TWENTIETH ANNIVERSARY OF THE REAL TIME SLUDGE AGE CONTROL

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ABSTRACT
Twenty years ago, the first wastewater facility implemented a real-time solids retention time (SRT) control system. Since then, such systems have provided the following benefits: an increase of plant capacity by as much as 30% due to the improved sludge settleability; foam reduction; decreased disinfectant usage due to lower secondary effluent TSS. Furthermore, SRT real time control automation led to up to 30 % reduction of aeration energy usage; reduction of polymer consumption by as much as on-quarter; and up to 90% decrease in process control related laboratory TSS tests. These improvements were realized by optimizing SRT targets to satisfy conflicting objectives and then reliably maintain these targets with ±2.5% accuracy.

Automatic SRT control software utilizes an activated sludge computer model, machine learning algorithms, and an advanced output data filtration module. A combination of these tools has been providing continuous improvements in both precision and reliability of the SRT control.

KEYWORDS: sludge age, solids retention time, SRT, SVI, bulking, foam control, activated sludge advanced automation, optimization of activated sludge, energy savings.

INTRODUCTION
Proper food-to-microorganism (F/M) population ratio is the most important parameter affecting the efficiency of an activated sludge system and health of the biomass. Sludge wasting using solids retention time (SRT) as the criterion is based on the fact that constant SRT leads to constant F/M.

The waste flow is usually a small fraction of the influent flow. However, minimal variations of waste flow over time may have a profound effect on the performance of an activated sludge system. Inadequate wasting may cause clarifier overloading, low F/M bulking, foaming, and increased air demand for biomass endogenous respiration. On the other hand, excessive wasting may result in poor removal of soluble pollutants, low D.O. bulking, and, in the case of nitrification, excessive chlorine demand due to inadequate nitrite removal. In addition, wasting also affects the sludge thickening process. Excessive wasting increases the load on the thickening facility and, more importantly, daily variation in wasted biomass results in excessive polymer consumption and reduces the efficiency of all types of sludge thickeners.

Adjustment of waste activated sludge (WAS) flow is based on calculations that utilize mixed liquor (ML) and return activated sludge (RAS) total suspended solids (TSS) concentrations. TSS concentration is conventionally measured by a gravimetric analytical method. Use of this routine for WAS flow calculation has the following problems:

- Due to influent and RAS flows variations, TSS concentration in a grab sample can be significantly different than the daily average concentration, resulting in daily waste calculations to be inaccurate.

- The frequency of sampling is usually restricted to once or twice a day due to extensive time and labor required for sampling and the gravimetric tests. Therefore, the waste sludge flow is calculated only once or twice a day, while the solids inventory and WAS concentration are constantly changing. As a result, the performance of the activated sludge system is not optimized.
- A gravimetric test takes 2-4 hours to perform. Consequently, the waste flow adjustment is always delayed by several hours causing an adverse effect on the performance of the activated sludge system.
- The average gravimetric test error for an individual sample is 5%. This poor accuracy and repeatability of the analytical tests cause inaccuracy in waste flow calculations.
- Mass solids loading on thickeners varies significantly, causing sub-optimized performance of sludge thickeners.
- Operators sometimes make errors in the tedious waste flow calculations, and that causes significant performance problems of the activated sludge system.

To overcome these problems, in 1996 the author developed a real-time SRT control system and implemented it at a Biological Nutrient Removal (BNR) facility of 170 MGD Daily Average Flow (Ekster,1997). Since then Ekster and Associates installed real-time SRT control systems at many plants throughout North America. This paper summarizes author's experience in designing and operating real-time SRT control systems.

METHODS AND MATERIALS

A basic SRT control system (see Figure 1) consists of two suspended solids meters, a controller, a waste flow meter, and a flow control element (a control valve or a pump with variable frequency drive).

