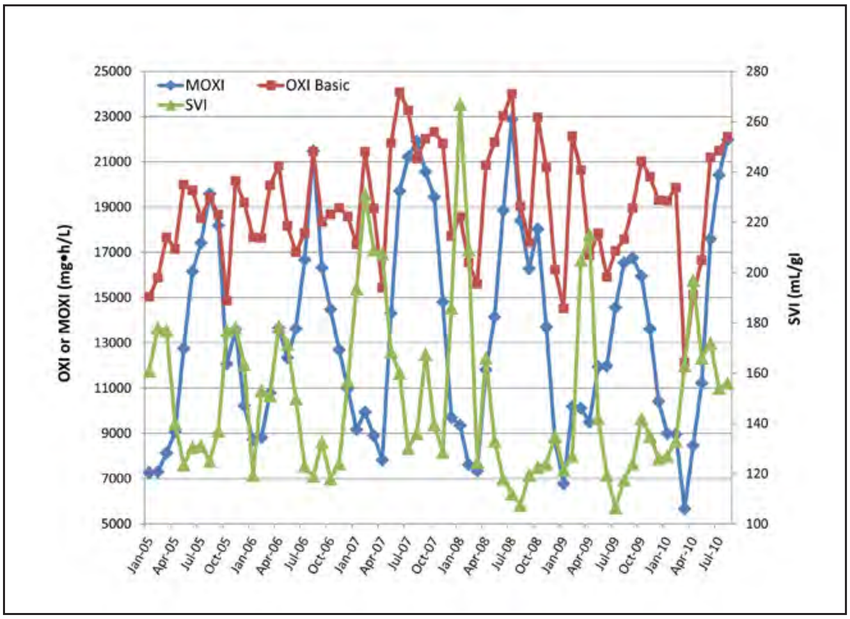
Several common parameters could be evaluated to determine the effect of changing OXI, including specific oxygen-uptake rate (SOUR), oxidation–reduction potential (ORP), soluble CBOD, and ammonia. SOUR would respond to OXI modifications by increasing when not enough OXI is applied and by decreasing when too much OXI is applied. This relationship is straightforward. ORP is not as easily used or understood, because the value depends on various factors, including what happens in aeration tanks and any anoxic areas. In other words, an observed ORP change may not correlate directly to a change in OXI. Soluble CBOD also is straightforward but is more useful from a historical perspective than for daily process control. Ammonia evaluation may be highly valuable, especially if on-line capability is present.

OXI and solids settleability

The authors were curious whether settleability responds to OXI control. Therefore, data were evaluated from two WWTPs to determine whether OXI correlated well with solids settleability. Sludge volume index (SVI) was used as the measure of solids settleability.

Both plants were evaluated to see how their historical process control approaches related to OXI, MOXI, and PLR. The first plant – the Fresno–Clovis (Calif.) Regional Water Reclamation Facility – had experienced severe increases in CBOD load because of activities outside its control. It continues to experience large seasonal changes in CBOD loads from the local agricultural economy. An OXI control approach was used to improve solids settleability under extremely high, variable organic loadings. The initial objective was to improve solids settleability and reduce high effluent TSS values, as total nitrification was not an issue. Meanwhile, the second plant studied – the Rockaway Valley Regional Service Authority (RVRSA; Boonton, N.J.) – receives consistent CBOD loads but is plagued by high wet weather flows. An OXI control approach was

Figure 4. Rockaway Valley Regional Service Authority OXI, MOXI, and SVI



OXI = oxidation index.
MOXI = modified oxidation index.
SVI = sludge volume index.

used to improve solids settleability and provide denitrification while maintaining full nitrification under variable, and overloaded, hydraulic conditions.

