Process Automation Significantly Reduces Secondary Treatment Costs

Introduction

A U.S. water authority collaborated with Emerson to automate control of the secondary treatment process at their wastewater treatment facility. Due to high process variability under existing manual controls and a strong correlation with excessive oxygen utilization, control of the aeration basin mixed-liquor depth and the effluent dissolved oxygen (D.O.) concentration were identified as the main targets for automation.

The introduction of automated balancing of mixed-liquor effluent flow in response to upstream process adjustments achieved a 74% reduction in day-averaged mixed-liquor depth interquartile range (IQR). Subsequent automation of aeration basin oxygen feed controls reduced variation in the day-averaged effluent D.O. IQR by as much as 59%. Annual oxygen usage in the secondary treatment process was reduced by 30%, resulting in a substantial annual oxygen cost reduction of $1.01 million per year at 2019 rates.

This white paper presents a summary of secondary treatment automation at the plant and details the impact on key process metrics.

Background

The reference plant has primary and secondary treatment capacities of 1700 and 930 million gallons per day (MGD), respectively. The facility's secondary treatment equipment consists of four high-purity oxygen aeration basins (A1, A2, A3, and A4) along with 25 circular clarifiers (Figure 1, Figure 2).

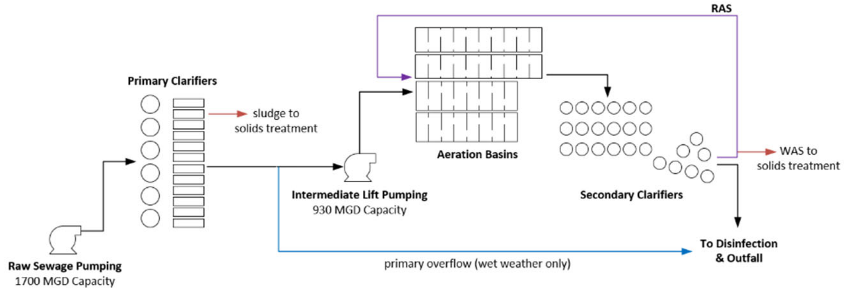

Figure 1: Liquid process treatment flow depiction.

Each aeration basin has a volume of approximately 17.8 million gallons. Flow to the basins is supplied by lift pumps, with the flow rate to each basin determined by upstream process demands. The basins are arranged in parallel, with three of the four basins in service at a given time. Each basin operates at an average influent flow of 226 MGD, with peak flow at 310 MGD per basin in wet weather. Return activated sludge (RAS) from the secondary clarifiers flows into the head of each basin is between 40 to 50 MGD. Flow meters measure the influent and RAS flow to each basin.

Internally, each of the four basins is segmented into ten (A1 and A2) or eight (A3 and A4) bays arranged in series from influent (bay 1) to effluent (bay 8 or 10). The bays within each aeration basin are connected via staggered openings that produce a snaking mixed-liquor flow pattern. Typical detention times are between 1.2 and 2.2 hours.

Wastewater depth is measured in real-time by differential pressure transmitters located in each basin. Each basin has a sidewall depth of 34’ and operates with a mixed-liquor depth of approximately 30’ (112.1’ elevation).

The oxygen necessary for microbial digestion of organic material is supplied from a common source line which divides to enter the headspace (i.e. above the waterline) of each basin at bay 1. Each basin is equipped with a butterfly valve and motorized actuator, allowing for independent oxygen flow rate control. Oxygen flows are measured at the common supply and at the feed valve to each basin.

Surface aerators with submerged mixer impellers (i.e. mixers) serve to transfer headspace oxygen into the liquid, increase contact between the microorganisms and organic matter, and promote a D.O. profile that is uniform through the depth of each bay. The D.O. content of the mixed-liquor is continuously measured by a luminescent dissolved oxygen probe submerged below the waterline of each basin’s final bay. Each bay in A1 and A2 is equipped with up to two mixers, while the bays in A3 and A4 have up to four mixers each. All available mixers are operated continuously to ensure adequate oxygen transfer throughout the length of each basin. Each mixer’s current and load are continuously monitored as indicators of mixed-liquor depth control upsets. Increasing (decreasing) current and load are indicators of rising (falling) depth.

To maximize headspace-to-liquid oxygen transfer, the mixed-liquor surface must make sufficient contact with each aerator blade. At low mixed-liquor depth, the blades do not sufficiently contact the liquid, while at high mixed-liquor depth, the blades can be submerged below the liquid. Either condition produces poor oxygen transfer (Figure 3) and high variation in the measured effluent D.O. concentration.