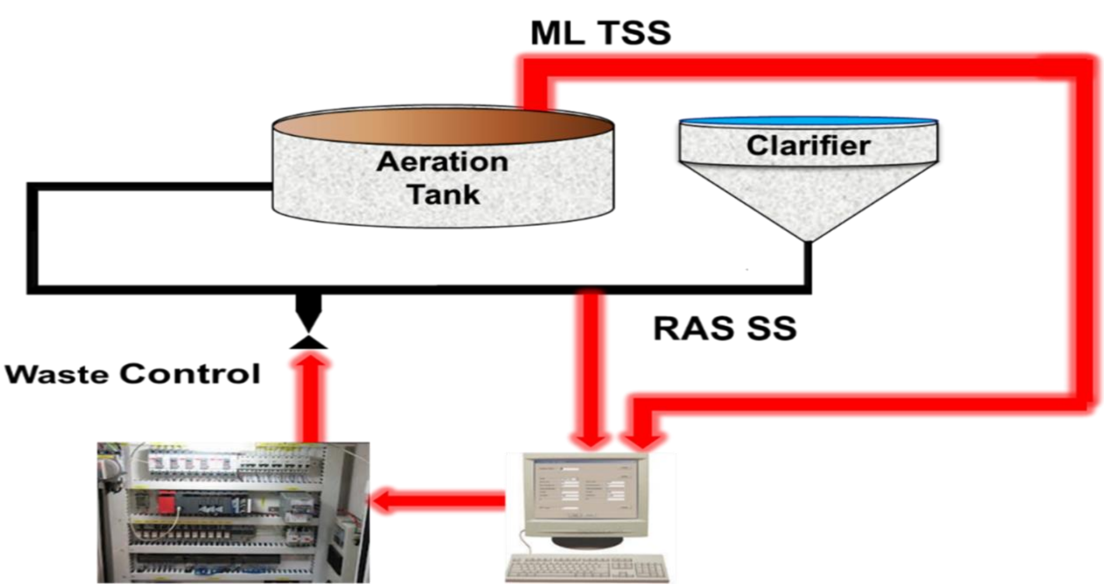

Figure 1. Schematic of the automatic solids retention time (SRT) control

Information from the suspended solid meters is sent to the controller; the controller then compares the operational criteria, such as mixed liquor TSS or the calculated real time sludge age, with the target value, calculates the necessary adjustment to the sludge waste flow, and sends a signal to the control element. Despite perceived simplicity of this control method, Ekster and Associates have experienced (and fixed) many pitfalls in their 20 years of implementing this control strategy. Below is the detailed description of each element of control scheme depicted in Fig.1 and their solutions to identified difficulties.

<u>Total suspended solids (TSS) meters/analyzers</u>. As it was shown in Fig.1, the real time solids retention time (SRT) control system uses the suspended solids on-line analyzers and waste flow meters. Suspended solids meters usually utilize optical technology. The major differences among TSS meters supplied by different vendors are wavelength, the number of light receivers and sensor cleaning methods. We did not observe any correlation between the number of light receivers and accuracy / repeatability of measurements. The absolute majority of suspended solids meters today utilize wavelength of near infrared spectrum of 880nm. The most significant difference among on-line analyzers is the method of automated cleaning of the sensors. Some vendors use mechanical wipers for cleaning (for example, HACH (Loveland, CO)), others use an ultrasonic method of cleaning (for example, Xylem (Yellow Springs, OH), or high-pressure air or water (for example, InsiteIG (Slidell, LA) and Cerlic Environmental Contol (Atlanta, GA)). Ekster and Associates (Fremont, CA) experience shows that TSS analyzers listed above perform well when they are installed in the open channel, wet wells, or sampling sink.

In-pipe TSS sensors installations proved to be significantly more challenging. For these installations, pipe flow always needs to be full; flow velocity, the distance from the inner wall of the pipe to the sensor and sensor installation angle need to meet vendor's design criteria; the self-cleaning system needs to be extremely effective, and meters need to have quick disconnect fixtures to provide an opportunity for manual cleaning. Ekster and Associates have many successful case studies with in-pipe TSS sensor installation, although our experience shows that success of this type of installations is not guaranteed, and not all TSS sensors installed in-pipe perform equally. An alternative to the in-pipe sensor installation was the construction of a small sampling sink open to the atmosphere, and placing a TSS sensor in the sink. The sink was connected to the pipe using a sampling line.

TSS meter calibrations originally were checked using laboratory data at least twice a week until SRT control software was enhanced and started to include an algorithm that automatically identifies TSS sensors drift. Since then the frequency of TSS meters calibration has been significantly reduced. Laboratory data used for TSS calibration of each on-line meter need to be extremely accurate. The grab samples need to be processed in duplicate or even triplicate for each on-line meter location to improve the accuracy of the gravimetric method. This protocol initially increased the workload on lab technicians because TSS concentration in grab samples needed to be analytically determined for each location of the permanent TSS meters. Improving accuracy of lab measurements without increasing lab technician's workload was achieved by purchasing a portable TSS meter supplied by the on-line TSS meter vendor, calibrating the portable meter using lab data, and using the portable meter to calibrate all on-line TSS meters. This protocol allowed for only one grab sample to be processed in duplicate/triplicate instead of processing samples from each on-line meter locations.

Waste Flow Meters. Waste flow meters usually use electromagnetic technology. These meters are usually extremely accurate if they are installed according to vendors' requirements. Unfortunately, in some cases, design engineers did not provide enough distance between the meter and elements of local hydraulic resistance (valves, turns, etc.). In these cases, accuracy and repeatability of flow measurements were significantly worse than guaranteed by the manufacturers. Reduction of accuracy and especially repeatability negatively affected the quality of SRT control.