Fresno–Clovis' highly variable organic loading

In 2001, the Fresno–Clovis staff addressed a near doubling of CBOD load that occurred within 1 month. Before the drastic increase in organic load, operations staff used a very low MCRT to minimize nitrification and control significant clarifier denitrification. The high organic load prompted an extremely high rate of bacterial growth, disrupting settleability. Combined with typical filament growth associated with septicity or low-DO conditions, solids settleability became unmanageable in late August and September 2001. Historically, septicity-type filaments benefited from septic conditions related to long, low-velocity sewers and large primary clarifiers. Growth of low-DO filaments commonly occurred because of aeration limitations and attempts to minimize in-clarifier denitrification. This situation typically resulted in effluent from the aeration tanks having DO levels around 1.0 mg/L.

Addressing solids settleability required a three-pronged approach. First, to help control septicity, primary clarifiers were taken off-line to reduce detention time and potential for fermentation and production of organic acids and sulfide. Control of high-rate bacterial growth was more problematic. Increased OXI using higher MCRT was initiated to slow microorganism growth. However, the longer age of the solids was anticipated to increase nitrification and, therefore, increase in-clarifier denitrification. Therefore, low-DO control was initiated to reduce the nitrification rate and accomplish simultaneous nitrification/denitrification to protect secondary clarifiers from excessive denitrification.

The low-DO approach, which consistently maintained DO levels at approximately 0.1 mg/L for about 2 months, appeared to control excessive nitrification that spiked from higher MCRT. Surprisingly, this approach also appeared to reduce growth of low-DO filaments. Low DO levels seemed to provide enough anoxic condition to control low-DO filaments. Minimal in-clarifier denitrification enabled an immediate 60% increase in MCRT from 2.5 to 4.0 days and a 131% percent increase in MLSS, from 1507 mg/L in August to 3487 mg/L in November. At the same time, as shown in Figure 1 (p. 3), lower RSF was initiated to increase SDT_A and resulting OXI by about 20%. Low RSF also reduced the solids load to the clarifier and maintained a higher concentration of soluble CBOD at the head of the aeration tanks to promote growth of floc-forming organisms.

These actions enabled OXI to more than triple within 3 months and immediately had a positive effect on SVI while the system met required treatment standards. However, longer-term data show that while treatment requirements were met, various combinations of MCRT, OXI, and DO resulted in SVIs that cycled up and down (see Figure 2, p. 3). By October 2004, OXI had consistently increased to values greater than 10,000 mg/L•h, enabling SVI to be maintained at less than 200 mL/g. When OXI was converted to PLR, it was shown that maintaining PLR values greater than 0.15 to 0.2 SVI provided control, with SVI remaining less than 200 mL/g (see Figure 3, p. 4). This level of control continues today.

The Fresno–Clovis OXI and MOXI do not vary significantly because of minimal temperature differences between seasons and relatively consistent SDT_A resulting from regular hydraulic loads. Therefore, OXI or MOXI can be used equally well. However, because organic load is highly variable, a plot of PLR versus SVI clearly shows a significant relationship.

RVRSA's highly variable hydraulic loading

In 1999, RVRSA's extended-aeration oxidation-ditch treatment system exhibited poor solids settleability, resulting in higher clarifier blankets that continually taxed the system. High RSF required using three to four clarifiers to hold the 3-m or higher sludge blankets and avoid overtopping the weir. OXI was increased to develop properly settling mixed liquor. However, accomplishing this objective required controlling in-clarifier denitrification. Similar to Fresno–Clovis, sections of the oxidation ditch were run at low or no DO levels to denitrify mixed liquor discharged to the secondary clarifiers. To maintain nitrification with the loss of available aerated volume, RSF was reduced from approximately 2×flow to less than 1×flow. The extra SDT_A enabled both nitrification and denitrification to occur. This plant still uses the OXI approach, enabling the system to run in an overloaded condition with a 90th percentile F:M of 0.34 kg BOD per kilogram of MLVSS (0.34 lb BOD per pound of MLVSS) and space loading greater than 0.48 kg BOD/m^3•d (30 lb BOD per 1000 ft^3•d).