For optimum biological growth and digestion of organic material, the effluent D.O. concentration of each basin must be maintained between two to four mg/L. Low D.O. concentrations promote the growth of undesired (filamentous) bacteria, while high D.O. due to over-supply of oxygen is an indicator of excess process costs.

Operation within the target D.O. concentration range requires both precise control of the mixed-liquor depth, and appropriate flow of oxygen into the headspace of each basin. While the motorized oxygen-flow valves provide a direct means of controlling the oxygen flow to each basin, control of the mixed-liquor depth is indirect, relying on the modulation of the total flow into the secondary clarifiers.

Gravity drives flow from the aeration basins (surface elevation ~112’’) into the secondary clarifiers (inlet elevation 92.3’’) through shared discharge channels. Each of the 25 secondary clarifiers (combined surface area = 785,000 ft2, average influent flow = 27 MGD per clarifier) is equipped with a motorized butterfly valve enabling control of the influent flow rate. The clarifiers are each equipped with a RAS pump that recirculates settled sludge to inflow channels leading to bay 1 of each aeration basin. Typical RAS flow rates (per clarifier) are between five and six and a half MGD. Dedicated magnetic flowmeters provide a measurement of each clarifier's influent and RAS flows.

Before automation, the secondary clarifier influent valves were operated in a leader-follower mode, with manual adjustments made 'as needed' to a single lead clarifier mirrored by the follower clarifiers. The timing, magnitude, and direction of clarifier valve adjustments were determined based on several factors including the upstream (primary) flow, mixer currents and loads, aeration basin mixed-liquor depths, and anticipated process changes. Effective manual control required the simultaneous monitoring of multiple process parameters, proper anticipation of emerging trends, and understanding of the impact of clarifier valve position on aeration basin mixed-liquor depths, and frequent adjustment – making proper control inherently challenging and prone to disturbance and high variability (Figure 4).

With D.O. concentration closely linked to mixed-liquor depth control; the limitations of manual depth control amplified the challenge of manual oxygen feed control. Historically, oxygen supply to each basin was adjusted 'as needed' based on a real-time trend of the effluent D.O. concentration. The time between an oxygen supply adjustment and its observed impact on the effluent D.O. can be more than five hours. This meant that effective manual D.O. control required an understanding of the relationship between the present oxygen flow and the future D.O. concentration. Combined with oxygen demand increases and decreases driven by highly variable mixed-liquor depth, this produced sub-optimal D.O. control, characterized by frequent over-correction (Figure 5).

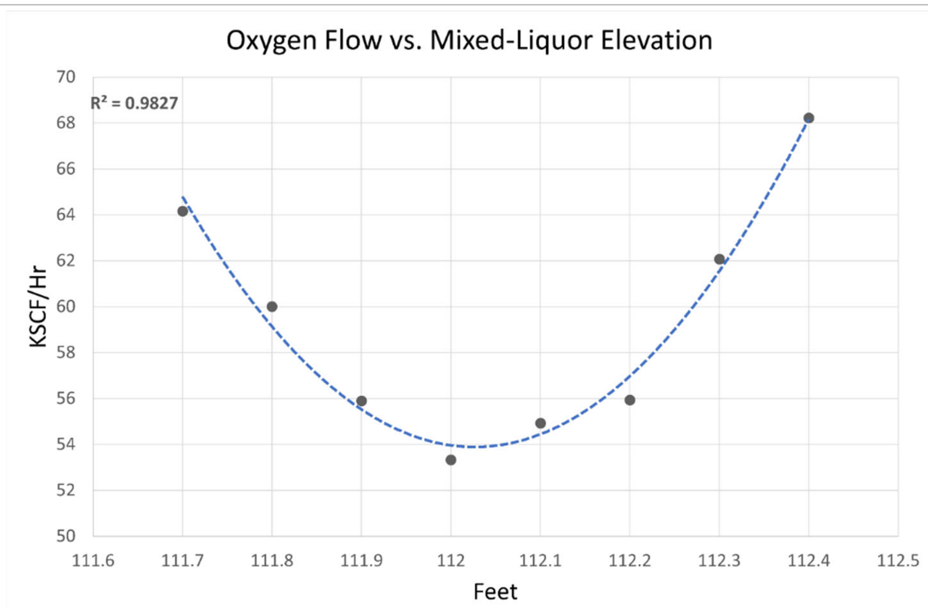

Figure 3: Aeration basin 1 (typical) oxygen flow in KSCF/Hour vs. mixed-liquor elevation. The oxygen supplied to the basin increases as the elevation diverges from ~112'