Multiple Waste Streams. If there is more than one sludge waste stream, then flow and TSS were measured in each waste stream, and the mass of waste sludge was summarized. Sometimes an intermittently discharged waste stream (for example, intermittent foam discharge) is mixed with a continuous sludge waste stream. In this case, flow and TSS were measured before and after the point where the intermittent waste stream is mixed with the continuous waste stream.

SRT control algorithm. The SRT control algorithm consists of the following algorithm blocks: data verification, calculations, and a safeguard (Figure 2).

Figure 2. Waste control algorithm.

A data verification block filters out erroneous input data and determines a meter drift. A TSS signal filter algorithm utilizes a proprietary pattern recognition method that is based on non-parametric statistics, autocorrelation, and other machine learning techniques. Nonparametric statistics is used instead of traditional statistical models because TSS data usually are not normally distributed.

An activated sludge model is used for detecting TSS meter drift and alerting operators about the necessity to recalibrate TSS meters.

The data verification block also detects problems with waste flow control by analyzing in real time the performance of a waste flow controller. If a problem with either flow meters or any other waste flow control elements (pump, valve, etc.) is identified, the program sends an alert to operators.

Finally, a data verification block automatically alerts operators when either sludge inventory in aeration basins or mass of waste flow exhibits significant deviation from normal. These pattern changes could be symptoms of a significant change in of the influent BOD or a change in sludge inventory distribution between aeration basins and clarifiers, which may be caused by an increase of sludge blanket in the clarifiers.

A calculation block is the pivotal part of the algorithm. The calculation block utilizes the proportional-integral (PI) control law. Preliminary analysis of the waste control loop showed that it would require up to a year to tune the PI controller using a traditional ‘trial and error” method. To reduce the time of algorithm development and tuning, a computer GPS-X activated sludge simulator was utilized. The GPS-X model for each plant was calibrated using field data. A match between calculated and actual wastage was used as the criterion for the modeling. After model calibration, computer simulated response of the system with SRT feedback is utilized for the selection of both reset time (Ti) and proportional gain (Kp). The following criteria are used for designing the SRT controller:

- At a proportional gain equal to twice the Kp design value, waste rate values shall not start to diverge.
- The magnitude of each successive oscillation peak of waste rate values during a change should not exceed one-fourth of the previous peak.

Kp and Ti values were investigated for the range of potential SRT set points. Both upward and downward steps toward a target value were simulated. The selection of each pair of optimum Kp and Ti for each target value usually requires at least ten simulations. Based on the simulation, the relationship between Kp and SRT is determined for each activated sludge system.

The calculated waste flow signal is filtered using a low-pass filtration algorithm also utilizing non-parametric statistics; then the signal is sent to a safeguard block. The purpose of this block is to check that the waste flow calculated by the controller will not have a negative effect on the Plant processes. Before the output signal is sent to the flow control element, the safeguard block checks whether new sludge waste flow may cause one of the following problems: a)overload of clarifiers, b) overload of sludge processing facility, c) underload of sludge processing facility, d) excessive variation of waste flow (load), or e) excessive change in biomass inventory. If any of the above conditions are identified, the waste flow output signal is automatically corrected to avoid these problems. Also, a waste flow output signal is corrected using a proprietary algorithm when minimum variability of waste mass over 24 hours was beneficial for the waste sludge processing facility (DAF, gravity thickeners, etc.).

<u>SRT controller hardware and communication with SCADA.</u> Due to the complexity of the above calculations, Windows-based personal or industrial computers were used to process the SRT control algorithm. Computers communicate with plant SCADA using the OPC communication protocol.

RESULTS

Performance of the automatic SRT controller. Results show that SRT was maintained within 5% of the set point; most of the time SRT is within 2.5% of the set point. Typical performance of the controller is shown in Figure 3.