Available data from January 2005 through July 2010 were evaluated to determine how the process control approach used then relates to OXI and MOXI. While hydraulic load typically peaks between winter and early spring, the highest CBOD load occurs in summer, most probably influenced by a fruit-juice bottler whose maximum production during summer can place a substantial load on the plant. During wet weather, OXI and MOXI plummet because of colder temperatures and lower SDT_A caused by the drastic increase in influent flow rate and relatively high RSF needed to ensure optimal clarifier operation. RSF must be maintained at about 60% to avoid plugging clarifier collector tubes at lower percentages of RSF. SVI increases during these periods of low OXI and MOXI, all of which are associated with low PLR.

OXI and MOXI are affected significantly by the average daily flow rate, which seasonally spikes because of wet weather flows. While OXI remains much more consistent, holding between about 15,000 and 23,000 mg/L•h, MOXI varies radically between approximately 7000 and 23,000 mg/L•h. When SVI is compared to OXI and MOXI, it is easy to see that SVI responds inversely to MOXI (see Figure 4, p. 5). During winter, high influent flow rates significantly reduce SDT_A. Therefore, to maintain good nitrification, RVRSA increases MCRT. With higher MCRT, colder temperatures, and no primary clarifiers to remove grease, filamentous *Microthrix parvicella* may grow profusely and can increase SVI to greater than 200 mL/g. Although MCRT is raised to maintain nitrification during winter, PLR plummets because lower temperatures and lower SDT_A affect the MOXI. PLR also relates inversely to SVI quite well.

Equations

Equation 1

$$OXI = MLSS \times SDT_A$$

where
MLSS = mixed liquor suspended solids concentration, mg/L, and
SDT_A = solids detention time in the aerator (bioreactor) during one single pass, h.

Equation 2

$$MCRT = \frac{\text{mass in aeration tank} + \text{mass in clarifier}}{\text{mass wasted intentionally} + \text{mass wasted in clarifier effluent}}$$

Equation 3

$$OXI = MLVSS \times SDT_A$$

where
MLVSS = mixed liquor volatile suspended solids, mg/L, and
SDT_A = solids detention time in the aerator, h.

Equation 4

$$SDT_A = \frac{V_A \times 24\,\frac{h}{d}}{Q + RSF}$$

where
V_A = aeration tank volume, m^3,
Q = influent flow rate into aeration tank, m^3/d, and
RSF = return sludge flow rate, m^3/d.

Equation 5

$$\text{Volume RAS} = \frac{MLSS}{RSC} \times \text{total test volume}$$

where
MLSS = MLSS in aeration tank, mg/L,
RSC = return sludge concentration, mg/L, and
total test volume = combined volume of RAS and influent, mL.

Equation 6

$$MOXI = MLVSS \times SDT_A \times 1.0718^{(T-20)}$$

where
MLVSS = MLSS in aeration tank, mg/L,
SDT_A = solids detention time in aerator, h, and
T = mixed liquor temperature, °C.

Equation 7

$$PLR_{BOD} = \frac{MLVSS \times SDT_A \times 1.0718^{(T-20)}}{\text{kg (lb) BOD removed/d}}$$

Equation 8

$$PLR_{BOD + NH_3} = \frac{MLVSS \times SDT_A \times 1.0718^{(T-20)}}{\text{kg (lb) BOD}\,\frac{\text{removed}}{d} + \text{kg (lb) } NH_3\,\frac{\text{removed}}{d}}$$

Conclusion

The basic OXI concept was developed and modified according to temperature, solids volatility, and applied organic load. Data from two WWTPs were analyzed, each plant exhibiting a different loading pattern. OXI, MOXI, and PLR versus SVI were evaluated to see if a useful process control relationship existed. As it happens, the Fresno–Clovis and Rockaway data revealed strong relationships. The data showed that OXI, MOXI, or PLR could be used at Fresno–Clovis, while MOXI and PLR showed the best relationship at Rockaway. This data suggest that OXI, MOXI, or PLR may relate to SVI and can be used effectively as a process control tool. However, one of the OXI parameters may relate better than others at a specific WWTP.

Ronald G. Schuyler *is wastewater process technical lead for engineering and architecture services, and* ***Joseph R. Tamburini*** *and* ***Steven J. Tamburini*** *are project engineers in the Denver office of Tetra Tech Inc. (Pasadena, Calif.).*