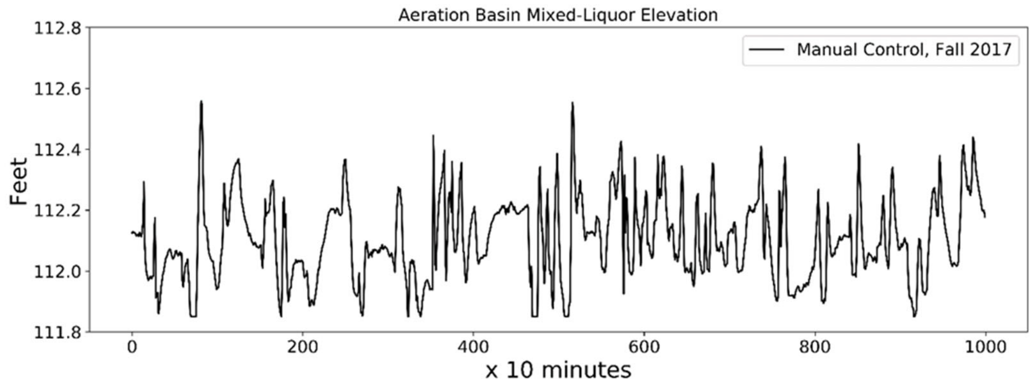

Figure 4: Aeration basin 1 (typical) mixed-liquor elevation under manual control.

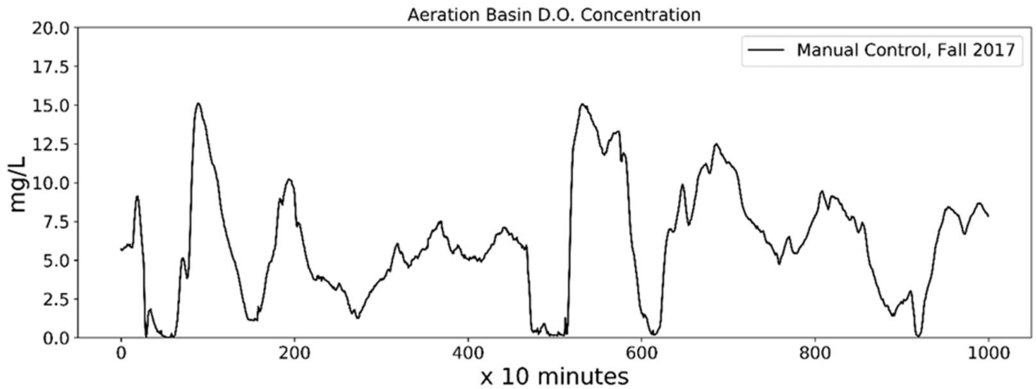

Figure 5: Aeration basin 1 (typical) effluent dissolved oxygen concentration under manual control.

Automation of secondary controls was introduced in two phases with the goal of reducing variation and excess oxygen use. The first phase focused on automating aeration basin mixed-liquor depth control through influent-effluent flow balancing. The second phase automated aeration-based effluent D.O. concentration control through model predictive control (MPC).

Optimized Depth Control Strategy

Analysis of historical process data and direct response-testing (using the existing manual controls) led to the adoption of a feedforward + feedback (Figure 6) automation strategy based on flow-balancing.

The flow-balance controls manipulate a common flow setpoint for each of the clarifiers. As level control is an integrating process, the mixed-liquor depth will rise or fall unless the inflow to the aeration basins matches the outflow, making the feedforward portion the primary means of control.

The feedforward loop serves to trim the flow setpoint to compensate for flow imbalances arising during transient events and other process disturbances. Setpoint adjustments are determined based on mass balance; as the sum of the total aeration basin influent (equal to the primary effluent + RAS flow) changes, the setpoint is adjusted to match the new influent flow.

Feedback consists of two proportional–integral–derivative (PID) loops, the first of which operates based on the maximum value of the available aeration basin level transmitters. The second feedback, the override circuit, utilizes the maximum of the basin-averaged mixer motor currents. In each control cycle, the highest output of the two feedback loops is selected and added to the feedforward loop.