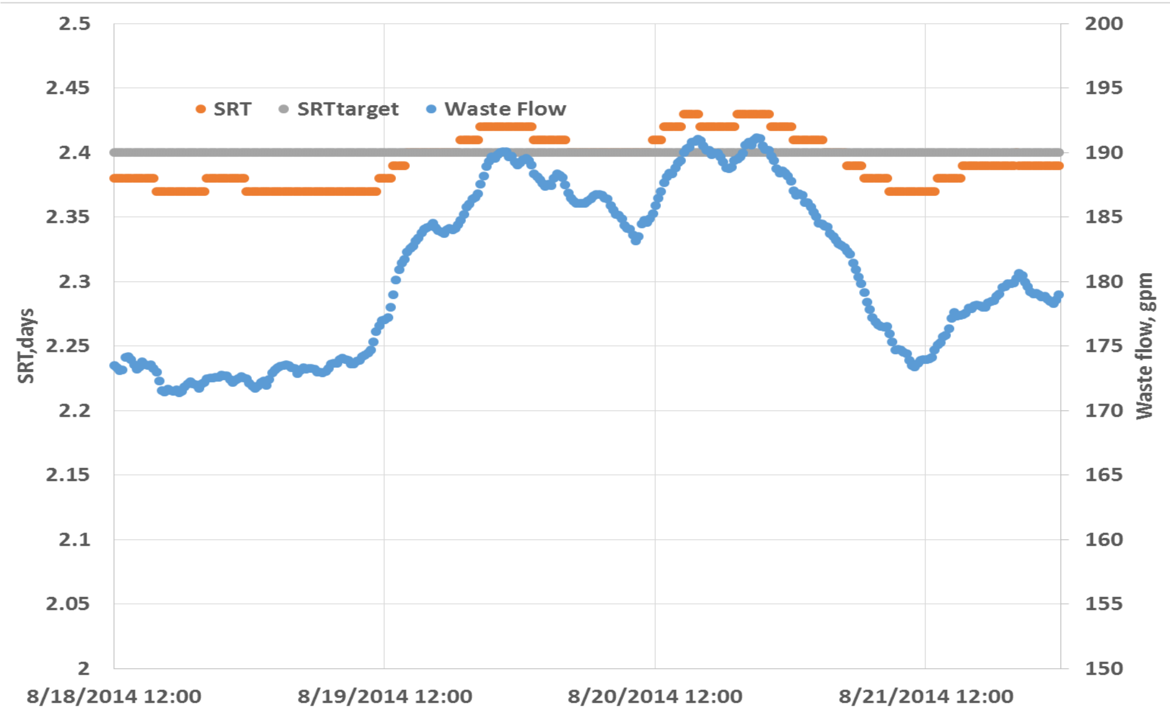

Figure 3. Typical performance of the SRT control system.

Ekster and Associates' proprietary stability waste mass algorithm has successfully reduced the variability of the mass of the wasted sludge. Daily variability of the mass of wasted sludge typically was reduced from 23% of daily average to just 3% (Ekster, 2001).

In 20 years there have been no recorded incidents of the controller using erroneous input signals. TSS and flow meters, as well flow controller problems were always timely identified and the software always automatically initiated operators' alerts that included troubleshooting tips. After implementing a real-time SRT control combined with automatic meters drift detection algorithm, the frequency of TSS meters calibration was reduced from at least two times a day to 1-3 times per month, yielding considerable reduction of workload.

The safeguard module successfully changes the waste flow calculated by the calculation block to the flow set point that prevents overload of clarifiers and thickening facilities or violation of the mixed liquor concentration range established by operators.

Treatment process improvements

Table 1 depicts case studies with the results typically achieved by optimizing SRT and automating SRT control.

Table 1. Typical Results of the SRT Control Optimization and Automation

Plant	Flow, M3/d*1000, (mgd)	Process	Recorded Improvements
BELLINGHAM WWTP	53(14)	Conventional AS	SVI reduction, 25% increased secondary treatment processing capacity
VICTOR VALLEY WATER RECLAMATION AUTHORITY	68(18)	BNR	SVI reduction, 30% increased BNR treatment processing capacity
SACRAMENTO REGIONAL WWTP	685(181)	Pure oxygen	Foam control, effluent TSS reduction, disinfection improvements
EBMUD WWTP	303(80)	Pure oxygen	Improvements of sludge settleability, foam control
Oxnard WWTP	121(32)	Trickling filter-Solids contact	SVI reduction, foam reduction, 25% energy and polymer reduction
SAN JOSE REGIONAL WPCP	643(170)	BNR	Foam control, improved nutrient removal, SVI reduction

DISCUSSION

In this section, we will try to explain the theoretical fundamentals behind the improvements reported in the results section of this paper.

Control of low DO/High F/M is bulking. Bellingham WWTP (53,000 m3/d, (14 mgd) capacity), Bellingham, WA, was originally designed as a pure oxygen plant. For several decades the plant experienced bulking problems caused by low DO filaments that are often found at low SRT environments. Approximately ten years ago the plant started using an anaerobic selector and SVI has improved, although sporadic increases of SVI were still observed. Recently the plant was converted to a conventional activated sludge system. This conversion, while providing many benefits, did not eliminate the periodic increases of SVI. After installation of the automated SRT control system and optimization of SRT set points for each season, the stability of SVI has considerably improved. Figure 4 illustrates an increase in the secondary treatment capacity due to SVI reduction after each plant upgrade. As it can be seen from this chart, optimization of SRT and automation of the SRT control increased this capacity by 25%.

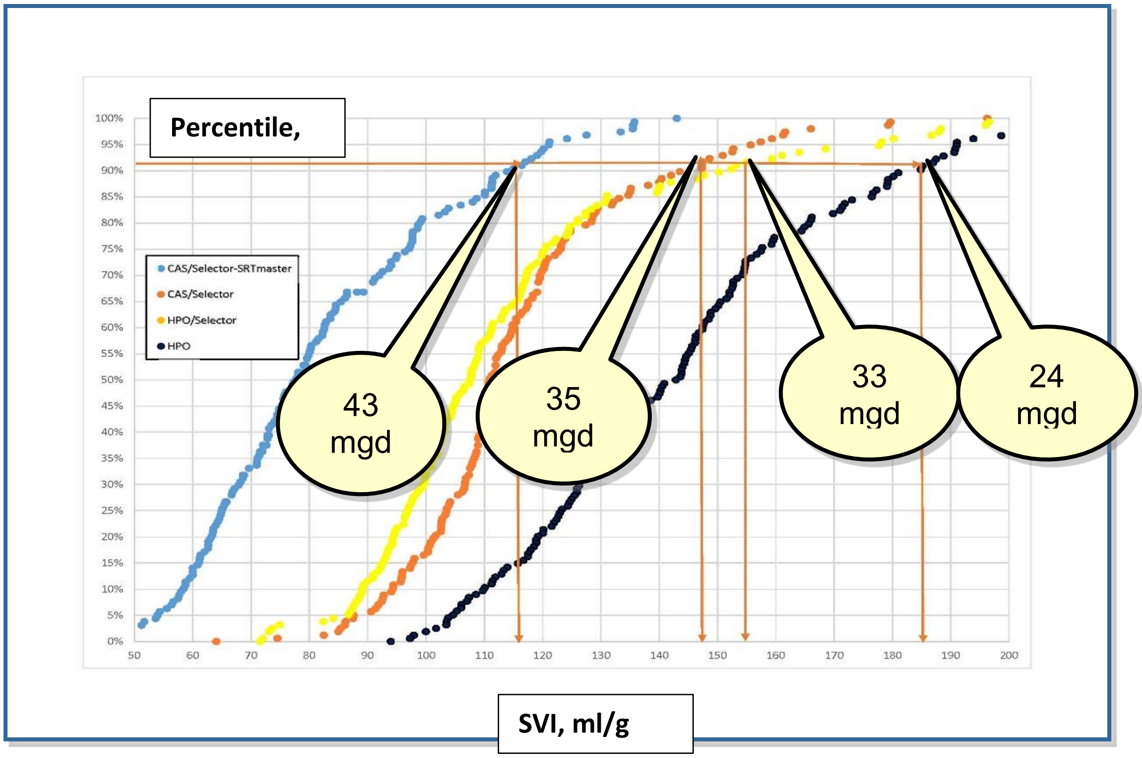

Figure 4. Effect of Bellingham WWTP process improvements on secondary treatment capacity

Following the implementation of SRT control, 92nd SVI percentile reduced from 148ml/g to 115ml/g. We believe that this SVI reduction was achieved by improving precision of SRT control five-fold, wherein the average control error was reduced from 0.5 days (15% of the set point) to 0.1 days (3% of the set point). Confidence in the precision of SRT control allowed an increase of aerobic SRT target just above the minimum required for phosphorus removal, but still below the minimum required for growth of nitrifying microorganisms. As it can be seen in Figure 5, only a very narrow range of SRTs satisfies both criteria.