The override circuit protects against high-depth upset events, overriding the normal behavior of the flow-balance controls in scenarios where the mixed-liquor depths rise towards the programmed mixer high-load protection trip setpoint. At normal depths and mixer loads, the override PID winds down to zero, leaving only the level-transmitter loop active.

To enable precise control, only 15 of the 25 clarifiers are placed in flow-balance mode, with the remaining operating with a constant inflow.

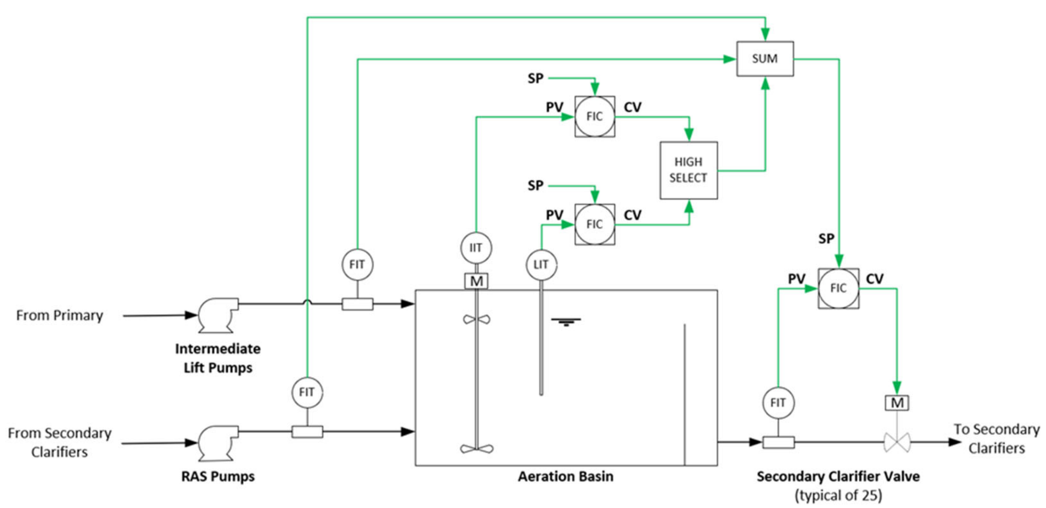

Figure 6: Depiction of the level control logic. Flow (FIT), mixer current (IIT), and level (LIT) transmitters are indicated. The three flow controllers (FIC) are depicted with setpoint (SP), process variable (PV) and controlled variable (CV) labelled. (Details in text).

DO Control Strategy

Due to the time lag between oxygen flow rate adjustment and the effluent D.O. concentration response, automation of aeration basin D.O. control adopted a model-based predictive control strategy with D.O. concentration feedback (Figure 7).

Model predictive control (MPC) is a control technique where a control sequence is solved from the optimization of a quadratic cost function over a prediction horizon at each sampling time. Only the first control move in the sequence is applied, and the whole optimization process repeats at the next sampling time. One of the major advantages of MPC is its ability to handle process constraints explicitly, additionally, MPC is inherently a high-order controller which makes it an ideal candidate for dealing with high-order process dynamics, such as the dynamics induced by large pure time delay.

The MPC controller produces an oxygen flow setpoint, which is transferred to an inner oxygen valve PID control loop (in cascade) that determines the oxygen flow valve setpoint.

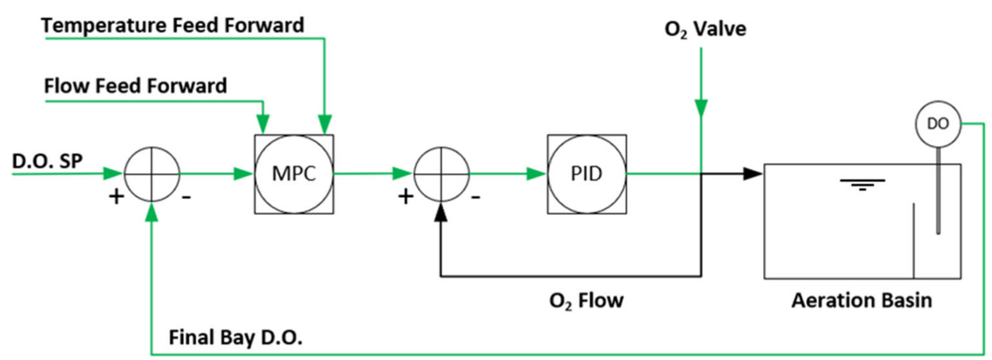

Figure 7: Depiction of the effluent dissolved oxygen (D.O.) control logic. (Details in text).