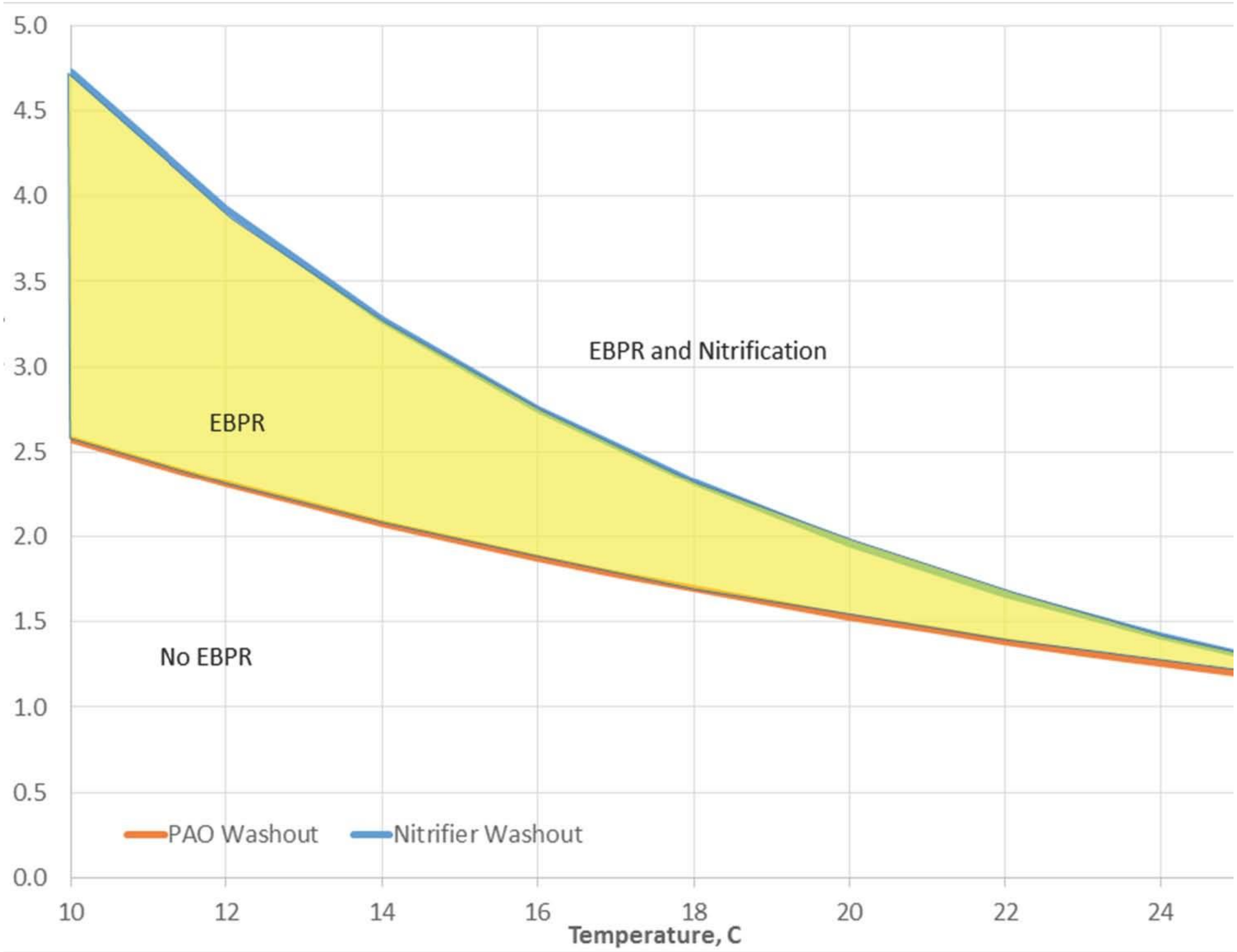

Figure 5. Effect of temperature on minimum SRT required for growth of PAO and nitrifiers.

Polyphosphate accumulation organisms (PAO) start to compete successfully against filamentous organisms and, as a result, sludge bulking was avoided throughout the year. Before the implementation of automatic SRT control, aerobic SRT was often set below 2 days to avoid nitrification, thus resulting in conditions that did not favor PAO. Therefore SVI was often elevated, especially in the summer.

Control of low F/M bulking. Victor Valley Reclamation Authority (VVWRA), a 68,000m3/day (18 mgd) capacity BNR Plant, experienced frequent low F/M bulking associated with long SRT. After installation of the automatic SRT control system and seasonal optimization of sludge age, SVI 95th percentile was reduced from 225 ml/g to 138 ml/g (Ekster et al., 2014). Fig. 6 llustrates a 30% increase of the BNR treatment capacity due to SVI reduction.

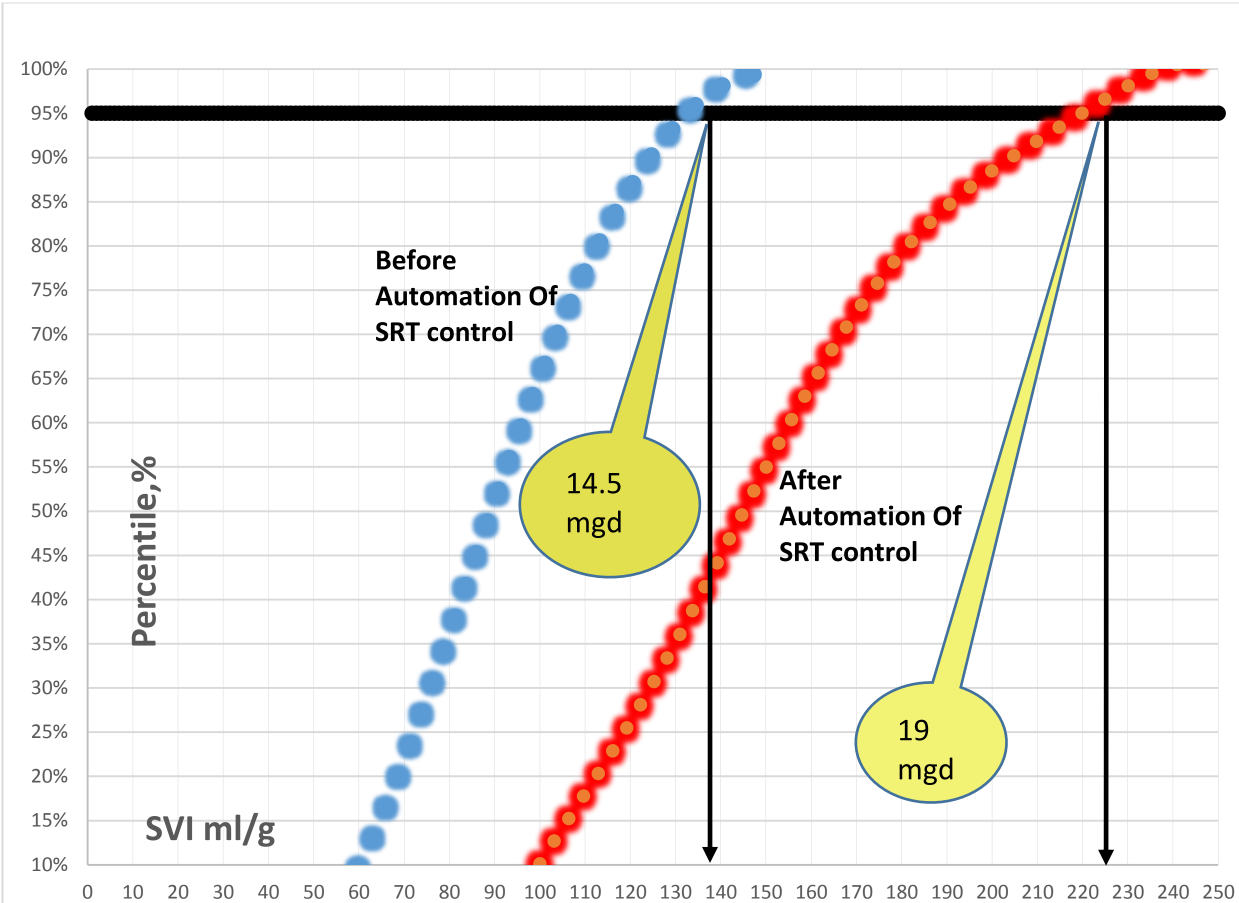

Figure 6. Effect of process improvements on VVWRA BNR capacity.

Automatic SRT control has improved SVI because the precision of SRT control has improved six-fold with the average control error reduced from 0.9 days / 15% of the set point to 0.15 day / 2.5 % from the set point. The precision of SRT control allowed the reduction of SRT set point to be just above the minimum required for stable nitrification, but below the minimum needed for growth of low F/M bulking organisms. Before implementation of automatic SRT control, sludge age was often raised above the minimum required for growth of low F/M filaments, thus causing an SVI increase.

Foam control. Sacramento Regional Sanitary District's Wastewater Treatment Plant (685,000 m3/d (181 mgd) capacity pure oxygen plant in Elk Grove, CA), has been experiencing significant *Nocardia* foaming every summer for many years. Ever since automatic SRT control was implemented, sludge age was seasonally optimized, and SRT was maintained on average at 5% from the set point, *Nocardia* foaming incidents have been significantly reduced (Boyce et al., 2011). As a result, frequency of digesters' covers cleanings and step screen cleanings have been decreased considerably, saving the plant significant O&M costs. Similar successes in foam control have been achieved at the 643,000 m3/d (167 mgd) BNR San Jose/ Santa Clara Regional Wastewater Facility, San Jose, CA (Ekster and Jenkins, 1998), at the 121,000 m3/d (32 mgd) Oxnard wastewater treatment plant utilizing a trickling filter-activated sludge process (Moise, 2005), at the San Francisco Public Utility Commissions' 243,000 m3/d (65mgd) pure oxygen, Oceanside wastewater treatment plant (Miot, 2016), and at the East Bay Municipal District 303, 000 m3/d (80 mgd) pure oxygen plant (Dickinson, 2015). The improved precision of the SRT control allowed for the reduction of SRT set point below the minimum required for proliferation of *Nocardia*, but above the minimum required for producing effluent in compliance with NPDES limits.

Effluent quality and disinfection improvements. 45,000 m3/d (12mgd) Chico wastewater plant, Chico, CA operates a nitrification process. The plant has been experiencing high turbidity caused by pin floc. Intermittent nitrification problems were also recorded. Both these problems resulted in an increase of chlorine dosage and, in some cases, an increase of coliforms above the NPDES limit.