The D.O. response to changes in oxygen flow rate was modeled based on historical process data (Figure 8) limited to periods of stable process conditions (i.e. constant wastewater flow, temperature, etc.) where the D.O. to oxygen flow relationship was more easily determined. The use of historical data eliminated the need for open-loop step response testing. Using the modeled response, two process feedforwards (temperature and influent flow, described below), and the D.O. feedback, the MPC determines the optimal series of oxygen flow adjustments required to minimize the deviation between the predicted D.O. trajectory and the target D.O. setpoint over a five-hour horizon. The first of these adjustments is forwarded to the valve control PID each control cycle.

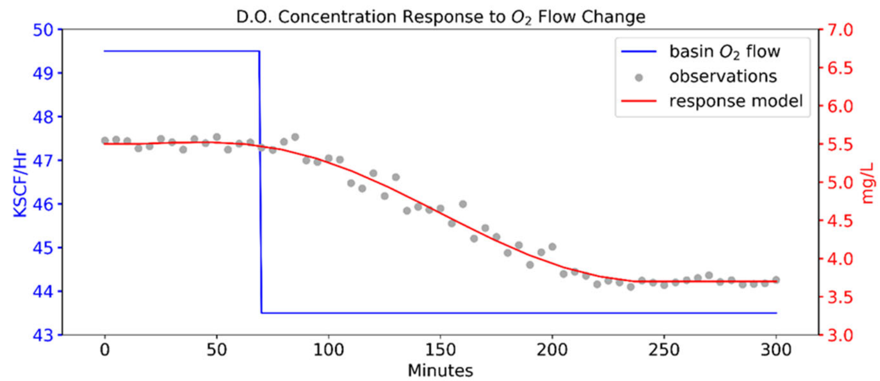

Figure 8: Representative D.O. concentration response to a step-change in oxygen flow. (Details in text).

The mixed-liquor temperature and aeration basin influent flow (including RAS) serve as (feedforward) inputs to the MPC, adjusting its output in response to live conditions in the basin. The feedforwards were selected based on modest correlation with the supplied oxygen flow as determined by analysis of historical data.

Identical logic was implemented for each aeration basin, with basin-specific tuning and setpoint optimization performed during initial control testing.

Two layers of constraint ensure that the D.O. control logic always provides appropriate oxygen to the aeration basins. The constraints (hard and dynamic) prevent over or under supply of oxygen in case of D.O. probe failure or erroneous low or high concentration readings. Hard limits prevent the MPC output oxygen flow setpoint from rising below or above seasonally adjusted (i.e., higher in summer and lower in winter) bounds. Dynamic limits are computed for each control cycle based on the real-time mixed-liquor temperature and aeration basin influent flow. Historical process data was used to determine a model of the 20th and 80th percentile oxygen flows as a function of the temperature and flow (Figure 9). The MPC output is constrained to fall between the maximum (minimum) of the hard and dynamic lower (upper) bounds.

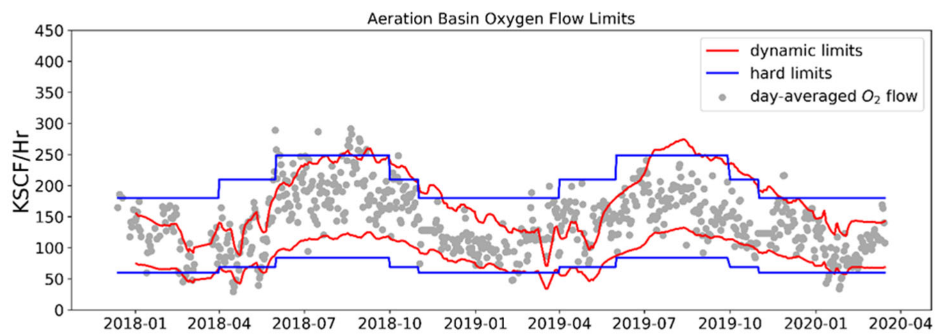

Figure 9: Dynamic and hard (seasonal) limits on the oxygen flow rate to all in-service basins applied to historical process data. (Details in text).

Results

Automated flow balancing and dissolved oxygen controls have produced substantial reductions in process variation and oxygen consumption (Figures 10 through 14).

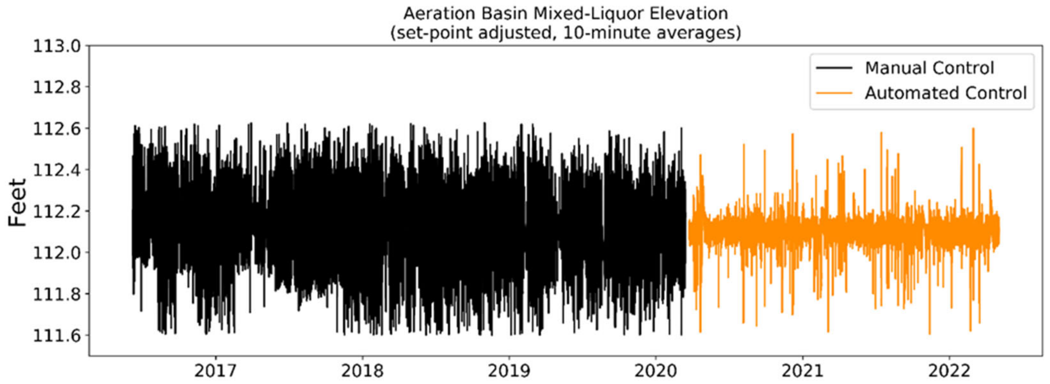

Figure 10: Operating set-point adjusted maximum mixed-liquor elevation of in-service aeration basins under manual (black) and automated (orange) control.

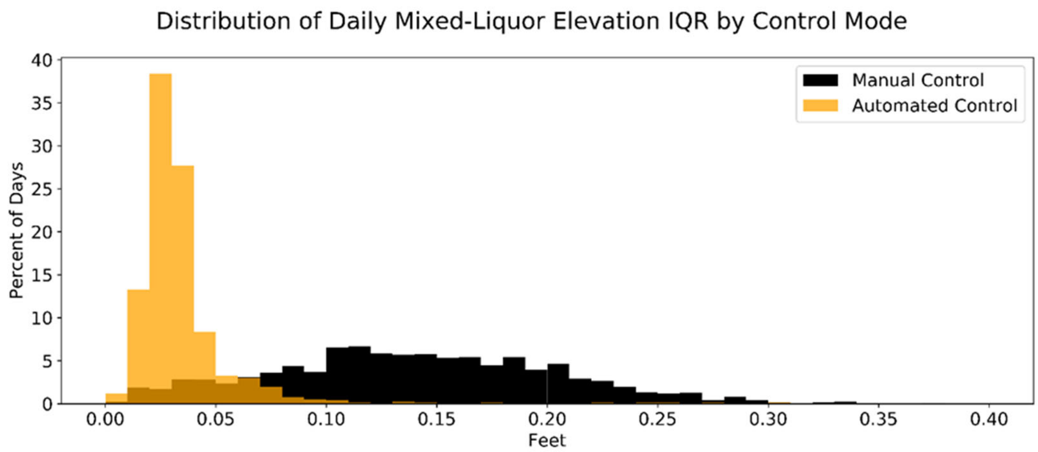

Figure 11: Distribution of the daily average mixed-liquor elevation under manual (black) and automated (orange) control. Automation achieves a 74% reduction in interquartile range compared to manual control.