After installation of the automated SRT control system and optimization of SRT set point for each season, the frequency of these problems was significantly reduced leading to the reduction of chlorine dosage; NPDES limit violations were eliminated completely. The optimized and precisely controlled SRT was long enough to achieve stable nitrification, but was still below the minimum required for developing pin floc. Similar success with water quality improvements by reducing incidents of pin floc was observed at the Topeka WWTP. Significant chlorine dosage reduction resulted from the improved effluent quality at the Sacramento Regional WWTP and saved the plant over $100,000/year in operating costs.

Polymer savings. Installation of the automatic SRT control system at the Oxnard trickling filter/activated sludge plant allowed to achieve 25% reduction in the polymer used for sludge thickening (Moise, 2005). Similar results have been achieved at the Chico WWTP and other treatment facilities that use polymer for sludge thickening. Savings were achieved due to a significant reduction in variability of sludge mass loading on thickening facilities. As it was discussed in the Methods and Materials section, Ekster and Associates' proprietary algorithm within the automated SRT control software provides the stability of sludge wasted mass.

Energy savings. SRT optimization and precise control can save energy. It is a well-known fact (Biological Wastewater Treatment, 1999) that an increase of SRT at a conventional activated sludge plant above the minimum required for nitrification can increase energy demand by as much as 100%. A 25% energy saving was reported at the Oxnard tricking filter-solids contact plant after optimization and automation of DO and SRT control (Moise, 2005, Moise, 2007). Savings were achieved by reduction of both SRT and DO set points and precise SRT and DO control.

Ekster and Rhoda, 2003 and Ekster, 2004 provided an example of a case when SRT increase combined with the reduction of DO and improvements of the SRT and DO controls led to a 20% energy reduction at a BNR plant. A simultaneous increase of SRT and reduction of DO combined with precise maintenance of the DO and SRT set points produced 10% energy savings at the BNR San Jose/Santa Clara WPCP (In Plant Optimization Report, 1998).

CONCLUSIONS

Optimization of sludge age and precise maintenance of an SRT target using real-time control provides the following benefits:

- reduction of SVI that led to as much as 30% increase of plant secondary treatment capacity;
- significant improvements in foam control;
- effluent quality improvements leading to reduced chemical usage for disinfection (chlorine);
- up to 25 % in aeration energy savings;
- up to 25% in polymer savings;
- reduction of TSS gravimetric tests by as much as 90%.

Optimization and automation of SRT were beneficial for the following types of activated sludge processes: conventional activated sludge, pure oxygen activated sludge, trickling filter-solids contact, and biological nutrient removal. Process improvements were realized by selecting SRT targets that satisfied conflicting objectives and by reliably maintaining these targets with the ±2.5% accuracy.

Excellent performance of the SRT controllers was achieved by combining advanced pattern recognition, data verification, use of model-based output filtering modules and the utilization of activated sludge models for the design of the control algorithm.

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REFERENCES

Biological Wastewater Treatment: Theory and Applications, edited C.P. Leslie Grady Jr., Glen T. Daigger, HenryC.Lim, Marcel Dekker, 1999.

Boyce, J., Nurmi, J.,2011. Automating Control in Biological Reactors for Diurnal Loadings. Proceedings of WEFTEC, Conference and Exposition, Los Angeles, CA.

Dickinson, K., 2015. Personal Communication.

Ekster, A., Colby, S., Corcoran, B., Karpe, 1997. Automation of waste control. Proceedings of WEFTEC, Conference and Exposition, Chicago, IL.

Ekster A., 2001. Automatic waste control. Proceedings of the 1st IWA International Conference on Instrumentation, Control and Automation. Malmö, Sweden.

Ekster, A. and Rodríguez-Roda, I., 2003. The effect of sludge age on the operation cost of activated sludge systems. Proceedings of WEFTEC, Conference and Exposition, Chicago, IL.

Ekster, A., 2004. Golden Age, Water Environment Technology, Volume 16, No. 6, June 2004, page 62-66.

Ekster A, Perez G, Ods L., 2014. Sludge Settling Improvements at the 18-MGD BNR Facility, Presentation at the annual California Water Environment Association Conference, Santa Clara, Ca.

In Plant Optimization at the San Jose/Santa Clara Water Pollution Control Plant, 1998. Report, City of San Jose.

Miot Alexandre, 2016. Personal Communication.

Moise, M., Norris, M., 2005 Process Optimization and Automation Improves Reliability and Cost Efficiency of Oxnard WWTP, Proceedings of WEFTEC, Conference and Exposition, Washington, DC.

Moise, M., Ekster, A., 2007 Operation of a Solids Contact Tank at Low Dissolved Oxygen and Low Total Suspended Solids Concentrations, Proceedings of WEFTEC, Conference and Exposition, San Diego, CA