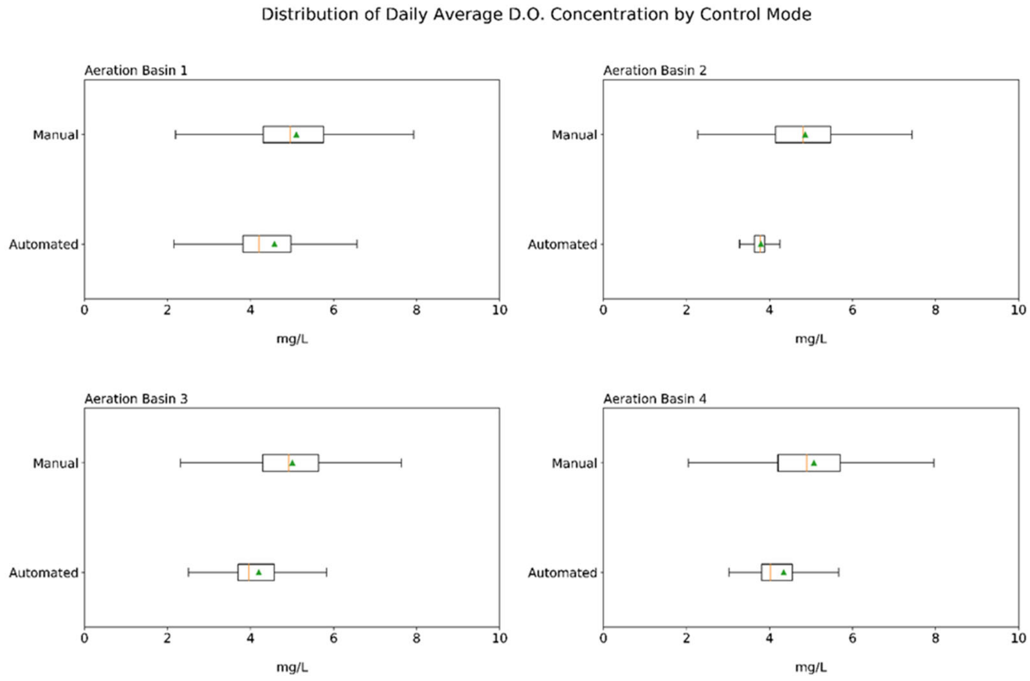

Figure 12: Distribution of day-average D.O. concentration by control mode for each of the four aeration basins. The IQR (box), median (orange line), average (green triangle), and whiskers (quartile 1 - 1.5 x IQR, quartile 3 + 1.5 x IQR) are depicted.

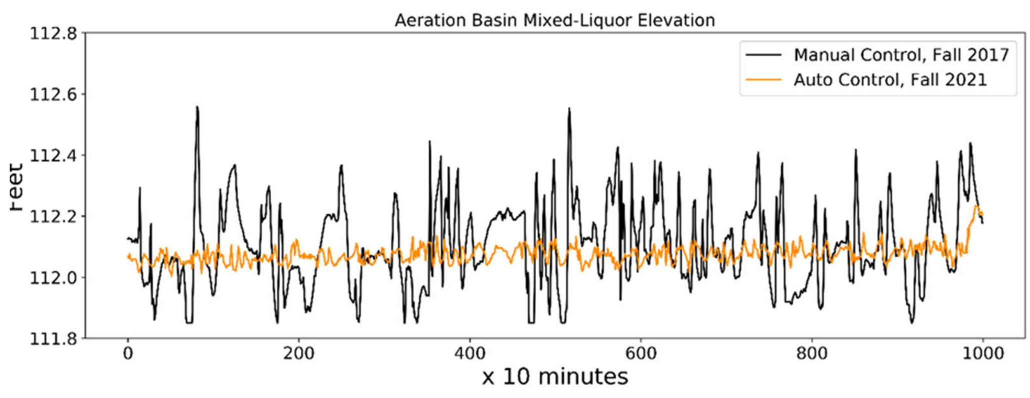

Figure 13: Typical mixed-liquor elevation under manual (black) and automatic (orange) control.

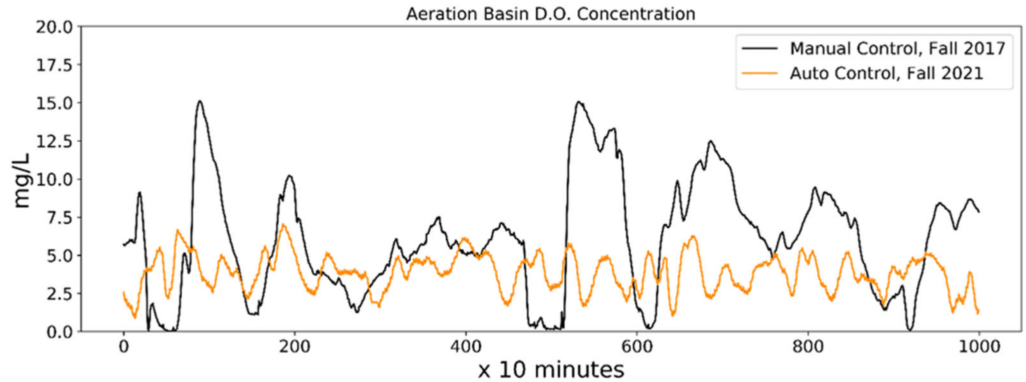

Figure 14: Typical effluent dissolved oxygen concentration under manual (black) and automatic (orange) control.

The combined oxygen flow rate to the aeration basins decreased from a baseline of 166 KSCF/hour under manual control to an average of 114 KSCF/hour under full automation (Figure 15). This reduction in oxygen usage represents a cost reduction of $1.01 million each year (at 2019 rates) when compared to the 2011-2019 baseline of $3.42 million per year (Figure 16).

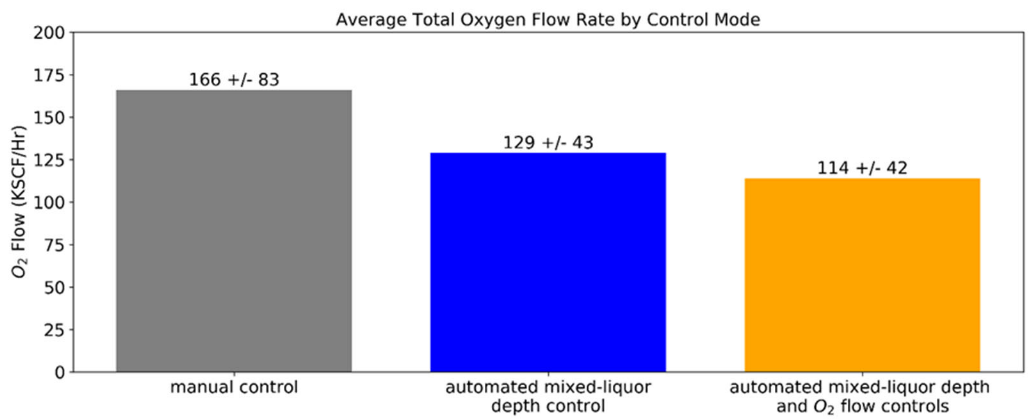

Figure 15: Average +/- one standard deviation of the total oxygen flow rates in KSCF/Hour to all in-service aeration basins by available control mode. The manual control (grey) average of 166 +/- 83 KSCF/Hour is based on a 2011 to 2019 baseline. The depth control (blue) average of 129 +/- 43 KCSF/Hour is based on 316 days of operation before the introduction of O2 flow control during which the automated depth controls were engaged 96.7% of the time. The depth + O2 flow control (orange) average of 114 +/- 42 KCSF/Hr is based on 465 days of operation, during which both depth and O2 controls were active 94.9% of the time. Eliminating periods of manual control reduces the automated depth control average to 122+/-30 KSCF/Hr, and reduces the automated depth + O2 flow average to 105 +/- 28 KSCF/Hr.

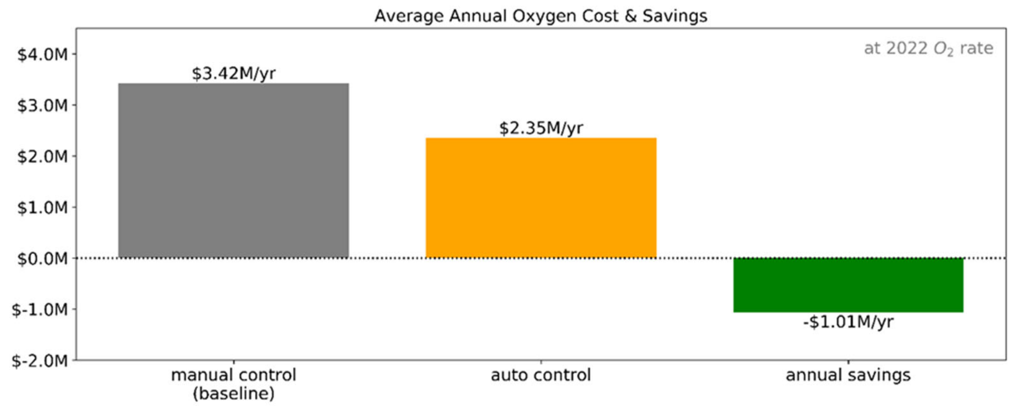

Figure 16: Average annual oxygen cost under manual control (2011-2019 baseline) and automated control. The introduction of automated control achieved a cost reduction of $1.01 million per year at 2019 rates.

Conclusions

The introduction of automated flow balance and oxygen supply controls produced substantial reductions in process variation and oxygen consumption. These reductions were achieved without negative effect on downstream wastewater treatment metrics and did not require the addition of new treatment infrastructure or instrumentation. The collaboration between Emerson and the water authority for the aeration control optimization project serves as an example of the beneficial impact of automation in improving treatment-process performance.

Further improvement may be achieved through the use of advanced diagnostic algorithms capable of detecting a malfunction of key control elements (e.g., dissolved oxygen probes, level transmitters, mixer motors) and through the incorporation of additional process data (e.g., headspace oxygen purity, additional D.O. probes located mid-basin).